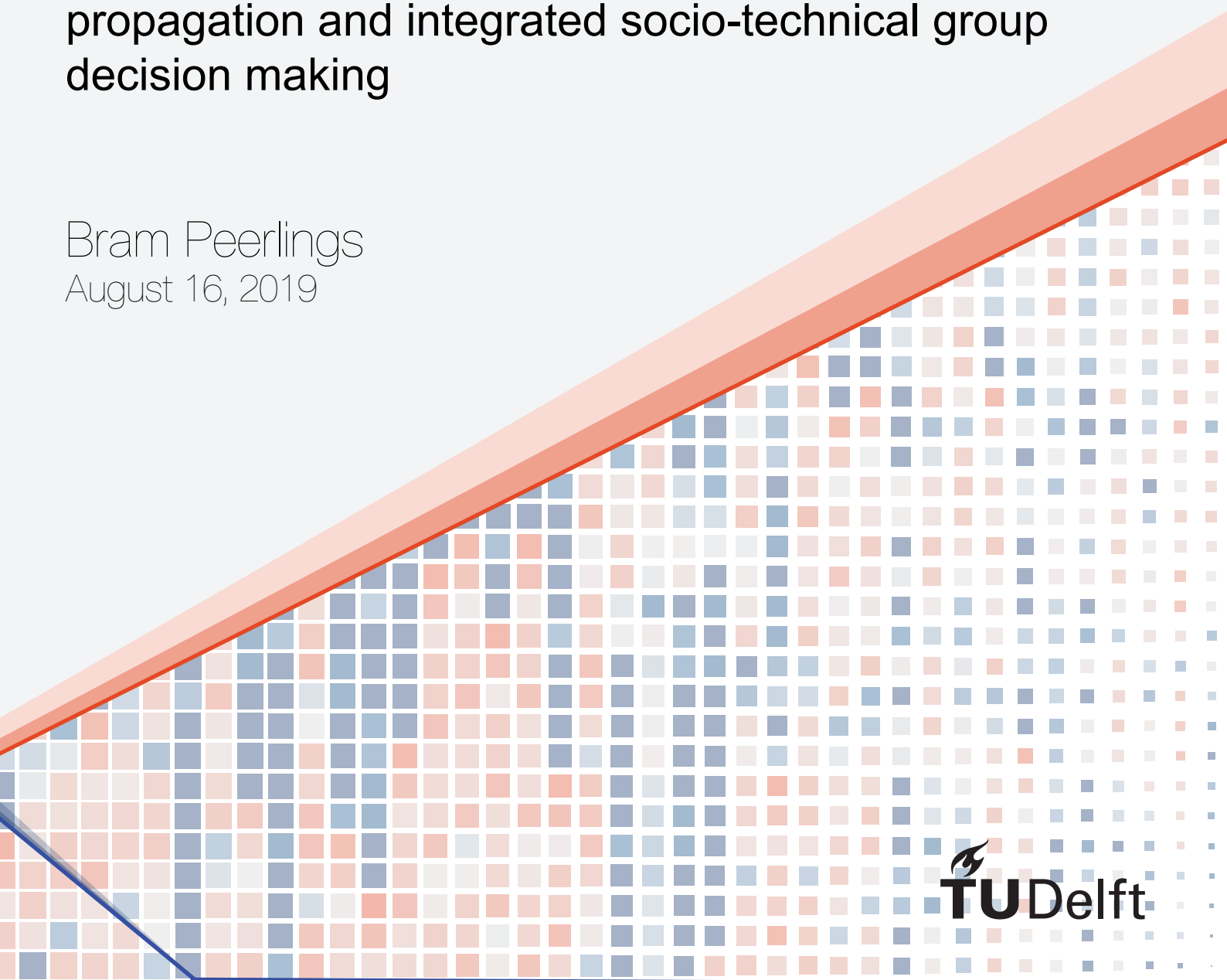
Holistically improving screening decisions under uncertainty in aircraft conceptual design and technology assessment

Insights on bottom-up uncertainty quantification and propagation and integrated socio-technical group decision making

Bram Peerlings

August 16, 2019



TU Delft

The cover art (spanning both back cover, spine and front cover) is a combination of two visualisations of which this report contains many, many examples. The diagonal lines and bands represent the socio-psychological perspective; the square blocks refer to the technical perspective. The colouring of these blocks – in an abstract way – summarise this report and thesis work: it is a heat map of the base-10 logarithm of the frequency of characters of the text (letters, numbers, operators, ...). Each row represents a different character and each column shows a set of pages. Low frequencies are blue and high frequencies are orange.

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Holistically improving screening decisions under uncertainty in aircraft conceptual design and technology assessment

Insights on bottom-up uncertainty quantification and propagation and integrated socio-technical group decision making

by

B. (Bram) Peerlings

in partial fulfilment of the requirements for the degrees of

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in Aerospace Engineering

and

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in Science Communication

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Preface

Halfway through June, 2017, the first ideas on this thesis manifested themselves. “Something involving conceptual aircraft design, uncertainty and decision making on that topic.” A little over two years later I find myself overlooking the campus of Delft University of Technology from the third floor of the Applied Sciences building, enjoying the sun, as it has finally managed to break through the clouds after a day of rain and storm.

It is a sight and an atmosphere I am surely going to miss when graduate life starts, not so long from now. Nevertheless, it is also satisfying to close the book – with the report that you have just opened. As the remainder of this text will show, my earliest ideas have stood the test of time. My thesis, a combined effort in Aerospace Engineering and Science Communication, explores group decision making about aircraft conceptual design and technology assessment and selection from two perspectives: one is largely technical, the other socio-psychological. The technical subject content is of course firmly rooted in the aerospace domain, but I am quite confident that people from different backgrounds and different industries can relate to the socio-psychological perspective without any problems. That holds even more so for the insights obtained from the integration of these two perspectives. As it is my total conviction that knowledge should not be contained in silos, but rather be spread and shared, I encourage everybody to turn the page and read on.

If you do, I would love to hear from you – if you choose to further explore one of the paths indicated as future opportunity, as well as if you find anything you disagree with or don’t understand. There is never a bad time for exchanging ideas on decision making, conceptual aircraft design, and how the ‘blue’ and ‘orange’ parts of life interact.

Bram Peerlings
Delft, August 16, 2019

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However much the ideas and results documented in this thesis are my own, I could not have hoped to complete this work without the help of so many others.

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Moreover, I would like to express my gratitude to Maurice Hoogreef and Reno Elmendorp for helping me navigate the extensive – but fairly poorly documented – collection of lower-level aerodynamic solvers in existence and providing feedback on my ideas on assessing uncertainty propagation with the Aircraft Design Initiator. Feedback from Richard Dwight, furthermore, was instrumental in separating the influence of solution method and flow model. Our first interactions immediately sent all the schemes I had devised up to then out the window, but surely made a change for the better. Closing the more formal part, I am grateful to the Science Education and Communication department for reimbursing software expenses as well as being a fantastic host to its graduate students, to the Technology Licensing Office of Massachusetts Institute of Technology for assisting me in obtaining one of the aerodynamic solvers investigated in this project and to various people of the TU Delft Library for helping my retrieve numerous sources I could not get my hands on in the first place.

And then, there is a long list of (former and current) fellow students and friends. My gratitude goes out to all with which I got to spend time in the Science Communication graduation room, as well as to the people that helped me unwind from that. In particular, I would like to show my appreciation to Anne, Eline, Linda, Sander, Anne, Martine, Oukje, Rik, Bianca and Sophie for helping me structure my thoughts on the integration of the technical and socio-psychological perspectives and writing this research down on paper. Both their support and encouragement, as well as the necessary critical remarks to get my feet back on the ground again have proven invaluable.

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Summary

Uncertainty about the performance of new technologies, as well as about market requirements, make aircraft design a difficult business. Especially in the conceptual design phase, the stakes are high. Decisions made in that phase determine committing to technology early on and going back on these choices is extremely costly. In that context, the current thesis makes a contribution to holistically improving group decisions about technology assessment and selection from two perspectives: a technical one and a socio-psychological one. Through the insights gathered this way, knowledge is gained about the integration of these two domains.

Lacking a clear description in literature, decision quality was first defined as the extent to which a (group of) decision maker(s) at the decision point is able to convince an ideal observer that the decision will yield the decision goal, insofar possible. Inspired by the notion of an ideal gas, the ideal observer was introduced to strike a balance between being able to objectively determine the quality of a decision and to do so based on trust in the decision-making process, generally corresponding to situations of low and high uncertainty. The results of an extensive systematic literature review into factors influencing decision quality were clustered into four main groups: contextual and supportive factors (such as time, facilities and resources), technical factors (information), socio-psychological factors (team, discussion and fit) and implementation factors (clarity and commitment to the decision). Of these groups, the first three influence decision making quality and thereby affect decision quality, whereas the implementation factors are proposed to directly influence the quality of the decision. An important distinction was made between decision quality and outcome desirability. Especially under uncertainty, external influences of which the decision maker(s) had no knowledge at the decision point can prevent a good decision from yielding a gratifying outcome.

In the technical perspective, the uncertainty associated to three two-dimensional aerodynamic solvers – following from physical flow model assumptions or numerical solution method differences – was assessed and propagated. Both a symmetrical and a cambered airfoil were investigated, at a wide range of Mach numbers and angles of attack. The influence of solution method was determined using grid refinement studies, whereas the impact of the incompressible and irrotational flow assumptions are analysed using a comparison of two solvers (XFOIL versus VGK and VGK versus MSES, respectively). The identified influences were propagated to different wing geometries using a vortex lattice method and their impact on aircraft(-level) characteristics and performance indicators was qualitatively assessed with a aircraft synthesis program. It was found that the influence of flow model clearly outweighs the impact of solution method. Three-dimensional effects were found to be consistent with two-dimensional results, affected by aspect ratio, sweep angle and taper. The aircraft synthesis program showed very little sensitivity to the effects of the assumptions investigated. Due to the uncertainty associated to the tool, the insignificant effect of the assumptions on the conceptual design could not be uniformly established. Nevertheless, given the earlier successful application of the tool to conceptual design processes, the results obtained raise critical questions about the currently observed push for higher-fidelity analysis methods in aircraft conceptual design.

In the socio-psychological perspective, document review, interviews and observations were used to define what socio-psychological factors negatively impact group decision making in project MANTA, an international public-private research consortium aiming to contribute to aircraft fuel burn reduction by devising, testing and evaluating novel concepts for wing movables in various stages of increasing detail. It was found that the quality of screening decisions is negatively impacted by the fact that goal uncertainty exists and is not sufficiently explicated, reduced or otherwise managed. Based on vigilant interaction theory and (the conceptual foundations of) effective intercultural workgroup communication theory, a theoretical framework was used to develop the TARE-model. At the core is the balance between task (TA) and relationship (RE) outcomes, which are related to uncertainty about the goals and how these can

be achieved. Whereas it is straightforward to actively shift focus in order to adjust the balance between task and relationship, the model shows other parameters – such as various forms of uncertainty – can be tuned to achieve the same result. Anticipated use of the model as a tool promotes explicit discussion about the goals to which decisions aim to contribute and gives insights into how group integration, uncertainty and the balance between task and relationship changes with time.

The insights obtained from the technical and socio-psychological domains were synthesised to answer the main question of this research: *How can technical and socio-psychological perspectives be integrated in order to improve group decision quality under uncertainty in aircraft conceptual design and technology assessment and selection?* Rather than answering it, its premise was refuted using a thought experiment: the technical and socio-psychological perspectives are already integrated, but that we struggle to appreciate that integration. Although both domains can evidently be distinguished, it was argued it is impossible to completely separate them. Uncertainty was put forward as the primary variable impacting the interwovenness of the two perspectives. Applying this conclusion to the results from the technical and socio-psychological domains and the observation that various other factors proved to have a much more driving influence on decisions than analytical results in project MANTA, the question is raised whether increased computational power and additional models are the most effective way to substantially improve the quality of decisions in conceptual design and technology assessment and selection projects.

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List of Abbreviations

Abbreviation	Definition
AAI	Adaptive Air Intake (project MANTA)
AB	Advisory Board (project MANTA)
ABET	Accreditation Board of Engineering and Technology
ACARE	Advisory Council for Aeronautics Research in Europe
ADI	Aircraft Design Initiator
AE	Aerospace Engineering
ARC2D	Ames Research Center 2D
AVL	Athena Vortex Lattice
BL	Boundary Layer
CFD	Computational Fluid Dynamics
CP	Consortium Partner (project MANTA)
CS	Clean Sky
CSJU	Clean Sky Joint Undertaking
DATCOM	US Air Force Data Compendium
DAV	Dassault Aviation
DERA	Defence Evaluation and Research Agency
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DNS	Direct Numerical Simulation
DoA	Description of Action (project MANTA)
DOC	Direct Operating Cost
EC	European Commission
ESDU	Engineering Sciences Data Unit
EXT	External party (project MANTA)
FAE	Fokker Aerostructures
FDM	Finite Difference Method
FEM	Finite Element Method
FF	Fuel Fraction
FM	Fuel Mass
FTH	Fokker Technologies Holding
FVM	Finite Volume Method
HSBJ	High-Speed Business Jet (reference aircraft platform, project MANTA)
IADP	Innovative Aircraft Demonstrator Platform
ICAO	International Civil Aviation Organisation
ITD	Integrated Technology Demonstrator
L0, L1, L2, L2.5, L3	Fidelity Level (low to high)
LE	Leading Edge
LES	Large Eddy Simulation
LLT	Lifting Line Theory
LR	Long Range (reference aircraft platform, project MANTA)
LRA	Long Range Aircraft (reference aircraft platform, project MANTA)
LST	Lifting Surface Theory
MANTA	MovAbles for Next generaTion Aircraft
MATRICS	Multi-component Aircraft Transonic Inviscid Computation System
MAV	Micro-Aerial Vehicle
MIT	Massachusetts Institute of Technology

Abbreviation	Definition
MDO	Multidisciplinary Design Optimisation
MTOM	Maximum Take-Off Mass
NACA	National Advisory Committee for Aerodynamics
NASA	National Aeronautics and Space Administration
NLR	Netherlands Aerospace Centre (Nederlands Lucht- en Ruimtevaartcentrum)
NRC	Non-recurring cost
OEM	Operating Empty Mass
OEM	Original Equipment Manufacturer
PMC	Project Management Committee (project MANTA)
POC	Point of Contact (project MANTA)
Q3D	Quasi-three-Dimensional aerodynamic solver
R&D	Research and Development
RAE	Royal Aircraft Establishment
RANS	Reynolds-Averaged Navier-Stokes
RC	Recurring cost
SA	Single-Aisle (reference aircraft platform)
SAAB	SAAB Group
SC	Science Communication
SC	Steering Committee (project MANTA)
SFC	Specific Fuel Consumption
T/W	Thrust-to-weight ratio
TBD	To Be Determined
TA	Target Application (project MANTA)
TE	Trailing Edge
TL	Topic Leader (project MANTA)
TLNS	Thin-Layer Navier-Stokes
TMT	Top Management Team
TRL	Technology Readiness Level
TS	Technology Stream (project MANTA)
TUD	Delft University of Technology
URANS	Unsteady Reynolds-Averaged Navier-Stokes
UAV	Unmanned Aerial Vehicle
VGK	Viscous Garabedian and Korn
VII	Viscous-Inviscid Interaction
VLM	Vortex Lattice Method
VSAERO	Vortex Separation Aerodynamics
W/S	Wing loading
WP	Work Package (project MANTA)
WPL	Work Package Leader (project MANTA)
XML	Extensible Markup Language

The abbreviations used to distinguish between the results of various (forms of) aerodynamic solvers in Chapters 6 and 7 are listed and defined in Table 6.1 on page 65.

List of Symbols

Latin symbols

Symbol	Context	Definition	Unit
$\mathcal{AR}$		Aspect ratio	[-]
a	MSES	Grid spacing tuning variable (1)	[-]
b	MSES	Grid spacing tuning variable (2)	[-]
b		Wing span	[m]
c		Chord length	[-]
c		Number of coordinate points at which convergence is obtained	[-]
$\bar{c}$		Mean aerodynamic chord	[-]
c_d		Drag coefficient	[-]
$c_{d,f}$		Friction drag coefficient	[-]
$c_{d,l/d_{max}}$		Drag coefficient at maximum lift-to-drag ratio	[-]
$c_{d,p}$		Pressure drag coefficient	[-]
$c_{d,v}$		Viscous drag coefficient	[-]
$c_{d,w}$		Wave drag coefficient	[-]
c_f		Local skin friction coefficient	[-]
c_l		Lift coefficient	[-]
$c_{l,\alpha}$		Lift curve slope	[rad^{-1}]
$c_{l,l/d_{max}}$		Lift coefficient at maximum lift-to-drag ratio	[-]
$c_{l,max}$		Maximum lift coefficient	[-]
c_m, $c_{m,c/4}$		Pitching moment coefficient about quarter-chord	[-]
$c_{m,\alpha}$		Pitching moment derivative	[rad^{-1}]
C_D		Drag coefficient	[-]
C_L		Lift coefficient	[-]
$C_{L,\alpha}$		Lift slope	[-]
$C_{L,max}$		Maximum lift coefficient	[-]
C_m		Pitching moment coefficient	[-]
$C_{m,\alpha}$		Lift slope	[-]
C_p		Pressure coefficient	[-]
$C_{p,0}$		Incompressible pressure coefficient	[-]
$C_{p,avg}$	XFOIL	Pressure coefficient, averaged over panel	[-]
$C_{p,diff}$		Difference between pressure coefficient at two adjacent panels	[-]
$C_{p,min}$		Minimum pressure coefficient	[-]
C_τ	XFOIL, MSES	Shear stress coefficient	[-]
d_x	XFOIL	Panel length in x-direction	[-]
d_y	XFOIL	Panel length in y-direction	[-]
D		Drag force	[N]
e		Oswald (span efficiency) factor	[-]
f		Body force	[N]
H	XFOIL, MSES	Boundary layer shape parameter, δ^*/θ	[-]
H^*	MSES	Boundary layer kinetic energy shape parameter, θ^*/θ	[-]
H_{avg}	MSES	Average boundary layer shape factpr	[-]

Symbol	Context	Definition	Unit
i, j, k		Indices	[-]
l/d_{max}		Maximum lift-to-drag ratio	[-]
$\dot{m}$		Mass flow	[kg/s]
M		Mach number	[-]
M_∞		Mach number, free stream conditions	[-]
$\overline{M_\infty}$		Mach number (grouped), free stream conditions	[-]
M_{Lsh}	VGK	Local Mach number, just upstream of the shock wave	[-]
$n, \tilde{n}, N$	XFOIL, MSES	Logarithm of the amplification factor of the frequency of the most unstable Tollmien-Schlichting wave	[-]
N		Total number of coordinate points	[-]
N_1, N_2		Class function parameters in CST-representation	[-]
N_{SG}	VGK	Number of radial grid lines	[-]
Q		Quantity of interest	
p		Pressure	[N/m^2]
r_x	XFOIL	Distance from the panel midpoint to the reference position in x-direction	[-]
r_y	XFOIL	Distance from the panel midpoint to the reference position in y-direction	[-]
Re		Reynolds number	[-]
S		Wing surface area	[m^2]
t		Thickness	[-]
u_e		Velocity at the boundary layer edge	[m/s]
V_∞		Velocity, free stream conditions	[m/s]
$(x/c)_{C_{p,min}}$		Chordwise location of minimum pressure coefficient	[-]
x_i	XFOIL	x-coordinate of panel i	[-]
x_{ref}	XFOIL	x-location of pitching moment coefficient reference location	[-]
y_i	XFOIL	y-coordinate of panel i	[-]
y_{ref}	XFOIL	y-location of pitching moment coefficient reference location	[-]

Greek symbols

Symbol	Context	Definition	Unit
α		Angle of attack	[°]
$\overline{\alpha}$		Angle of attack (binned)	[°]
$\alpha_{l/d_{max}}$		Angle of attack at maximum lift-to-drag ratio	[-]
$\alpha_{L=0}$		Zero-lift angle of attack	[°]
α_{step}		Angle of attack step size	[°]
γ_i	XFOIL	Vortex strength at panel i	[m/s]
δ^*		Boundary layer displacement thickness	[m]
Δs	MSES	Local arc-length increment	[-]
Δs_{avg}	MSES	Average arc-length increment	[-]
ϵ	VGK	Artificial viscosity parameter	[-]
κ		Local surface curvature	[-]
$\bar{\kappa}$	VGK	Mean surface curvature over a section up to the foot of the shock	[-]
θ		Boundary layer momentum thickness	[m]
θ	VGK	Angle with chord, in airfoil representation	[°]

Symbol	Context	Definition	Unit
κ_w	VGK	Local surface curvature at the foot of the shock	[-]
λ	VGK	Partially-conservative parameter	[-]
λ		Taper ratio	[-]
Λ		Sweep angle	[°]
ρ		Density	[kg/m^3]

Common subscripts

Subscript	Definition
$clean$	Clean conditions
$cruise$	Cruise conditions
e	Edge of the boundary layer
$exit$	Exit of the wake
$landing$	Landing conditions
u	Unswept
s	Swept
$take-off$	Take-off conditions

Operators

Operator	Definition
$\pm$	Plus-minus, used to indicate two values of exactly opposite sign
$\approx$	Approximately, used to indicate a variable is almost equal to a value
$\lvert\ \rvert$	Magnitude
Δ	Difference

1

Introduction

Making good decisions is difficult. Especially under uncertainty, people are known to be biased and act irrationally (Kahneman, 2011; Tversky and Kahneman, 1974; Ariely, 2008), resulting in sub-optimal choices. Furthermore, uncertainty and ambiguity favour opportunism – yielding groups that pursue more or less, but not exactly, identical objectives and hence are not able to make the decisions that help them reach their desired end result (Um and Kim, 2018; Williamson, 1985; Walker and Weber, 1984; Carson et al., 2006). In the aerospace industry, where large sums of money are involved and both design processes as well as product life times are long, the cost of such a wrong decision can be tremendous. These costs can be incurred by the company making the decision – as it might put its product at a competitive disadvantage – but might have consequences far beyond the factory walls. For example, a new aircraft introduced that is only a little bit less fuel efficient than it could have been, will be transporting passengers and cargo – thereby impacting the environment – for decades to come.

As this thesis was written as part of a joint research effort of Aerospace Engineering and Science Communication[1], it addresses the aforementioned challenge from two perspectives. The first is mostly technical: how can we quantify the uncertainty associated to innovations considered for implementation in new aircraft? The second is largely socio-psychological: how can we improve the decision making process, in order to improve the quality of the decisions that result? By subsequently integrating these perspectives, a holistic solution is pursued.

The questions raised before are broad ones, on which one could spend a lifetime. As that is not available, this thesis investigates one particular project: project MANTA. Project MANTA, short for MovAbles for Next generaTion Aircraft, is a part of the European Union's Horizon 2020's Clean Sky 2 research programme in which Delft University of Technology cooperates with various research centres and industry partners to develop aircraft movables to improve airframe efficiency and reduce CO_2-emissions. As such, it fits in a wider research and development trend aiming to realise a step change in wing design, investigating approaches as load control and higher functional integration of previously separated (sub)systems (Reckzeh and Wijn, 2019).

The remainder of this introduction is structured as follows. Section 1.1 elaborates on the motivation of this research. The research objectives – both on an industry and an academic level – are treated in Section 1.2, before moving on to the research questions in Section 1.3. Section 1.4 (graphically) illustrates the outline of the project and explains the structure of this thesis report. That section also includes a reading guide.

[1] The Science Communication programme is scheduled to be renamed *Communication Design for Innovation* from academic year 2020/2021 onward. Everywhere this thesis reads *Science Communication*, it could have read *Communication Design for Innovation*, as the problem type and research methodologies employed are typical of the updated programme.

1.1. Motivation

Whereas improvements in speed, range and luxury once were main drivers of aircraft innovation, reductions in fuel consumption and emissions today are of primary concern. Air travel doubles every 15 years and is expected to continue to do so (Airbus S.A.S., 2017; Boeing Commercial Airplanes, 2017). On the other hand, battling climate change is higher on the agenda than ever. Although the aviation industry is no party to the 2015 Paris Agreement (Air Transport Action Group), the International Civil Aviation Organisation (ICAO) and industry have committed to achieving carbon-neutral growth by 2020 and a reduction of net CO_2-emissions by 50% in 2050, compared to 2005 levels (Air Transport Action Group, 2015).

Even though not everyone is convinced of the fact that these goals will be enough (e.g. Peeters (2017), who argues that the only way to meet the Paris goals is to reduce our appetite for air travel), they yield a continued quest to lower emissions. Some efforts to achieve that are of a more disruptive nature, such as hybrid- or full-electric aircraft, novel configurations or new transportation concepts altogether. Others focus on incremental improvements by increasing efficiency, for example on an aerodynamic, structural or operational level.

Project MANTA firmly belongs to that second category[2]. In this project, a multitude of concepts is generated and subsequently evaluated, after which the most promising ones are selected for further development. The technology assessment is done at both concept as well as system or aircraft level, in order to also take (synergistic or discordant) second-order effects into account. A conceptual aircraft design tool under continuous development at Delft University of Technology (called the *Aircraft Design Initiator*), in the faculty of Aerospace Engineering's department of Flight Performance & Propulsion, is used to perform these higher-level analyses.

Whereas the tool has currently mostly been used for design studies (van Dommelen and Vos, 2014; van Bogaert, 2015; Zohlandt, 2016; van den Dungen, 2017; Cnacino Queirolo, 2018; Brown and Vos, 2018; Mancini, 2018), application in technology assessment programmes is relatively novel (van Haver and Vos, 2015; Bertels et al., 2016). Although the tool was successfully employed in these cases, it is argued that it is not optimally equipped for it. Indeed, although uncertainty quantification is of critical importance for technology assessment (Helton et al., 2007) and its opportunities in design are recognised in literature (Roelofs and Vos, 2018b; Zang et al., 2002), it has only been developed to a limited extent in the Aircraft Design Initiator (van Haver and Vos, 2015), using an interval analysis to propagate input uncertainties obtained from expert elicitation. Whereas that indeed provides a (partial) quantification of output uncertainty, it treats the tool as black box, so that no *knowledge* is gained regarded the origin, behaviour and interaction of the uncertainties. This impedes improvement of these models, at is remains unknown what interventions will have most effect on increasing the capabilities of the system.

Having an quantification of the uncertainty of particular data, however, does not directly yield a good decision. Decision makers, for example, need to interpret the data and assess what level of uncertainty is acceptable, given the context and goal of the decision. Furthermore, as the first paragraph of this report already indicated, a host of other factors can influence the decision making process and its outcome. Which one is – or which ones are – most important in projects such as project MANTA, however, remains largely unknown. And similar to the technical perspective, it difficult to effectively improve a system of which its exact inner workings are unknown.

1.2. Research objectives

The overall goal of this project is to *make a contribution to holistically improving group decisions about technology assessment and selection under uncertainty in aircraft conceptual design*, which is realised by *proposing a way of integrating technical and socio-psychological perspectives on decision making*

[2] This classification is kept regardless of the fact that sources of the project itself describe the task project MANTA is to achieve calls for a "revolutionary approach" (Fokker Aerostructures BV et al., 2014, p. 10). The single-digit improvement goals are argued not to be revolutionary or disruptive in comparison to the examples presented in the previous paragraph.

under uncertainty. Following the split introduced earlier, this research has two underlying objectives, corresponding to the two studies present in this report. Each of these objectives, in turn, consists of an industry and an academic part. These are treated in the sections below.

1.2.1. Uncertainty quantification

The first objective is to *make a contribution towards providing decision makers with a usable assessment of epistemic model uncertainty of the Aircraft Design Initiator and the impact thereof on its output*. This is the applied or industry-focused research objective. The academic objective shows how the industry objective is reached, namely by *proposing a bottom-up methodology to quantify model uncertainty in aircraft conceptual design, by studying the effects of different assumptions on relevant model output of various aerodynamic analysis methods relevant in the conceptual design phase*.

Some clarifications are in place. First of all, 'a usable assessment' is defined as an assessment that is clear, relevant and in-time, so it can truly contribute to the decision making process. Second, 'epistemic uncertainty' is uncertainty related to a lack of knowledge. This is different from 'aleatory uncertainty' (also known as stochastic, statistical, ontic, ontological or variability uncertainty (Roelofs and Vos, 2018b; Walker et al., 2003)), which is due to the "inherent variation in variables" (Roelofs and Vos, 2018b, p. 6). Epistemic uncertainty can be reduced but is difficult to quantify; aleatory uncertainty is easier to quantify, but very hard to reduce.

Third, the term 'bottom-up' is used to indicate that the uncertainty quantification method will start from model(ling) assumptions, simplifications and limitations. Although this is not completely analytical – and therefore does make use of experiments or simulations – it is conceptually very different from other simulation-based uncertainty quantification method, such as Monte Carlo methods. Those approaches rely on random sampling in order to arrive at a distribution of possible outcomes and thereby treat the model as a black box. On the contrary, the method proposed here intents to show a causal and traceable relation such that new knowledge and insights about the origin, influence and quantity of uncertainty are gained.

1.2.2. Decision making

The second objective is to *make a contribution towards improving group decision making about technology assessment and selection in the context of aircraft conceptual design*. Again, this first part is the industry research objective. It will be reached by *proposing a model and subsequent support tool which contributes to solving a (combination of) relevant challenge(s) in aircraft conceptual design and technology assessment*.

In this objective, 'technology assessment and selection' is defined as the evaluation of various concepts with respect to a (number of) pre-set goal(s), followed by the selection of one (or more) best-performing concept(s). Although these goals are likely to be predominantly technological, they do not necessarily have to be. Also – as the technology assessment and selection is a group process – socio-psychological influences might influence the selection process and/or outcome.

In comparison to the first objective, this second – talking about 'a (combination of) relevant challenge(s)' that is not yet defined – is clearly much less concrete. This logically follows from the fact that the topic of interest treated in the first objective (uncertainty quantification) is chosen up front based on literature, whereas the second objective is approached with a much wider scope. This, in turn, is because case-specific information about project MANTA plays a much more important role in achieving the second objective than it does in the first.

1.2.3. Overview

Table 1.1 provides an overview of the research objectives, subjects and dominant study programmes.

Table 1.1: Overview of research objectives, subjects and dominant study programmes

	Uncertainty quantification	**Decision making**
Industry	Provide uncertainty assessment of Aircraft Design Initiator output	Improve group decision making about technology assessment and selection
Academia	Propose a methodology for bottom-up uncertainty quantification	Propose a model and tool for solving relevant challenges of decision making
	Aerospace Engineering	*Science Communication*

Comparing the various objectives, it can be seen that the overall goal is concerned with the decision: a *result*. The first objective deals with information to the decision-making process: *input*. The second objective, then, is about decision-making itself: the *process*.

1.3. Research questions

The overall goal gives rise to the overall question to be answered in this thesis.

> How can technical and socio-psychological perspectives be integrated in order to improve group decision quality under uncertainty in aircraft conceptual design and technology assessment and selection?

Subsequently, a number of research questions is defined, which are all split up in multiple sub-questions. Research question 0 is – as the number suggests – mostly exploratory and forms a basis for research questions I and II. These directly correspond to the two research objectives introduced before.

Research question 0

What factors contribute to high-quality group decisions?

- 0-a. What is decision quality?
- 0-b. What factors influence decision quality?

Research question I

How can model uncertainty be quantified, assessed and propagated bottom-up, i.e., starting from model(ling) assumptions, simplifications and limitations?

- I-a. Which (kind of) flow models, solution methods and combinations thereof (i.e., solvers) are suitable for aerodynamic analysis in a conceptual design process?
- I-b. Which criteria are relevant for the comparison of different aerodynamic analysis models in a conceptual design process?
- I-c. What assumptions, simplifications and limitations are associated to these models, solution methods and solvers?
- I-d. What (predictable and unpredictable) uncertainties in the model output do these assumptions, simplifications and limitations introduce?
- I-e. How do aerodynamic model uncertainties propagate through the Aircraft Design Initiator, thereby (possibly) influencing the output uncertainty?

Research question II
How can a (combination of) relevant socio-psychological factors negatively impacting group decision quality be combined in a conceptual model and subsequent tool that helps to understand and mitigate that impact?

- II-a. What does group decision making in project MANTA look like?
- II-b. What socio-psychological factors negatively impact group decision making in project MANTA?
- II-c. What theories or frameworks can be used to improve understanding of the most relevant of these factor(s) impacting group decision making?
- II-d. How can the insights from these theories or frameworks be combined in a conceptual model?
- II-e. How can this conceptual model be used, through transformation into a tool?

Sub-questions II-c, II-d and II-e are more general, whereas sub-questions II-a and II-b are specific to project MANTA. This choice is made based on the answers to questions II-a and II-b, from which it is argued that the decision making process and most relevant factors impacting that process are not limited to project MANTA only.

1.4. Structure

This report is segmented into five elements, as shown in Figure 1.1. Chapter 2 follows this introduction and provides context to the research topic, discussing a short historical overview of civil aviation and treating the aircraft design process. Chapter 3, then, treats the “good decisions” this report mentioned at its very start and answers research question 0. Together, these three chapters establish a foundation on which further analyses of the problem are based.

As the figure shows, Chapter 3 – in which factors that contribute to high quality decisions are identified, visualised by the circular markers in Figure 1.1 – forms the basis for the work performed in Parts I and II. The former explores one of the technical factors: uncertainty quantification and propagation. As such, it deals with the first research objective and first research question. Chapter 4 addresses model and criteria selection. The selected solvers are then detailed in Chapter 5. Chapter 6 is the largest chapter within this part and is about uncertainty quantification. Chapter 7 follows up on that and investigates how the quantified uncertainties propagate throughout the larger design process. The entirety of Part I is closed in Chapter 8, which answers research question I.

Next, Part II treats the socio-psychological perspective and correspondingly answers research question II. Mentioned before, and contrary to Part I, which focused on uncertainty quantification and propagation from the start, Part II starts with a broader problem exploration and definition phase, reported in Chapter 9. This is illustrated in Figure 1.1 by the multitude of factors connected to the right column. Following the selection of one factor, Chapter 10, then, establishes a theoretical framework that fits the problem and its context. It is subsequently used to develop a model, which is presented in Chapter 11. Chapter 12 discusses possible use of the model as a tool. Chapter 13 closes the part, answering research question II as well as its sub-questions.

Indicated in Figure 1.1 as well, both parts consist of five chapters that conceptually follow the same structure, somewhat alike the *double diamond*-model (Design Council) and a recently proposed, more iterative and less-strictly separated alternative to it (Lipiec, 2019). The first chapter scopes the topic, before obtaining a further (theoretical) understanding in the next chapter. The third chapter within each part (Chapters 6 and 11, respectively) then formulates the predominant results and completes the converging phase. Next, the fourth chapter (Chapters 7 and 12) builds up on and extends these results, slightly diverging again. Both parts close with a chapter presenting the answers to the sub-questions raised there and discuss (methodological) limitations, validity and reliability (Chapters 8 and 13).

Whereas Parts I and II clearly focus on one particular perspective, Part III sets out to combine and

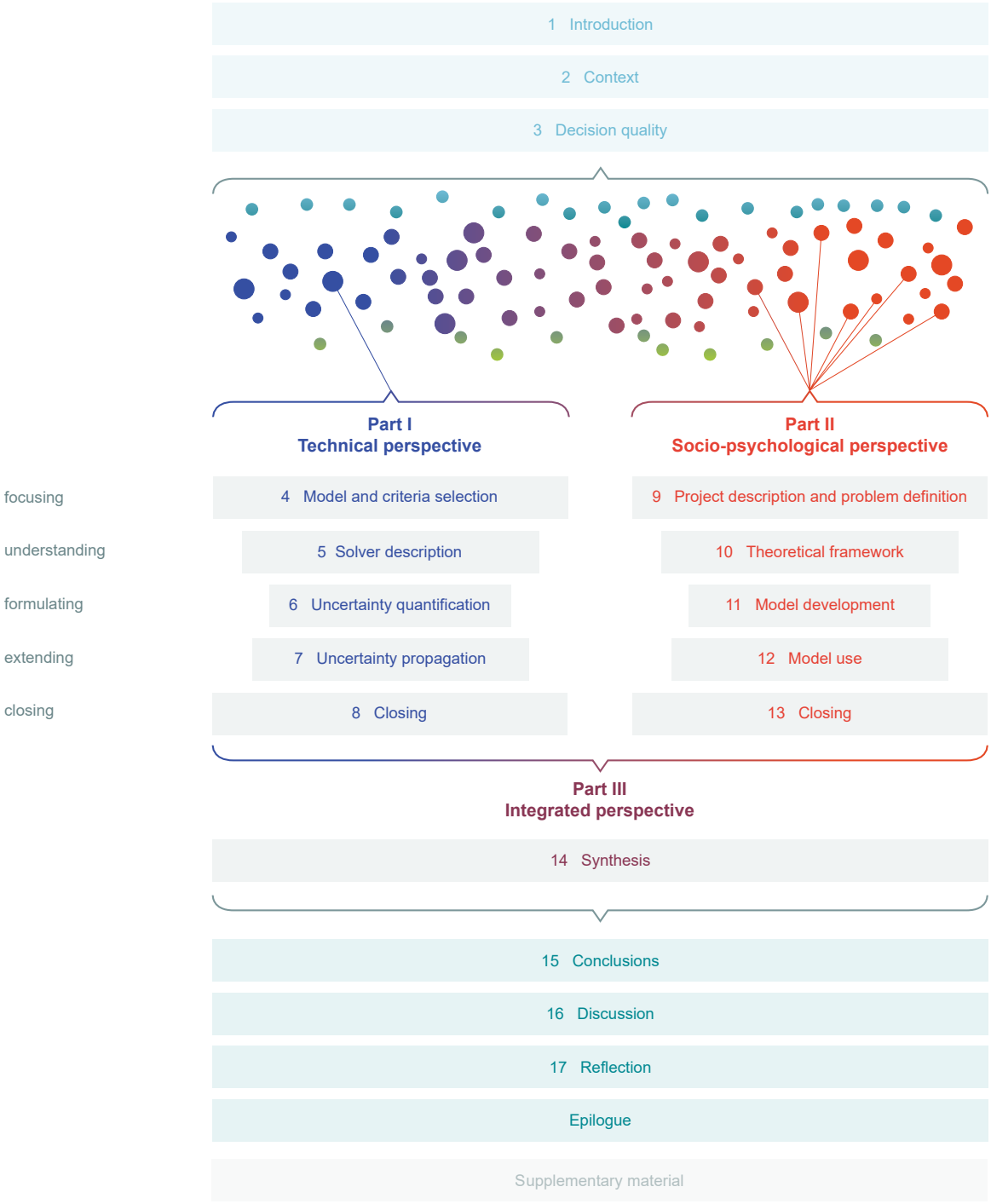


Figure 1.1: Report structure

integrate those. It does so in Chapter 14. Even though this parts only contains one chapter, it should be seen at the same conceptual level as the other two.

Finally, the fifth element – which continues to treat the two perspectives concurrently – brings the report to a close. Chapter 15 presents the conclusions that were obtained. These are subsequently discussed in Chapter 16. This discussion takes a somewhat more distanced perspective, outlining scientific contributions and treating opportunities following from the current research rather than specific methodological limitations. A largely personal reflection can be found in Chapter 17. It is followed by an epilogue.

Supplementary material is included at the end of this report. First is the list of reference, which is followed by various appendices. Specific appendices are referred to in the chapters for which they contain supplementary material. Nonetheless, Appendix A, providing an overview of basic aircraft nomenclature and an introduction into aerodynamic forces might be relevant information for readers without a background in aviation or aerospace engineering that helps to understand the technical content of this report.

1.4.1. Reading guide

As this research project set out to explore the possible integration between technical and socio-psychological perspectives, only reading one might be regarded as a somewhat ironic sign of under-appreciation of the complexity of the problem treated in this text. Nevertheless, some readers might simply be limited in time.

For those situations, readers with a particular interest in the technical perspective (i.e., uncertainty quantification and propagation) can limit themselves to Part I. Readers interested socio-psychological perspective (i.e., decision-making) are suggested to only pass over Part I, because Part II builds upon information presented in Chapter 2 and Chapter 3. Reading Part III in isolation is possible, although it does not come recommended, as it is heavily based on deliberations started in other parts of the text. People attempting to do so are therefore urged to first read Chapter 3, discussing decision making and decision quality, and the last chapter of Part II, Chapter 13.

Throughout the text, so-called boxes are used for further clarifications or to share personal opinions related to the more factual information presented in the main text. Although they provide some additional background, they can be passed over without missing out on information critical to the thesis.

> **Example of a box**
> This is an example of a box. It sometimes contains information that further clarifies or illustrates the main text. It is also used to share opinions, or more opinionated interpretations.

2

Context

This chapter introduces the context that is relevant for this project. As such, it forms an important basis in understanding the remainder of this report. Besides, it anticipates and supports choices on what is important and what is not, made in subsequent parts and chapters.

Section 2.1 first provides a compact historical overview of aircraft development aircraft. Section 2.2, then, describes the aircraft design process. Both sections – as the remainder of this report – are focused on transport aircraft, used mostly for civil applications. This fits with the scope of project MANTA, the use of the Aircraft Design Initiator and the flight regimes for which the tested aerodynamic models are applicable.

The information contained in the following sections might be familiar to aerospace engineers or aviation enthusiasts. However, as this thesis is also geared towards an audience less familiar with this industry, this background is nevertheless included.

2.1. Historical overview of aircraft development

From the days of ancient Greece, mankind has looked to conquer the skies. In early Greece, there were Daedalus and Icarus with their mythological set of wings. In the Renaissance, Leonardo da Vinci worked on countless ideas allowing people to fly. Then, some 250 years ago, came along the Montgolfier brothers, who constructed a hot-air balloon which could lift a person off the ground, followed a little later by the first fixed-wing aeroplane design by George Cayley. The first sustained, controlled and powered flight of a heavier-than-air machine by the Wright Brothers in 1903, however, is best known and generally seen as the start of modern aviation, kicking off the “Century of Flight” (Anderson, 2005).

Three ages of aircraft development

In this relatively recent history, developments rapidly followed one another and are generally grouped in three phases as shown in Figure 2.1 (La Rocca, 2011). In the *pioneering age* – roughly spanning the 1900s to the 1950s – aircraft moved from wood and linen to metal riveted structures and the world saw the first civil application of the jet engine. After the Second World War, in the *commercial age*, air travel started to become available to the masses. Aircraft grew in size (especially with the introduction of the Boeing 747 Jumbo Jet in the late 1960s) and from the end of the 1970s, deregulation paved the way for partnerships (e.g. Northwest Airlines and KLM on transatlantic flights), consolidation and new business models (Doganis, 2010). The third and current period, having started around the year 2000, is aimed at realising sustainable growth, with more efficient designs and cleaner forms of propulsion. To some extent, one might argue that the return of smaller but more fuel-efficient jets operated on point-to-point

flights (as opposed to the hub-and-spoke system[1]) such as the Boeing 787 and Airbus A350, can already be seen as proponents of this time.

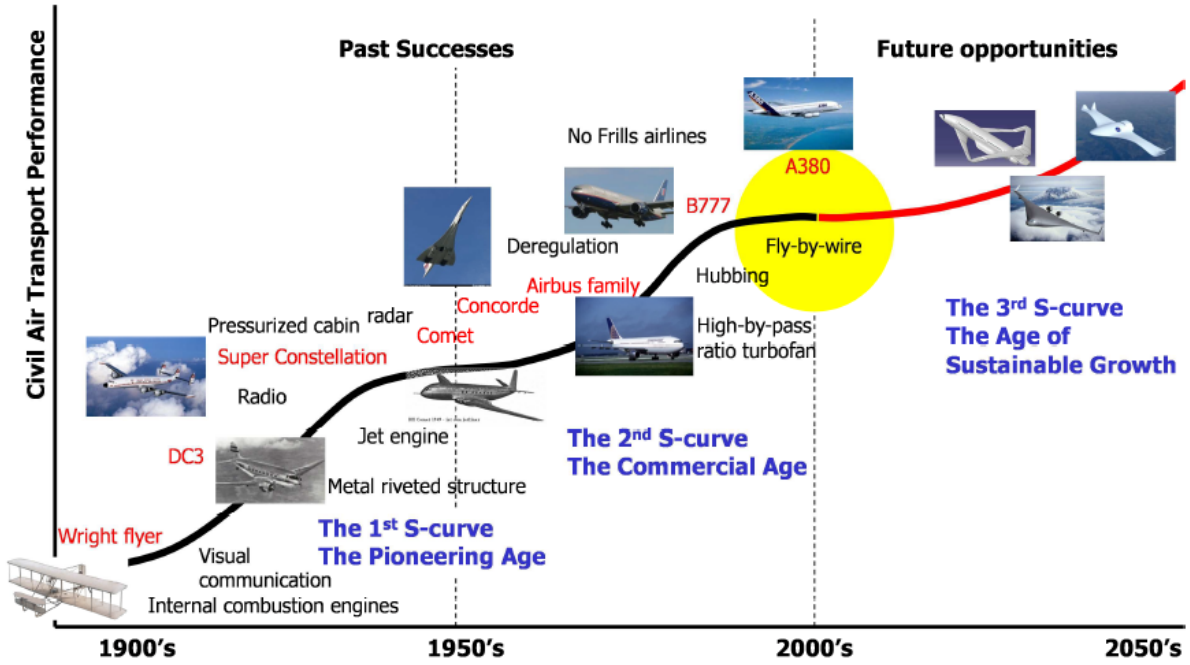


Figure 2.1: Civil air transport performance (La Rocca, 2011; ACARE, 2002)

As can be seen in Figure 2.1 (La Rocca, 2011; ACARE, 2002), the civil air transport performance follows an S-shaped pattern. At the start of a phase, progress is relatively low, as designers and engineers are developing new technology or getting acquainted with it. Then, when techniques mature and manufacturers grow their skill, things move forward quickly. At the end of a phase, the line levels off again – waiting for new breakthroughs in more fundamental development.

Electric or hybrid-electric propulsion might be one of these developments and has indeed been getting more and more attention of the past few years. Whereas the energy density of batteries currently forms a major barrier to application in larger or longer-range aircraft (Stückl et al., 2012), Airbus Innovations has reenacted the Channel crossing with their E-fan electric aircraft in 2014 (Airbus, 2017) and is developing a hybrid-electric aircraft demonstrator based on the BAe 146 together with Rolls-Royce[2], scheduled to fly in 2020 (Siemens, Airbus and Rolls-Royce). The Slovenian manufacturer Pipistrel is already producing a commercially available two-seater electric training aircraft (Pipistrel Aircraft) and trade journal *Aviation Week* named electric aviation as one of the highlights of the 2019 Paris Air Show (Norris and Trimble).

Incremental change

The industry gearing up for disruptive innovation, however, is no reason for efforts of incremental change to be put on hold. As such, manufacturers indeed continuously improve their aircraft models and model portfolios. With the introduction of the Boeing 737 MAX, the American manufacturer is building a fourth generation 737[3], a model that was first introduced in the 1960s. According to company specifications, the MAX 8 reduces fuel consumption by 11% compared to the size-equivalent 737-800 (The Boeing Company, 2011). Existing aircraft models, furthermore, are also continuously improved. The Boeing

[1] In a hub-and-spoke network, smaller aircraft transport passengers from smaller to larger airports, so-called *hubs*. Then, passengers transfer to a larger jet, which flies from one hub to the next. To get to their final destinations, people can take another smaller flight. In point-to-point networks, people travel from their origin to their destination in one flight. Hub-and-spoke networks are generally seen as more economical, as airlines can capitalise on the economies of scale of larger aircraft by *feeding* these hub-to-hub flights. On the other hand, travel times and distance travelled – and thereby emissions – are increased.

[2] Siemens was previously involved as well, but its eAircraft-unit has since been acquired by Rolls-Royce (Norris, 2019).

[3] The 737-100 and -200 are the original series, then came the 737-300, -400 and -500, which were followed by the 737-600 to -900 *Next Generation*. The 737 MAX 7, 8, 9 and 10 have recently entered service or are currently under development.

777-300ER, for example, has lost a few thousand pounds of operating empty weight since its entry into service and thereby seen improved fuel efficiency (Norris, 2015; Blum, 2016).

2.2. Aircraft design

As stated in the previous section, commercial aircraft have long life cycles. The aircraft design process itself is lengthy, too: 15 years between first idea and entry into commercial service is no exception. (For breakthrough ideas as the Flying-V concept recently unveiled by Delft University of Technology and KLM, this can be even longer: up to 30 years (CNN, 2019).) This section treats the various design and development stages, highlighting the vast consequences of decisions made early on in that process. Special attention is paid to technology assessment, relevant during the earlier stages of design.

2.2.1. Conceptual, preliminary and detailed design

The aircraft design process is usually split up in three phases: the conceptual design phase, the preliminary design phase and the detailed design phase (Torenbeek, 1982). They are schematically shown in Figure 2.2. As can be expected, later design phases take more time and involve greater numbers of engineers.

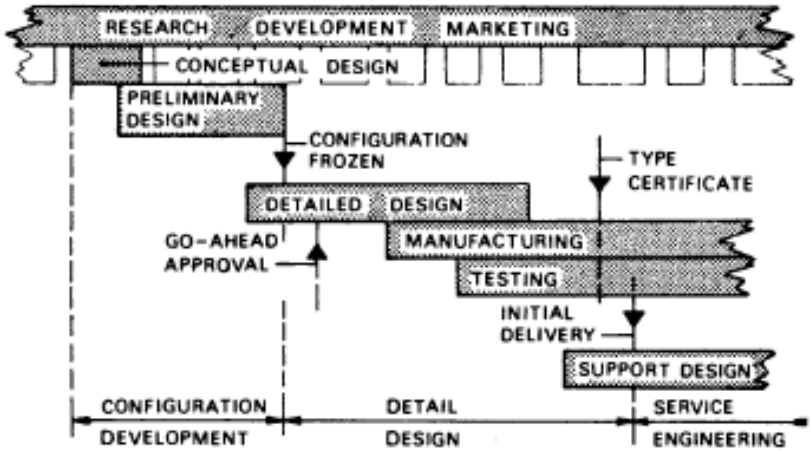


Figure 2.2: Aircraft design and development phases (Torenbeek, 1982, p. 4)

Although the figure shows some overlap between the different phases, the decision making process often follows a stage-gate (or stage-gate inspired) model (Johansson, 2014; Sadraey, 2013). The work is done in *stages* and each stage is followed by a so-called *gate* where the work in the stage is reviewed. Following that review, a decision is made whether or not to continue with the project (Cooper, 2008) and (continue to) make associated investments. Section 3.1.4 treats these kind of decisions in further detail.

Conceptual design phase

The conceptual design phase – at the top left of fig. 2.2 – is about assessment of the requirements of (potential) customers, top-level choices – such as the ones regarding range, capacity and speed – and concept generation. Research might be carried out to determine the feasibility of particular novel configurations or (manufacturing) techniques, but most numbers will be far from definitive. As many design candidates and alternatives are considered, there is only limited time to spend on each one. Therefore, empirical data based on previous own designs or competitor aircraft might be used for sizing and weight estimates (Torenbeek, 1982; Jenkinson et al., 1999). At the end of the conceptual design phase, a so-called *baseline design* is chosen, which moves on to the next phase (Torenbeek, 1982).

It also happens that design concepts never make it into preliminary design, such as the McDonnell-Douglas MD-12 and Boeing Sonic Cruiser concepts shown in Figure 2.3.



(a) McDonnell-Douglas MD12, 1990s (Wikipedia, 2008)



(b) Boeing Sonic Cruiser, 2001 (Boeing, 2001)

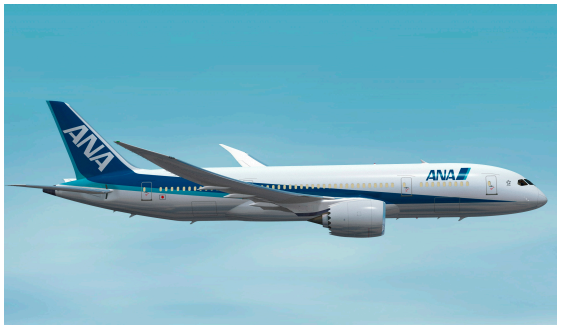
Figure 2.3: Discontinued conceptual aircraft designs of McDonnell-Douglas and Boeing

Preliminary design phase

In the preliminary design phase, more thorough analyses are carried out, such as efforts to determine the sensitivity of particular design parameters. The general aircraft layout will be optimised for the goals defined earlier in the process (Jenkinson et al., 1999). Design efforts furthermore focus on system and subsystem design, such as the high-lift systems, handling and control systems, and integration of powerplants and airframe. Even though more specialists are involved and more detailed analyses are performed, many parameters are not fixed at the end of the preliminary design phase (Torenbeek, 1982). Figure 2.4 illustrates the layout changes that can still be made during preliminary design, with the Boeing 787 Dreamliner concept moving from a 'shark-fin tail' to a regular vertical stabiliser.



(a) Shark-fin tail (Aerospace Technology)



(b) Regular tail (Boeing)

Figure 2.4: Preliminary design change of vertical stabiliser layout of Boeing's 787 design

Detailed design phase

Completely fixing the design happens in the detailed design phase, where every last nut and bolt are designed. At this time (as shown in Figure 2.2), the configuration is *frozen*, meaning that it is no longer possible to make large changes to the aircraft layout. Parts that will not influence the general layout will be optimised and at the end of the detailed design phase, drawings and schematics will be sent to production so the first test aircraft can be built (Jenkinson et al., 1999).

2.2.2. Calculations and decision making

Following the previous description of design phases that continuously get more specific, it becomes clear that choices during the earlier phases – such as the conceptual design phase – have tremendous consequences on the final design. As illustrated by the bold line in Figure 2.5, it is estimated that up to 70% of the life-cycle cost is committed based on choices during the early stages of design (Sadraey, 2013). As

the more detailed analyses and selections made later on depend on the earlier information, making large changes late in the process is very difficult and therefore costly. In other words, it is very important to "get the aircraft right" early on (Jenkinson et al., 1999, p. 14). It is often said that aircraft manufacturers bet their entire company's worth when they give the go-ahead for a new program[4] (Raymer, 2002). Large aircraft manufacturers normally break-even only after ten (Sadraey, 2013; Buxton et al., 2006; Johansson, 2014) to twenty years of production and aircraft programmes that turn into true money makers are relatively rare[5].

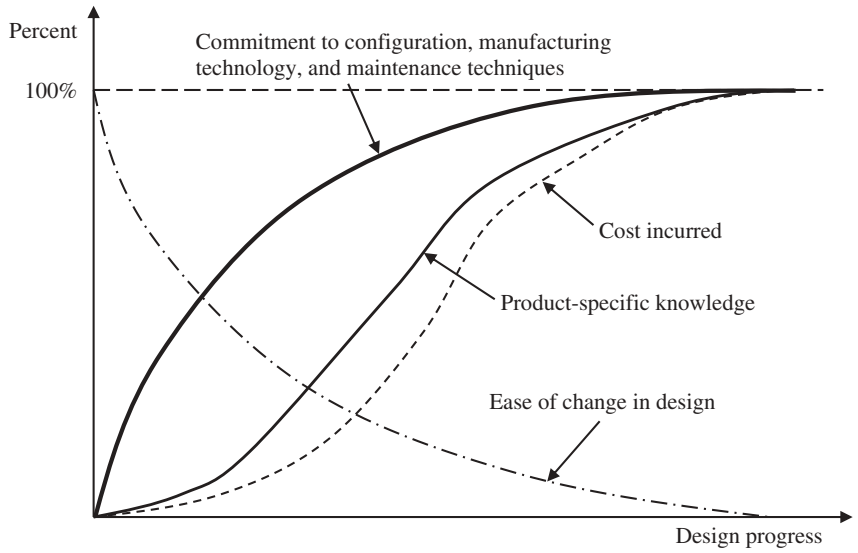


Figure 2.5: Cost committed, cost spent and ease of change over time (Sadraey, 2013, p. 8)

Confirmed by Figure 2.6, designing the right aircraft is not only a matter of making proper calculations. According to Sadraey (2013), decision making is just as important. This fits with the definition of engineering design by the Accreditation Board of Engineering and Technology (ABET) (Sadraey, 2013, p. 4), which also defines engineering design as a "decision making process"[6].



Figure 2.6: Groups of design activities in aircraft design (Sadraey, 2013, p. 2)

The duality shown in Figure 2.6, which also inspired the two-sided research objectives shown in Section 1.2, especially holds for the earlier design phases. There, the design freedom is larger and more high-impact choices can (and need to) be made.

[4] Manufacturers are often reassured by sales made before production starts. However, these sales are made based on performance estimations that the airliners (or lessors) use to make the business case for the acquisition. If actual performance is worse than predicted performance, it is not unusual for customers demanding compensation from the manufacturer. In turn, that has an obvious effect on the break-even calculations of the aircraft programme itself. Also, even early commitments – either sales or options – rarely bring in so much money that a break-even can be guaranteed. Lastly, the lion's share of the payment is only collected at delivery.

[5] For Airbus, this would be the A320 and A330-families; for Boeing, the 737, 747 and 777-programmes. The Airbus A350 and Boeing 787 are on their way to becoming one.

[6] ABET defines engineering design as follows: "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objectives [sic]. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation." (Sadraey (2013, p. 4), citing Accreditation Board of Engineering and Technology (2012).)

2.2.3. Current trends

Given the challenge of getting it right early on, the industry as well as research institutions have been and still are trying to improve this process in order to prevent costly mistakes. The ever-increasing available computer power is a key enabler in this objective. Rather than having to manufacture and test technologies or designs in real-life, concepts can be evaluated in computer simulations. Similarly, computer aided design greatly simplifies the process of making changes, without having to re-do drawings in print.

The advent of computer systems also spiked interest in early-on design optimisation, especially in the form of multidisciplinary design optimisation (MDO) (Torenbeek, 2013, pp. 5-6). Torenbeek notes that in the European Union, various programmes "have stimulated the industry, research institutions, and academia to cooperate in order to improve aircraft design technology" and that "[t]hese efforts have resulted in improved possibilities for designers to gain insight into the impact of new technologies and concepts on the design quality in pre-competitive phases before excessive resources have to be committed".

Even though it does not include an optimisation-component (yet), the Aircraft Design Initiator too, can be seen as an example of a system that Torenbeek describes. The program helps to create and evaluate conceptual aircraft designs in a rapid manner (Elmendorp, 2014). Based on both physical and empirical models, it iterates towards particular key performance indicators (such as maximum take-off weight and fuel efficiency) and thereby provides aircraft designers with insights on what novel concepts or technologies are especially promising (Vos, 2017).

3

Decision quality

Decision making "steers the course of society" (Simon et al., 1987, p. 11). It is hence unsurprising that much research is done into how we can make better decisions and how we can better make decisions – two things not necessarily the same, as this chapter will show. The interest goes back to approximately the Second World War (Beach, 1998). Whereas economic models initially assumed rational behaviour, researchers from the 1950s onward observed that rationality in fact had its limits. In 1979, Kahneman and Tversky for example presented a new theory for decision making under risk, as they had shown that people faced with risky choices do not behave according to utility theory. Since then decision science has even grown to become a separate field of research, combining insights from (behavioural) economics and psychology, among others.

This chapter discusses decision making and – especially – decision quality: what it is and by what factors it is influenced. Section 3.1 treats the former, Section 3.2 the latter. Through this discussion, this chapter forms the basis for the remainder of this work.

3.1. Definitions

Before investigating ways to improve decision quality, it is important to set some definitions. First, decisions themselves are discussed, before moving on to the process of decision making and – subsequently – decision quality.

3.1.1. Decision

In this report, a decision is defined as *the conclusion of a deliberation process*. Decisions can be as simple as the choice between tea or coffee, or as complex as setting policy to achieve long term government goals. In all cases, decisions set in motion a sequence of events. When deciding on a plan to work towards a particular goal ('Do we go for option A or B?'), for example, this is explicit. On the other hand, in a court ruling ('Is the suspect found guilty or innocent?'), the consequences might be implicit. In case somebody is acquitted, the decision is to find the suspect innocent and to reinstate particular rights: a mere – although important – *consequence* of the acquittal. It is important to realise that deciding *not* to do something (including postponing a difficult choice) still is a decision (Porter, 1996).

In popular speech, the decision process is sometimes also referred to as a decision. In this text, however, a decision is strictly seen the result of the decision making process. It is worthwhile to stress that this is not (the end-state of) the sequence of events set in motion by a decision. As will be further discussed in Section 3.1.2, the consequences are defined as the *outcome* of the decision.

3.1.2. Decision making

The definition of decision making, unfortunately, is not very clear-cut. In the previous section, it was simply described as the process of making decisions, without specifying where that process starts or ends. Simon et al. (1987, p. 11) state that decision making is the part of "evaluating and choosing", which follows the problem-solving phase in which issues are identified, goals are set and (design) solutions are formulated. Schulz-Hardt and Mojzisch (2012) and Chang (2011) draw a similar line, stating that decision making is a choice between known alternatives (i.e., (design) solutions), which are unknown in case of problem-solving. Elwyn and Miron-Shatz (2010) take a more process-related perspective and discern between *deliberation* (the process) and *determination* (the actual decision) and place the result (or effect) of the decision outside of the decision making process. That is contrary to Taylor and Dunnette (1974) (as cited by Malhotra et al. (2007, p. 183)), who, besides a 'predecision stage' and a 'decision point', also see a 'postdecision stage', grouping outcome and evaluation, in the decision process.

That notion of a discrete decision *point* – as opposed to something continuous – corresponds well to the previously adopted definition of what a decision is. Including the outcome and evaluation as Taylor and Dunnette do, however, raises the question where exactly the postdecision stage ends.

As such, decision making in this thesis is defined as *the process that starts with investigating and evaluating alternative solutions to some pre-set goal and ends right at the point where a decision is made and the decision makers commit to an action or approach*. This definition extends the description by Simon et al. at the start of the process in order to contain the situation where solution ideas are adjusted or give rise to new ideas – an iterative loop common in opaque (Howard, 1988), unstructured (Banathy, 2013), complex (Cartwright, 1973) and wicked (Rittel and Webber, 1973) problems (Courtney, 2001) – within the decision making process. In case the result of the decision is different from the anticipated, planned or desired result, a new problem solving starts with the goal to make a decision that reorients the unfolding history towards the objective of the initial decision.

A schematic representation of the larger problem solving process, corresponding to the definitions above, is shown in Figure 3.1. The main flow is shown using black lines; possible iterations are indicated in grey. Left of the decision line is the problem solving process, consisting of a problem definition phase, a design phase and the actual decision making phase[1]. Right of the decision line is the outcome. The outcome can be described as a new state (possibly, but not necessarily, an end state) of the problem domain after it has been influenced by the decision.

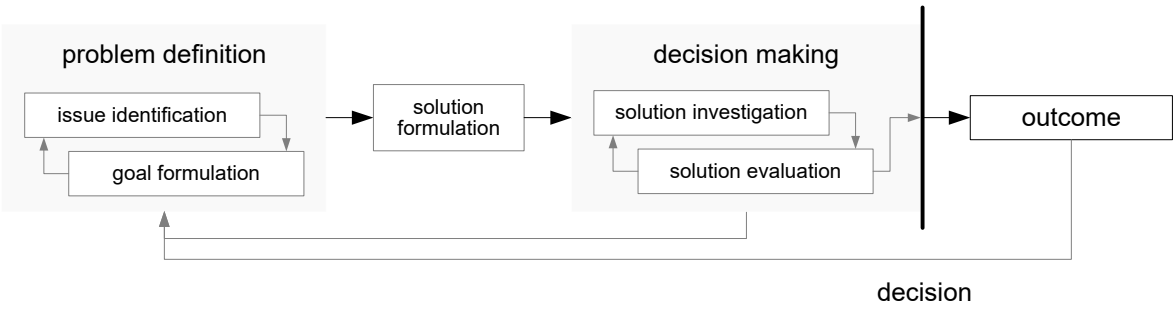


Figure 3.1: Schematic representation of the problem solving process

This representation largely follows the process steps outlined in Dewey (1910) (Littlejohn et al., 2017, p. 295) on which many functional theories are based. It is important to highlight the difference that the current schematic allows for iteration in the major phases. Dewey's steps of *expressing a difficulty*, *defining the problem* and *analysing the problem* correspond to the *problem definiton*-phase in Figure 3.1. *Suggesting solution* holds a one-to-one relation with *solution formulation*. *Comparing alternatives and testing them against a set of objectives or criteria* is the phase defined here as *decision making*. *Implementing the best solution*, Dewey's last phase, is not included in Figure 3.1, as it is seen as essentially a new

[1] Orasanu and Salas (1993, p. 327), too, describe decision making fitting in the "broader problem solving" process, supporting the current representation.

problem solving process of devising a process to most effectively and/or efficiently move or transform the system to a new state.

3.1.3. Group decision making

Both individuals as well as groups of people can make decisions – with 'larger' (e.g., more complex, yielding larger consequences, impacting more stakeholders) decisions often being made by multiple decision makers. These are called *group decisions*.

Scholars see groups as better equipped to process larger amounts of information (Açıkgöz and Günsel, 2016; Coyle et al., 2015). Also, group discussion reduces the potentially negative effects of individual biases (Chang, 2011; Coyle et al., 2015). Grouping a number of individuals furthermore combines their expertise and experience (Robert et al., 2008; Stasser and Titus, 1985) and (might) introduce a wider variety of perspectives that can be taken into account in the decision making task. All in all, it is felt that the sum is more than its parts (Schulz-Hardt and Mojzisch, 2012; Ruhstaller et al., 2006; Fargason Jr. and Haddock, 1992). If not – that is, if a task is simple enough and a single decision maker can identify the optimal decision right from the start – various scholars argue that group decision making is not of added value (Schulz-Hardt and Mojzisch, 2012; Oetzel, 1995).

Besides the advantages and opportunities, group decision making also introduces socio-psychological complexities: people need to work together. A prime challenge is the integration of information and, as one might say, the 'unification' of the group members into a group. Much research has been done in this area of so-called *hidden profile situations*, in which some information is *shared* among the entire group, whereas other information is initially *unshared*: only one or a few parties have access to it (Stasser and Titus, 1985; Lu et al., 2012; Schulz-Hardt and Mojzisch, 2012). The crux of a hidden profile situation is that the optimal decision can only be made when all information – shared and unshared – is considered. Hence, group members have to exchange the information they have, even if they do not know up front if and how that piece of information will contribute to the decision making process.

Although the validity of the hidden profile paradigm has been criticised for lacking realism (Wittenbaum et al., 2004), it is argued here that the group dynamics in hidden profile situations are very comparable to the team interplay in situations with high levels of uncertainty. If it is unknown what information has to be taken into account in such a situation, it seems better to share the information that *might* be relevant, rather than withhold it. On the other hand, time limitations might move actors to do the exact opposite. One important point of critique discussed by Schulz-Hardt and Mojzisch (2012) however, is not so easily refuted: possible strategic behaviour. Although the present author does not agree with the notion of Wittenbaum et al. that hidden profile situations are completely free of this conduct (also in a laboratory, people might strive to attain individual goals, such as saving face as their initial preference is refuted by the group), this might indeed play a much more important role in real-life situations. However, hidden profile experiments can be adapted to include more explicit competitive behaviour (Toma and Butera, 2009) and individual incentive (Kelly, 2010).

3.1.4. Screening decisions

A special type of group decisions relevant to the current research context of project MANTA are so-called *screening decisions* (Hammedi et al., 2013). These decisions, also known as go/no-go decisions, determine whether a project is continued, or put to a halt. A simple example is a group of HR-advisors literally screening resumes to determine which applicants to invite to an interview; more difficult ones are the selection of new product or R&D ideas to further develop (R&D portfolio management) (Cooper et al., 1997) or "idea-to-launch" decisions (Cooper, 2009, p. 47). The fact that relatively little information and time are available to make the decision, while uncertainty is large and the decision environment is dynamic (Cooper et al., 1997), make screening decisions to one of the most difficult tasks for managers (Hammedi et al., 2013; Cooper, 2009). This is even more so for decisions having a large impact.

The people involved in a screening decision (sometimes regarded as the *screening committee*) usually

fulfil a (higher) management role and are often compared with top management teams (TMTs). These groups are often of a temporary nature – at least in their role as screening committee. Added to the difficulties of group decision making introduced in Section 3.1.3 are therefore challenges such as lack of team structure (Hammedi et al., 2013; Edmondson et al., 2003) and limited interaction (Hammedi et al., 2013; Hambrick, 1995), sometimes resulting in a "team that is not a team [...] but a mere constellation of senior executives pushing their own agendas, with a minimum of collaboration or exchange among them" (Hambrick, 1995, p. 111).

3.1.5. Decision quality

With the decision and decision making process defined, it is time to move on to a definition of decision quality. Given the importance of decision making, it is surprisingly difficult to find one in literature. Although many publications present research regarding decision making or team effectiveness, these do not focus explicitly on decision quality. Rausch and Anderson (2011), too, indicate decision quality is rarely treated in literature. Furthermore, even studies explicitly aiming to improve decision quality do not clearly define their objective, or each have their own.

Kee et al. (2004), for example, take the (predicted) net utility loss[2] as a metric for decision quality, for example, whereas Blazeby et al. (2006) (in a medical context) determine decision quality based on agreement between the treatment decided upon and the treatment implemented. Similarly, Rausch and Anderson (2011) look to the difference between actual and desired outcome (and can therefore be only measured after-the-fact). These differences are problematic: on a smaller scale, as it becomes more difficult to compare study results; as well as on a large scale, as it stands in the way of systematic research into how we can improve the quality of the decisions we make. Or, in the words of Chen and Chien (2009, p. 87): "without a clear definition of a 'good' decision, it is like shooting the dart without a dartboard".

In a recent article reviewing medical literature, Hamilton et al. (2017) observe three major strands: defining the quality of decisions in terms of the process, the outcome, or the expected utility. Whereas the first is clearly different, the latter two might still be regarded ambiguous. Hamilton et al. categorise satisfaction with the decision experience and lack of regret as outcome and label health outcome (whether a treatment improves a patients condition, for example) as expected value. Following the definitions presented earlier in this section, it is argued that the decision experience should be seen as part of the process, whereas the result of a decision (improving ones health) would be the outcome. Besides the possible ambiguity, the limits of expected utility theory have long been shown (Kahneman and Tversky, 1979) and we have learned that rationality is bounded (Kahneman, 2003). At the very least, this suggests limitations of defining decision quality using this rational metric.

Although Hamilton et al. do not necessarily argue otherwise (as they discuss *expected* value), it is important to stress the fundamental distinction between decision and outcome, advocated in both a general sense (Howard, 1988) as well as in a medical setting (Elwyn and Miron-Shatz, 2010). Howard (1988, p. 682) even goes as far as saying that this difference is "the most important distinction needed for decision analysis". Both authors note that good decisions in uncertain situations can lead to bad outcomes due to changing circumstances and vice-versa, simply due to chance, and agree that that fact should not be an influence on the decision quality metric. Baartmans and Kosolosky (2015, p. 337, translated) also explicate this uncertainty and see the *best* decision as the decision that is "fitting given the available information" or "epistemically most legitimate"[3], hinting at a (partially) subjective assessment also seen by Kamis and Davern (2005) and Amason (1996) (using self-assessment to measure decision quality). If the outcomes are not separated, outcome bias will result (Baron and Hershey, 1988).

Based on the above, a new definition for decision quality is proposed: *the extent to which a (group of)*

[2] "The difference between the expected utility of the recommended treatment and the *maximum utility derived from the clinician's predictions of the outcomes* (the net utility loss) following all potential treatment modalities was calculated as an indicator of quality of the decision", Kee et al. (2004, p. 602, emphasis added).

[3] "Wanneer we spreken over een 'betere', de 'beste' of de 'juiste' beslissing bedoelen we 'gepast gegeven de beschikbare informatie'. [...] bedoelen we dus 'beste' in de zin van 'het gewenste resultaat opleverend' én 'epistemisch meest gerechtvaardigd'"

decision maker(s) at the decision point is convinced the decision will yield the decision goal, insofar possible. This definition combines a number of previous observations and solves or circumvents some of the problems with other definition attempts:

- it respects the distinction between decision and outcome, as the decision is evaluated before its outcome is known;
- it includes an 'escape' for situations where the goal is unattainable, without opening up to decisions that only (potentially marginally) *contribute* to a goal that is well within reach;
- it can be applied to situations with both low and high levels of uncertainty, because of the inherent balance between goal optimisation and robustness[4]; and
- it leaves room for emotional aspects of the decision making process and group work, but only values these to the extent they contribute to the decision itself;

An ideal observer

The above definition, however, is not free from problems. First of all, as the definition point (by definition) is infinitesimal, measuring decision quality by this definition will be impossible – adding to the problem that measuring decision quality in general is difficult (Bakay et al., 2014; Coyle et al., 2015; Amason, 1996).) Second, and probably more important, by defining decision quality based on the conviction of the decision makers themselves, they 'mark their own paper'[5] – which might lead to dishonesty. (Amason (1996), however, notes a 0.91 reliability of this perceptual measure.) This is solved by introducing a so-called *ideal observer*, inspired by the concept of an *ideal gas*. In an ideal gas, for example, it is assumed that intermolecular forces play no significant role. Similarly, an ideal observer is an idealised entity, highly transparent, unbiased and rational, completely independent and unaffected by face concerns or power struggles. With the inclusion of the ideal observer, the definition of decision quality is adjusted as follows: *the extent to which a (group of) decision maker(s) at the decision point can convince* an ideal observer *that the decision will yield the decision goal, insofar possible.*

The first and foremost benefit is that the ideal observer removes the previously identified problem of decision makers judging their own decisions. It is therefore expected that decision maker biases (such as blind-spot bias, choice-supportive bias, confirmation bias, ostrich effect and overconfidence (Lebowitz and Lee, 2015; Croskerry, 2003)) are avoided. Second, it is expected that this change results in a more objective assessment of the decision, as the ideal observer is a stakeholder in neither the decision making process nor its outcome. Still, absolute objectivity is not required – not desired, even – as that would be too constraining in situations with "known unknowns" (U.S. Department of Defense, 2002, Rumsfeld). That is where the 'ideality'-property comes into play, which aims to strike a balance between objectivity and trust. An ideal observer will ultimately base its quality assessment on its confidence in the ability of the decision to yield the decision goal. Objective information about the decision under consideration can influence that confidence, but if that is not enough, other (more emotional) aspects can be used.

> **A balance between objectivity and trust**
>
> Although the balance between objectivity and trust as just discussed might feel 'soft', the idea is not uncommon. Regarding climate change, for example, absolute certainty about the way human and other influences drive global warming has not been attained. However, the scientific community is (mostly) in agreement about these relations and policy makers make decisions based on it. In this case, the impressive amount of evidence (the objective facts) are helped by the trust in the models, scientists and institutions – and their procedures.
>
> Associated to the topic of this research more closely, a parallel can be drawn to the aerospace industry. Rather than regulating bodies checking every nut and bolt on an aircraft consisting of millions of pieces, airworthiness is not only determined based on the result of a number of tests and demonstrations (objective

[4] Imagine a situation with little uncertainty. Robustness might not be necessary, but as long as it does not stand in the way of reaching the goal, it is accepted. However, if it does hinder goal satisfaction – for example, when the goal is optimising rather than satisficing in nature – unnecessary robustness will reduce the decision quality. In a situation with much uncertainty, however, not including robustness might reduce trust in the ability of attaining the goal at all, yielding to a situation where robustness helps in reaching the goal and a robust decision is therefore valued as higher quality.

[5] Or, in Dutch: beslissers worden hierbij de slagers die hun eigen vlees keuren.

facts), but also by standards upheld by the organisations involved in the design and development. Even though compliance with these standards is externally audited and thereby (to a large extent) objectively established, trust plays a crucial role in transcending this evidence to the all-encompassing concept of airworthiness. (The fact that this system is not immune to failure is indicated by the recent crashes of two Boeing 737 MAX aircraft and the subsequent inquiries of the role of the Federal Aviation Administration, questioning whether the agency has not shifted too much work to Boeing (Gelles and Kitroeff, 2019).)

Last, the idea is also found in law, where decisions (e.g., to convict a felon) are made if something is proven *beyond reasonable doubt*.

Limitations and translation into practice

The benefits associated to introducing an ideal observer, however, also come at a cost. It makes the decision less practical, as a true ideal observer – just as an ideal gas – only exists in theory and is a simplification of reality. Two ways are foreseen with which to steer this theoretical definition back towards the realm of practice.

The first is to simply tolerate the non-ideality and accept an approximation of an ideal observer. This could be a person who is indeed not involved with and unaffected by (the outcome of) the decision making process, but who still not is perfectly unbiased. This is what Kozlowski and Ilgen (2006) propose in relation to evaluating team effectiveness. An example of this could be an inspectorate (such as the Dutch Health Care Inspectorate[6]), with the difference that the observer in this case does not only judge between right and wrong (dichotomous variables), but can further specify it on an ordinal or interval scale (Bryman, 2012). Supervisory boards can to some extent also take on the role of observers, although their independence cannot always be guaranteed. In the following box, some additional considerations and analogies are treated.

External ideal observers in real life

Finding a perfect real-life example of an ideal observer is difficult, if not impossible. Inspectorates and supervisory boards come closest, but these analogies have limitations as well. For example, the observer is known up front – making it possible for a decision maker to influence an inspector before the decision point.

Other examples have also been considered, such as a judge in a court room. He or she is (should) not (be) involved with and affected by the outcome of the decision and uses a strict method, books of law, jurisprudence and debate to promote an objective assessment. Still, judges are able to rule in cases of uncertainty, where pure logic and objective reasoning alone do not yield a conclusion. On the other hand, of course, a judge obviously *is* involved in the decision making process. Furthermore, an attorney, defendant or victim might do or say something to which the judge responds irrationally.

Building on to this example, the Supreme Court is distanced from involvement in the decision making process it audits. One has to make an appeal and the court indeed observes after the fact. Nevertheless, when the Supreme Court rules, its judges do – again – get involved in the decision making process. (This would have been different if the Supreme Court only ruled whether a lower court acted correctly or not, without confirming or overthrowing the earlier verdict.)

In terms of removing emotion from a judgement, grading rubrics applied by teachers also come to mind. Such a structured grading process fits the view of an observer (the teacher) and something that is observed (the test) before its consequences are clear. Furthermore, rubrics (rather than cold right/wrong answer models) allow for incorporating factors in the assessment that can be shown, but are hard to measure on an absolute scale. On the other hand, teachers also are involved in the decision making process, as well as its outcome (whether a student will pass or fail a course, and the consequences of that).

The second way for the theoretical ideal observer to yield practical application is to instantiate it as a mental observer in the minds of the decision makers. Contrary to the first approach (which focused on the *observer*-part of the ideal observer), this second approach lets go of an external observer and puts emphasis on the *ideality*-property. This approach draws its inspiration from religion, where often an all-

[6] Inspectie Gezondheidszorg en Jeugd.

knowing and almighty entity (i.e., God) judges people's actions and thoughts based on common values and beliefs. Even though the existence of a such an entity cannot be objectively established, people act in such a way they feel this entity would want them to act. The same holds for cultural standards and "social virtues", interalised by means of Freud's *super-ego* (Ariely, 2008; Campbell, 1964; Henrich et al., 2001, p. 203). Economic theory already suggests that people will only commit a crime if the benefit is high enough (i.e., expected value of gains outweighs the expected cost of getting caught and being punished), but both psychological research as well as ones own imagination (and experience, probably) show that there also is a real cost associated to letting *oneself* (or: one's super-ego) down (Greenwald, 1980; Griffin and Ross, 1991; Sanitioso et al., 1990). In other words: even though a crime might have a(n objectively established) positive expected value, (most) people will be reluctant to commit it – simply because it would go against their own, their peer's or their religion's moral standards[7]. In the current context, the 'crime' considered is dishonesty – in assessing the quality of one's own decision.

Based on experiments run with students from prestigious universities in the United States (in terms of intelligence and social status thereby roughly comparable to the decision makers in this case), Mazar et al. (2008) concluded that reminding people of the value of honesty (using both religious and non-religious symbols, such as the Ten Commandments or a university ethics code) significantly reduces cheating (i.e., dishonesty) – even if this is incentivised. It is possible that a similar tactic might result in people more honestly assessing the quality of their decisions. Although a replication study did not find any significant effects (Verschuere et al., 2018), Mazar et al. (2008) do provide some theoretical support for their approach. Referring to Aronson (1969), Baumeister (1998) and Bem (1972), the authors argue the behaviour observed in their experiment has to do with "the way people view and perceive themselves", something termed *self-concept*. Mazar et al. (2008, p. 634) argue that confrontation with non-compliance with one's own standards (of honesty, in this case) will negatively influence one's self-concept, which is "aversive". They suggest two ways to prevent one from having to 'update' one's self-concept and bear the consequences: one is accepting (some) dishonesty (as in case of a white lie), another one is to avoid the confrontation with one's standards. Whereas individual reflective thinking might not be enough to trigger that confrontation, other group members might be.

In addition to the above it is hypothesised that there is an inherent benefit to self-assessment (at a group level, at least), as long as honesty is somehow guaranteed. By asking people to set their own standards to which they compare their performance (i.e., define their own ideal), people might be likely to set more ambitious goals – as they know they are making it easy for themselves if they do not and do not want to see themselves as taking the easy way out.

3.2. Influences on decision quality

Through an extensive deliberation, the previous section defined decision quality as *the extent to which a (group of) decision maker(s) at the decision point can convince an ideal observer that the desigin will yield the decision goal, insofar possible*, following discussions on what a decision is and what the process of decision making entails. With that all established, attention can now be focused on improving group decision quality.

In literature, a host of factors influencing group decision quality are found. Probably stemming from the lack of a clear definition of decision quality, some of the factors concern the actual decision whereas others deal with the decision making process. As both are deemed important, both are included in this section. Second- and especially third-degree influences are – generally – not included. The same goes for factors contributing to the larger objective of 'team effectiveness', except for the case where it is explicitly linked or equated to decision (making) quality.

The literature search strategy as well as the unprocessed results are documented in Appendix B and are summarised and analysed in this section. Four groups of factors were identified: contextual and support-

[7] This is not to say that everyone upholds the same (internal or external) moral standards, just to say that the standards that people do uphold, influence their actions. For some, some people might be perfectly alright with operating in the legal 'grey zone' when filing a tax return in order to pay less taxes, whereas others might see this as tax evasion.

ive factors (also mentioned by Oetzel (2017) and Pavitt (2014)), technical factors, socio-psychological factors (split up into group and personal factors by Pavitt (2014), but combined here) and implementation factors. In the next sections, these are treated further.

3.2.1. Contextual and supportive factors

Contextual and supportive factors determine the context in which the decision making process takes place. Hamilton et al. (2017, p. 55) name decision characteristics, such as "the urgency of the decision" or importance of the topic (Cooper et al., 2001), other authors mention medium (Hollingshead, 1996; Radford et al., 1994) and (associated) facilities, equipment, models and resources (Baker and Albaum, 1986; Taylor et al., 2013; Lamb et al., 2011a; Hahlweg et al., 2017; Hamilton et al., 2017; Lin et al., 2017). The incentive provided to an individual or group (Kelly, 2010) is also seen as contextual factor. Available time – both for the discussion itself as well as for (individual) preparation – and resources are other noted influences (Hahlweg et al., 2017; Lamb et al., 2011b, 2012, 2013; Larson Jr. et al., 1994; Kerr and Tindale, 2004; Pavitt, 2014). Grouped with the factor of time is also excessive workload, which is mentioned by both Taylor et al. (2013) and Lamb et al. (2011b). Lastly, decision procedures such as the way groups 'vote' (majority rule, consensus, aggregation, deliberative acceptance, or other), structure the problem or work together (e.g. in meetings) have been found to influence decision making (Baartmans and Kosolosky, 2015; Burleson et al., 1984; Gillet et al., 2009; Hirokawa, 1982; Garvin and Roberto, 2001; Schweiger et al., 1986; Bakay et al., 2014; Sullivan et al., 2016; Priem et al., 1995; Schweiger et al., 1986; Edmondson et al., 2003; Mathieu et al., 2000; Kerr and Tindale, 2004), as well as procedural rationality (McNally et al., 2009; Hammedi et al., 2011).

3.2.2. Technical factors

Technical factors are mostly hard, rational, factual influences: information (Hirokawa and Scheerhorn, 1986; Chen et al., 2013; Lamb et al., 2012; Taylor et al., 2013; Bhugra et al., 2011). Decision quality is influenced by information about the (external) context (Lanceley et al., 2008; Lamb et al., 2011c,d; Hamilton et al., 2017; van Riel et al., 2011) as well as the (internal) content of the problem (Hamilton et al., 2017; Blazeby et al., 2006; Wood et al., 2008; Lamb et al., 2011c,d,a; House, 1996; McLeod, 2013; Pavitt, 2014). It should be readily available (Lamb et al., 2013; Seretis et al., 2014; Lamb et al., 2011b; Sauter, 1999; Smith and Gamberoni, 1956; Albar and Jetter, 2013; Rochford, 1991; Hsu et al., 2003; Mohanty et al., 2005; Chan and Ip, 2010), adequate (Shah et al., 2014; Rochford, 1991; Hsu et al., 2003; Mohanty et al., 2005; Chan and Ip, 2010), complete (in the sense of spanning all relevant domains of information (Lamb et al., 2012), meeting the requirements of decision models used (Sauter, 1999; Smith, 2003; Albar and Jetter, 2013)), including specialist input (Shah et al., 2014; Pavitt, 2014)) and of good quality (Hirokawa and Pace, 1983; Lamb et al., 2013; Hahlweg et al., 2017; Rochford, 1991; Hsu et al., 2003; Mohanty et al., 2005; Chan and Ip, 2010). The information amount is also found to be of impact on decision quality, as suggested by Mullins and Sabherwal (2014) and Scudder et al. (1994), as is the presentation format (Lamb et al., 2013). Kerr and Tindale (2004, p. 637) (citing Sawyer (1997) and Sheffey et al. (1989)) explicitly mention information availability during the discussion "rather than [having to rely] on memory" and discuss information exploration as relevant contributor (Larson Jr. et al., 1994; Wittenbaum, 1998, 2000).

Just as in situations with a high degree of certainty, information is of importance in (more) uncertain situations – even though in that case, the information is likely to be less hard and factual (Hamilton et al., 2017; Chen and Chien, 2009; Elwyn and Miron-Shatz, 2010), but might be probabilistic instead (Elwyn and Miron-Shatz, 2010). Bhugra et al. (2011) furthermore name the influence of evidence-based practice. Knowledge brokering – interaction between the decision-maker and the source of the information – can contribute to that, say Urquhart et al. (2011).

Somewhat less rational are factors grouped under information exchange or information processing. These were nevertheless categorised as technical factors, as they first of all influence which information is discussed and second of all determine how the information is translated into a shared understanding. Information exchange and distribution includes whether the problem is a hidden profile one (Lu et al.,

2012; Edmondson et al., 2003), discussed in Section 3.1.3 and if so, to what extent (and how often and how intense) *unshared* information is exchanged to become part of the pool of *shared* information (Waddell et al., 2013; Atas et al., 2017; Stasser and Titus, 1985; Zhou et al., 2018; Schulz-Hardt and Mojzisch, 2012; McLeod, 2013; Edmondson et al., 2003; Kee et al., 2004; Winquist and Larson Jr., 1998; Kerr and Tindale, 2004; Cruz, 2000; Van Swol et al., 2003; Larson Jr. et al., 1998b). Reminders of unequal information distribution can aid in the exchange (McLeod, 2013). Information processing, then, deals with the use of information (van Riel et al., 2011) and with (the approach of the (De Brentani and Dröge, 1988; Chan and Ip, 2010)) assessment and evaluation of the situation, decision requirements, alternatives, opinions and assumptions (Hirokawa, 1988; Hirokawa and Scheerhorn, 1986; Hirokawa and Pace, 1983; Scudder et al., 1994; Jackson et al., 2014; McLeod, 2013; Orlitzky and Hirokawa, 2001; Chan and Ip, 2010; Hammedi et al., 2011). A last factor that "strongly influences decision quality" (Clark et al., 2000, p. 211) is the interpretation of information (Weick, 1995; Thomas et al., 1993).

3.2.3. Socio-psychological factors

As explained in the previous section, the technical factors include influences up to the point where the information is put on the decision making table. From that moment on, socio-psychological factors start to play a role. These are "soft" factors (Ceschi et al., 2014, p. 213) which are related to human interaction, involvement, emotion and needs (e.g. the need for approval and cognition (Pavitt, 2014)). To some extent, social factors can be seen as the *how*-component. Kee et al. (2004) mention discussion type, format and structure as influences, the latter two confirmed by Lamb et al. (2013) and Lamb et al. (2012), respectively. According to Lamb et al. (2011c), Lamb et al. (2011d) and Edmondson et al. (2003), an open and inclusive team discussion also promotes increased decision quality. This is supported by psychological safety (Edmondson et al., 2003). Simons (1996, p. 41) also mentions the "open expression of difference in an executive group" as a "key to making high-quality strategic decisions". Kozlowski and Ilgen (2006) and Salazar (2009) point to team climate and atmosphere; both also indicate group efficacy as contributor to high-quality decisions. In the medical context of a large amount of the papers included in the literature review, patient preference (Wood et al., 2008; Hamilton et al., 2017), patient choice (Elwyn and Miron-Shatz, 2010; Blazeby et al., 2006) and patients' "holistic needs" (Taylor et al., 2013, p. 79) are seen as a factor of influence. Besides fit with client preferences, Fargason Jr. and Haddock (1992, p. 163) mention organisational fit and stress that "integrative solutions can reach high-quality decisions [...] more frequently".

The socio-psychological factors mentioned most often, however, have to do with the decision making team. This concerns team-cultural factors, structure, cohesiveness, communication and general team working skills (Sullivan et al., 2016; Lamb et al., 2011b, 2013; Kidger et al., 2009; Lamb et al., 2012; Taylor et al., 2013; Seretis et al., 2014; Hirokawa, 1988; Mullen et al., 1994; Kidger et al., 2009; Carmeli and Schaubroeck, 2006; Ceschi et al., 2014; Pavitt, 2014; Kozlowski and Ilgen, 2006). Team composition is mentioned regularly, both in general (Lamb et al., 2012, 2011a, 2013; Malhotra et al., 2007; van Riel et al., 2011) and in specific situations, for example with regard to balance of power, dominance or status (Kee et al., 2004; Lanceley et al., 2008; Hamilton et al., 2017; Bakay et al., 2014; Burris et al., 2009; Hirokawa and Pace, 1983; Pavitt, 2014), size (Lu et al., 2012), cohesion (Kozlowski and Ilgen, 2006), competencies (Kozlowski and Ilgen, 2006) and diversity (Atas et al., 2017; Simons, 1996; Yaniv, 2011; Brodbeck et al., 2002; Lamb et al., 2012; Bhugra et al., 2011; Wanous and Youtz, 1986; Fargason Jr. and Haddock, 1992; Edmondson et al., 2003; Pavitt, 2014; Mannix and Neale, 2005; Chan and Ip, 2010). A separate subcategory is defined to group decision quality influences related to conflict, dissent, devil's advocacy and reflexivity (Lin et al., 2017; Gillet et al., 2009; Lang et al., 2008; van de Vliert and de Dreu, 1994; Hamilton et al., 2017; de Dreu et al., 2000; House, 1996; Schwenk and Cosier, 1993; Waddell et al., 2013; Salazar, 2009; Kozlowski and Ilgen, 2006; Hammedi et al., 2011). Various authors argue that (some) task-related conflict directly or indirectly improves decision quality (Chang, 2011; Choi and Thompson, 2005; Nemeth and Rogers, 1996; House, 1996; Schulz-Hardt et al., 2006; Schulz-Hardt and Mojzisch, 2012; Amason, 1996; Brodbeck et al., 2002; Kerr and Tindale, 2004), also as this aids exchange of hidden information and prevents dominant (but not necessarily right) opinions from taking centre stage (Kee et al., 2004). Related to this is vigilant interaction, discussed in relation to decision quality by Salazar (2009), Larson Jr. et al. (1998a), McLeod (2013) and Oetzel (2017). Affective or relationship conflict, however, is warned

against (Kotlyar et al., 2011; Waddell et al., 2013; Kozlowski and Ilgen, 2006), as this has a negative influence on decision quality or its implementation. Reaching consensus is another often-cited factor. As stated, Schulz-Hardt et al. (2006, p. 1091) have found that "group decision quality benefits from pre-discussion dissent among group members". Initially different ideas and opinions lead to considering a wider array of different perspectives, improving the decision quality. At later stages of the decision making process, conflict and disagreement about the course of action however can be a negative effect, highlighting the importance of opinion aggregation (Lamb et al., 2013; Kee et al., 2004) to yield agreement (Kidger et al., 2009; Schwenk and Cosier, 1993; Lamb et al., 2011a). Furthermore, teams should not only have a good composition on paper, but make sure that all team members attend the meetings (Lamb et al., 2012, 2013; Taylor et al., 2013; Kee et al., 2004; Lamb et al., 2011b,a; Clark et al., 2000; House, 1996) and contribute to and participate in these (Lamb et al., 2013; Pavitt, 2014). Other group-wide socio-psychological factors are goal setting (Hirokawa and Scheerhorn, 1986; Sassenberg et al., 2014; McLeod, 2013), internal team structure and roles clarity (Sullivan et al., 2016; Taylor et al., 2013; Mathieu et al., 2000; Kerr and Tindale, 2004) and team coordination and regulation (Kozlowski and Ilgen, 2006). Stressed very often is the importance of leadership, their behaviour, style or the information they possess (Shah et al., 2014; Lamb et al., 2011b,a,d, 2013; Taylor and Dunnette, 1974; Kee et al., 2004; Kidger et al., 2009; Henningsen et al., 2004; Kim et al., 1998; Larson Jr. et al., 1998b; Burris et al., 2009; Mullen et al., 1994; Meyer et al., 2016; Chen et al., 1996; Larson Jr. et al., 1994; Kerr and Tindale, 2004; Pavitt, 2014; Hammedi et al., 2011; Larson Jr. et al., 1998b; Edmondson et al., 2003).

Hirokawa and Scheerhorn (1986) state that cognitive reasoning factors also have an influence on decision quality, of which plenty of evidence is indeed found in literature. Prime examples of this are the various cognitive biases (Simon et al., 1987; Bhugra et al., 2011; Kahneman et al., 2011; Tindale et al., 1996; Kerr et al., 1999; Kerr and Tindale, 2004) and heuristics (Albar and Jetter, 2013), of which Croskerry (2003) provides an extensive overview. Specifically, Dennis (1996), Stasser and Titus (1985), Schulz-Hardt and Mojzisch (2012) and Zhou et al. (2018) mention discussion, information sampling bias or information repetition bias (the extent to which already shared information is re-introduced and discussed again, at the cost of discussing unshared information) and Sassenberg et al. (2014) and Schulz-Hardt and Mojzisch (2012) treat evaluation or processing bias (the extent to which people regard preference-consistent information as more important than information that does not support their initial preference) and reasoning orientation (Innami, 1994). Groupthink is mentioned by Janis (1972) (in Salazar (2009)) Jones and Roelofsma (2000), Kaba et al. (2016) and Kahneman et al. (2011). Furthermore, framing aspects play a role (Simon et al., 1987; Burtscher and Meyer, 2014). Bhugra et al. (2011), then, indicate a balance between intuition and experience in more and less experienced professionals, respectively, which is also clustered in this group of socio-psychological factors.

A last set of influences – on a somewhat grander scale – is grouped in the category *team integration*. Ceschi et al. (2014) cite Van Der Vegt and Bunderson (2005), who have shown that collective identification is positively related to decision-making performance. Ceschi et al. (2014) (citing Van Der Vegt and Bunderson (2005)), Kozlowski and Ilgen (2006), Robert et al. (2008) and Kozlowski and Ilgen (2006) furthermore mention group learning, knowledge integration and shared mental models; various others discuss the potential of a so-called Transactive Memory System (TMS) (Hammedi et al., 2013; Kozlowski and Ilgen, 2006; Moreland, 2006; Edmondson et al., 2003; Stewart and Stasser, 1995; Kerr and Tindale, 2004). Such a TMS "describes a social network of individual minds" (Wegner, 1987, p. 206) that – among other things – has been shown to promote information exchange (e.g. in hidden profile situations discussed earlier) (Edmondson et al., 2003; Kerr and Tindale, 2004) and decision quality (Hammedi et al., 2013). Although the currently reviewed literature does not provide direct evidence for it, these ideas of integration, (social) identity (Kane et al., 2005) and knowledge sharing also bring to mind Wenger (2000)'s communities of practice, leading to a possibly interesting outlook for a larger, higher-order influence on decision quality.

3.2.4. Implementation factors

Implementation factors have to do with commitment to and implementation of the decision. This includes the ability to implement a decision (Lamb et al., 2012), the clarity of the decision that is made (Kidger et al., 2009; Jackson et al., 2014), the commitment to the decision (Kotlyar et al., 2011) (stimulated

by contribution to the decision-making, according to Vroom and Yetton (1973) and Edmondson et al. (2003)), the implementation and recording of the decision (Lamb et al., 2011a) and the acceptance in the organisation (Cross et al., 2009).

3.2.5. Schematic representation of influences on decision quality

The factors found in literature are combined with the decision making process layout sketched in Figure 3.1 to yield Figure 3.2, an hypothesis for a schematic representation of influences on decision quality. Through the combination and abstraction of factors into the schematic, the figure is deemed to hold beyond the specific contexts from which it was essentially derived.

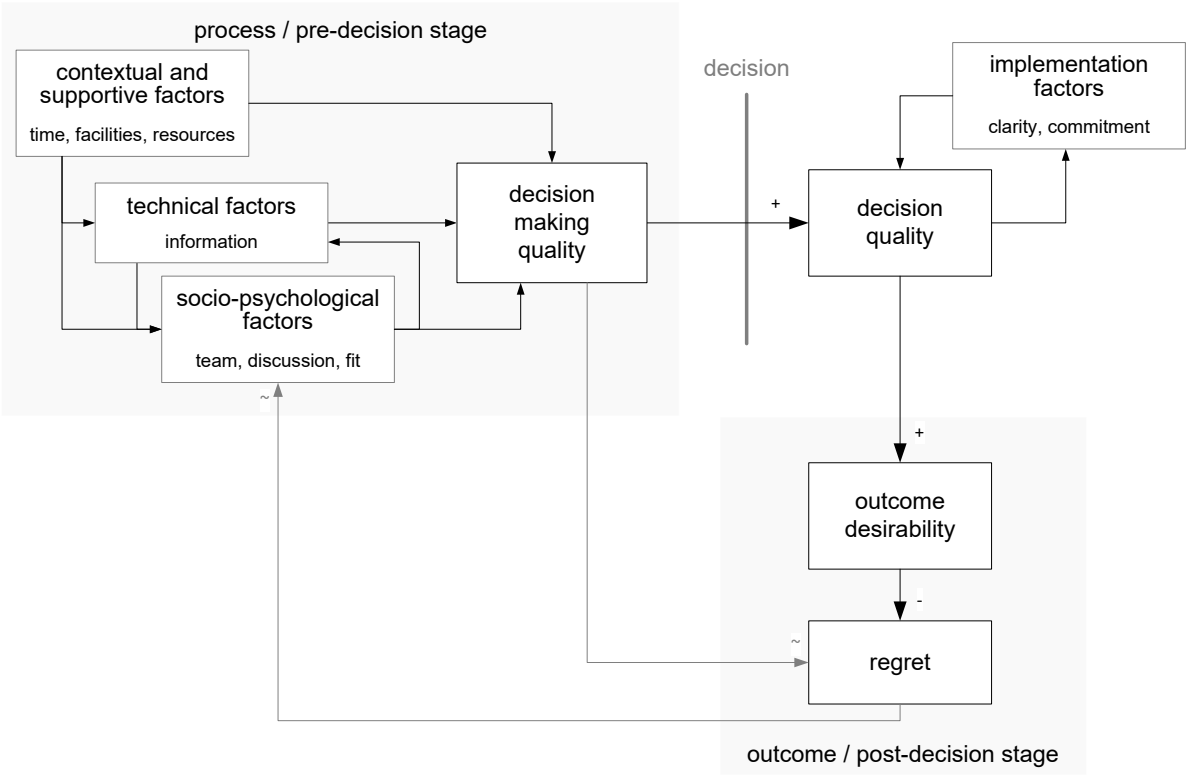


Figure 3.2: Schematic representation of influences on decision quality

Three of the four clusters discussed in the previous section play a role in the *process / pre-decision stage*. The different groups influence each other, for example in the situation where people in a team need to feel comfortable (socio-psychological factor) to share their insight (technical factor), or (the other way around) where the presentation of information (technical factor) influences how it is discussed (socio-psychological factor). Then, it is suggested that decision making quality has a positive influence on decision quality, consistent with observations by e.g. Hirokawa and Rost (1992). The fourth group of influences (implementation factors) is hypothesised to influence decision quality directly – and is in turn influenced by decision quality. This is confirmed by e.g. Oetzel (1995).

Moving away from the decision and focusing on its outcome(s), it is proposed that a good decision contributes to a desirable outcome. Then, both a good decision making process and a good outcome are hypothesised to reduce the regret decision makers feel. Lastly, people are expected to learn from past decisions. An example of this would be a situation where people experience an unsatisfactory decision outcome for which they (correctly or incorrectly) blame the decision making process, and place more importance on (that part of) the decision making process in future decisions they are involved in.

In order to increase the clarity of the diagram, uncertainty was not explicitly included. However, it has an

influence on nearly every block in the system. Examples of this are a (positive or negative) impact on the outcome desirability, on the implementation factors or on any of the clusters in the pre-decision stage.

Technical perspective

Having explained the context and investigated factors that influence decision quality, a foundation has been set on which to base a further exploration of the problem defined in the introduction. The current part investigates improving decision quality from a technical perspective. From the factors in that group identified in the previous chapter, information in and about uncertain situations was selected as topic of interest (Helton et al., 2007; Roelofs and Vos, 2018b; Zang et al., 2002; Elwyn and Miron-Shatz, 2010). More specifically, the next five chapters deal with uncertainty quantification and propagation thereof in the Aircraft Design Initiator. As such, it aims to achieve the first research objective, repeated below.

> Make a contribution towards providing decision makers with a usable assessment of epistemic model uncertainty of the Aircraft Design Initiator and the impact thereof on its output, by proposing a bottom-up methodology to quantify model uncertainty in aircraft conceptual design, by studying the effects of different assumptions on relevant model output of various aerodynamic analysis methods relevant in the conceptual design phase.

Connected to this research aim is the first research question, also quoted below:

> How can model uncertainty be quantified, assessed and propagated bottom-up, i.e., starting from model(ling) assumptions, simplifications and limitations?

The sub-questions to this research question, presented in Section 1.3, are answered in the various chapters contained in this part. Chapter 4 aims to focus and provides an overview of different aerodynamic models, solution methods and solvers. Also, it presents the selection of models that is the subject of the subsequent analysis and discusses criteria selection, thereby answering research questions I-a and I-b. Following in Chapter 5 are somewhat more detailed descriptions of the solvers and analysis tools under investigation, to help in understanding their workings. This answers research question I-c. Although these are mere instances of the aerodynamic flow models that are the true topic of this research, it is deemed relevant to discuss their specific assumptions, simplifications and limitations. This chapter also provides more detailed information about the Aircraft Design Initiator. Next, Chapter 6 treats uncertainty *quantification*, formulating an answer to research question I-d. Chapter 7 aims to extend those insights and is concerned with uncertainty *propagation* (research question I-e). The part is closed in Chapter 8, where conclusions are drawn and limitations are discussed.

4

Model and criteria selection

This chapter forms the basis for the remainder of this part, as it introduces the various forms of aerodynamic models and solution methods in existence and selects a set that will be analysed in subsequent chapters in this part. This is the topic of Section 4.1, which thereby answers research question I-a: *Which (kind of) flow models, solution methods and combinations thereof (i.e., solvers) are suitable for aerodynamic analysis in a conceptual design process?* Next, Section 4.2 answers research question I-b: *Which criteria are relevant for the comparison of different aerodynamic analysis models in a conceptual design process?* Although this chapter is limited to aerodynamic flow models and solvers, the concepts discussed can largely be generalised to other disciplines, such as structural analysis and design.

4.1. Model selection

Models come in a variety of shapes and sizes. Although all are aimed to describe the world around us – or part thereof – their uses are vastly different. This also has an effect on model complexity. For example, in order to explain the concept of global warming, one could show a half-page illustration of how the atmosphere works. However, if a model has to provide input to discussions about policy measures mitigating climate change in a very specific location, this illustration would not suffice. Instead, one would need a much more complete and detailed description of the atmosphere – which only a few topic specialists might be able to correctly interpret, and is certainty not suitable for treatment in middle school.

This section is about that dilemma: what is the right tool for the job? Section 4.1.1 presents an overview about various types of aerodynamic flow models and illustrates the trade-off that is often at the heart of model selection: accuracy versus (computational) cost. Section 4.1.2 treats the ways in which the flow model equations can be mathematically solved and Section 4.1.3 discusses solvers – computer programs that combine (a) flow model(s) with (a) solution method(s) and thereby form the actual tool. Section 4.1.4 discusses the applicability of flow models, solution methods and solvers on conceptual design, introduced in Section 2.2. Based on all these considerations, Section 4.1.5 concludes the section and presents a selection of models to be considered in the remainder of this project.

This section is closely based on the results of a literature review, conducted in preparation of the current research project (Peerlings, 2018). Readers interested in a more in-depth treatment of the topics under discussion are referred to that document.

4.1.1. Overview of flow models

In general, flows are governed by three basic principles: the conservation of mass, momentum and energy. How these laws of conservation are translated into equations, however, differs. This section treats

those differences, outlining two philosophies of simplifying the governing equations and the (modelling) assumptions that come from both.

The most accurate way a flow can be modelled are using the **Navier-Stokes equations** (Anderson et al., 2009; Peyret and Viviand, 1975). The computational cost associated to solving these equations however prevents their 'full' (or time-dependent) form to be of practical use in industry for decades to come (Spalart, 2000; Argyropoulos and Markatos, 2015). Hence, the computational cost has to be brought down, for which there are two philosophies: replace part of the physical models by empirical relations or simplify the flow model by making assumptions.

Empirical modelling

Starting with the first strand, a first differentiation is made by the extent to which turbulence is resolved or modelled. Fully (physically) resolving turbulent flow structures in the Navier-Stokes equations is done with *direct numerical simulation* (DNS). *Large eddy simulation* (LES) only resolves the larger turbulent structures, but models the smaller (and more universal) eddies using empirical relations (Cummings et al., 2015; Ferziger and Perić, 2002). The well known *Reynolds-averaged Navier-Stokes* (RANS) equations completely model turbulence (using a turbulence model, as discussed in e.g. Cummings et al. (2015) and Argyropoulos and Markatos (2015)) and only resolve laminar flow (Blazek, 2007; Elham, 2013; Leschziner, 2010; Cummings et al., 2015). By default, RANS is limited to steady flows, but unsteady RANS (URANS) allows to model transient effects as well (Nanda, 2016; Salim et al., 2011; Léonard et al., 2015; Spalart, 2000). In any case, the RANS approximation requires Reynolds numbers to be high (i.e., the inertial forces are much higher than the viscous forces), such that turbulence is limited to the smaller scales that can be empirically modelled relatively well. If Reynolds numbers are sufficiently high ($Re > 10^4$), a further approximation can be made which results in the *thin-layer Navier-Stokes* (TLNS) equations. These assume that all turbulent effects are constrained to the boundary layer and therefore neglect viscous derivatives parallel to the surface of the object under analysis (Pulliam, 1986; Mouch and Lan, 1993). Assuming the pressure is constant throughout the boundary layer yields the **boundary layer** equations (Anderson, 2001; Lock and Williams, 1987). In contrast to the TLNS equations, the boundary layer equations are not able to model flow separation (Cummings et al., 2015; Hassan and Munts, 2000; Baldwin and Lomax, 1978; Pulliam, 1986). Often, boundary layer equations are coupled to an inviscid model (using a viscous-invsicid interaction (VII) method) to yield a solution that holds over the entire domain. This matching is not necessary in case the TLNS equations are used (Pulliam and Steger, 1978).

Model simplifications

Taking the other path – of assumptions to simplify the flow model – first finds the **Euler** equations, which assume inviscid flow (Jameson, 2004). Assuming irrotational flow yields the **full potential** equation. This assumption makes this flow model unsuitable for modelling flow downstream of a shock wave (Freestone, 2004). Two possibilities exist of simplifying the full potential equation: linearising it or assuming incompressible flow. The **linearised potential flow** equation (also known as the **Prandtl-Glauert** equation) assumes small perturbations and as such cannot be used to describe transonic flow ($0.8 \leq M_\infty \leq 1.2$) (Cummings et al., 2015). The incompressible **Laplace** equation is limited flows at $M_\infty < 0.3$ (although compressibility corrections can be used to increase this limit to $M_\infty \approx 0.7$), but on the other hand is not restricted to small perturbations (Anderson, 2001, 2002).

Overview

Figure 4.1 graphically summarises the previous discussion. Colours are used to indicate the *fidelity level* (Gu et al., 2018; Ciampa et al., 2013; Jungo et al., 2018). Level L3 indicates "the most detailed representation of the physics phenomena", L2 a "more detailed representation of the physics phenomena" and L1 a "*simplified* representation of the physics phenomena" (Jungo et al., 2018, p. 617, emphasis in original). Fully empirical methods, such as the ESDU Aerospace Package (IHS) and the US Air Force DATCOM methods (Hoak, 1978), are labelled as level L0. Level L2.5 was added to the classification found in literature (in which TLNS and boundary layer equations are not discussed) to fit between levels L2 and L3 (Peerlings, 2018).

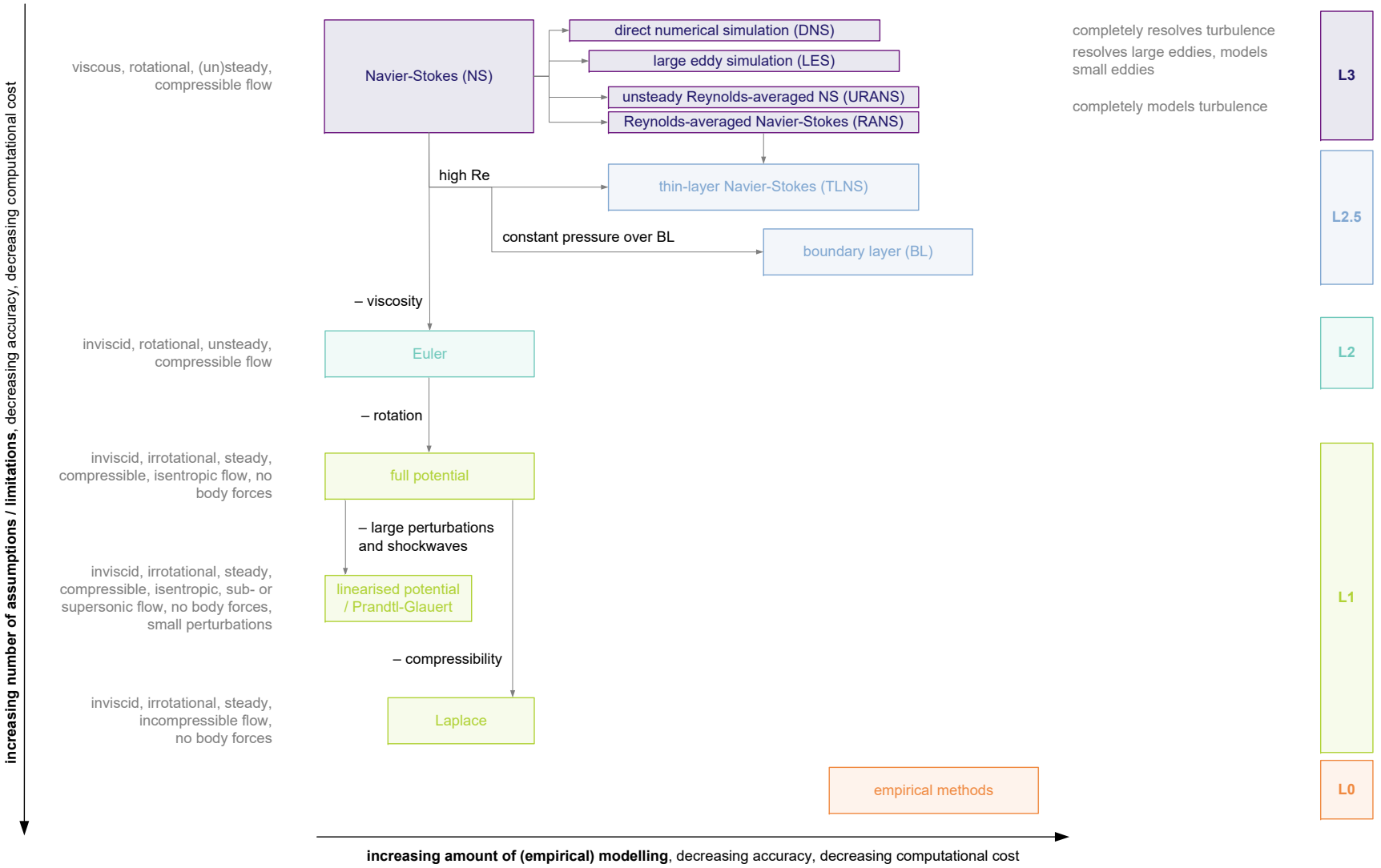


Figure 4.1: Hierarchical overview of aerodynamic flow models, based on Jameson (2004, p. 11), Mariens (2012), Schmidt (2013), Gu et al. (2018), Cummings et al. (2015, p. 139), Gerritsma (2002) in Elham (2013, p. 77), Anderson (2002) and Spalart (2000), copied from (Peerlings, 2018). Larger-size versions available through repository.tudelft.nl.

4.1.2. Overview of solution methods

As the flow models are expressed in potential differential equations which cannot be solved algebraically, numerical solution methods are required to actually obtain pressure distributions and other flow properties. The underlying concept of all the methods treated below is the discretisation of the differential equations, which yields a set of algebraic forms that can be solved numerically – either simultaneously or iteratively (Anderson, 2001; Bakker, 2006; Kuzmin). This section treats various solution methods, again based on Peerlings (2018).

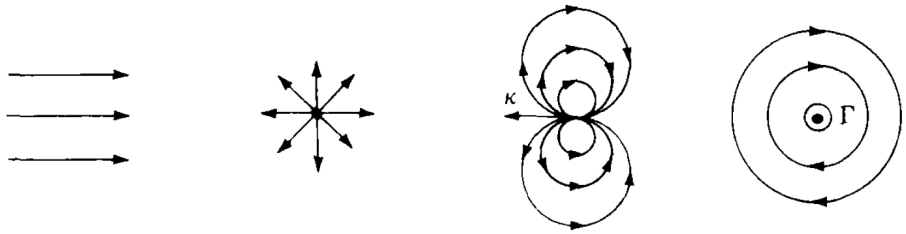
Non-linear methods

A primary distinction is made between two types of numerical methods: non-linear methods are applied to solve non-linear flow models (Navier-Stokes in its various forms, Euler and full potential). Most often, either **finite volume (FVM), element (FEM) or difference (FDM) methods** are used (Blazek, 2007). In FVM and FEM, the geometry under investigation is split up into finite volumes or elements (in 2D often triangular; in 3D tetrahedral) for which the flow model is solved. The more volumes or elements, the more precise the solution will be, although this comes at increased computational cost. Finite difference methods take a different approach. They require a structured grid (as opposed to the possibly unstructured grids or *meshes* used for FVM or FEM) and approximates the derivatives of the flow model (a set of differential equations) using a Taylor series expansion (Anderson, 2001; Kuzmin). Non-linear methods generally require a more detailed description of the geometry (Mariens, 2012).

Given a particular aerodynamic flow model, all non-linear methods should theoretically arrive at the same results. In practice, differences are formed by the convergence rate of various models, as well as differences regarding for example discretisation and tolerances.

Linear methods

Linear numerical methods are applied to the linearised potential and Laplace equation (Anderson, 2001). These methods start at the notion of *elementary solutions* – shown in Figure 4.2 – which can be (linearly) combined to represent any (linear) flow. Only vortex flow (shown in Figure 4.2d) has finite circulation and therefore (through the Kutta-Joukowski theorem) produces lift. If a line of vortices is placed "behind" each other, a vortex filament is created. Vortex filaments cannot end in a flow, but have to continue to infinity or form a closed loop.



(a) Uniform flow (b) Source flow (c) Doublet flow (d) Vortex flow

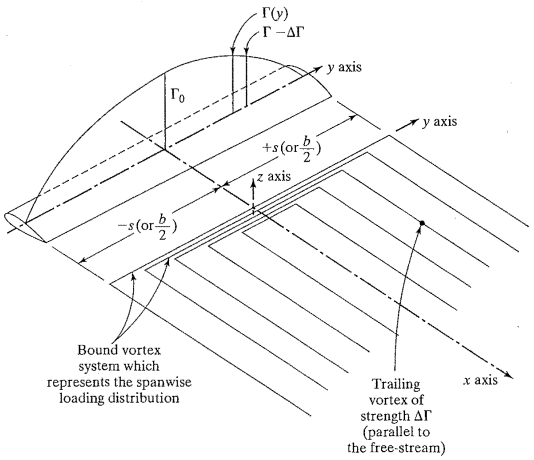
Figure 4.2: Elementary flow solutions (Anderson, 2001)

As with the non-linear methods, multiple linear solution methods exist: lifting line and lifting surface theory (LLT / LST), vortex lattice methods (VLM) and panel methods. **Lifting line theory** replaces the wing by a single vortex filament, bound between the wing tips. At the tips, two trailing vortices are formed – yielding a single horseshoe vortex. Additional lifting lines can be superimposed to better approximate the lift distribution[1].

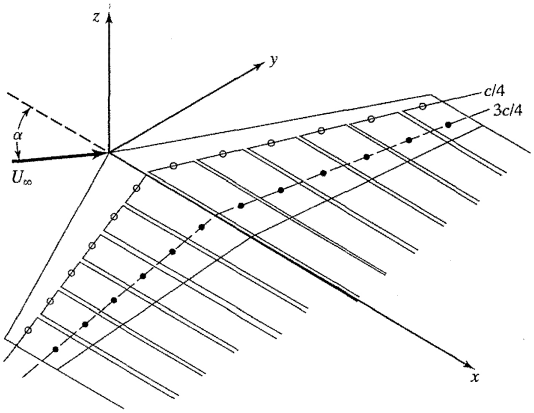
The lifting line theory is limited to thin, straight and relatively slender ($\mathcal{AR} > 4$) wings (Anderson, 2001). In order to circumvent some of these restrictions, a distribution of horseshoe vortices can also be added in chordwise direction to give rise to a lifting surface. **Lifting surface theory** is still limited to thin surfaces,

[1] The ideal to which wings are generally designed is an elliptical lift distribution. Most lift is generated at the root of the wing - where the structure is strongest and best equipped to handle these bigger loads. Towards the tip, the lift force is reduced.

but can for example handle wing sweep. Whereas the lifting surface theory is based on lifting lines that span the complete wing, the conceptually related **vortex lattice method** (VLM) takes a different approach by first dividing the geometry into panels and then placing a horseshoe vortex on each one. This simplifies the solution procedure (Peerlings, 2018). A comparison of the horseshoe vortex arrangements of LST and VLM is shown in Figure 4.3. In both cases, the lift distribution, lift force and induced drag can be computed from the sheet of downstream trailing vortices (Anderson, 2001). Lifting line, lifting surface theory, and the vortex lattice method all assume small angles of attack.



(a) Lifting surface theory: superposition of a number of horseshoe vortices (Bertin and Cummings, 2009, p. 324)



(b) Vortex lattice method: distributed horseshoe vortices (Bertin and Cummings, 2009, p. 355)

Figure 4.3: Comparison of the horseshoe vortex arrangement, as implemented in lifting surface theory and vortex lattice methods (Peerlings, 2018). Please note that only one vortex is used in chordwise direction (x-axis).

Contrary to aforementioned solution methods, **panel methods** are able to model three-dimensional geometries (Hess, 1988), such as thicker wings, fuselages or nacelles. As VLMs, they cover the geometry in panels (as shown on the left of Figure 4.4) to which (combinations of) the elementary solutions previously discussed are added. Summing over all panels yields a distribution of the strengths of the singularities, from which the pressure distribution and resulting lift distribution can be calculated.

The geometrical differences are shown in Figure 4.4. The left image is illustrative of the three-dimensional, thick wing panel methods as just discussed. The right image, on the other hand, is representative of lifting surface and vortex lattice methods (in this case extended with a slender body model of the fuselage and tail booms). In the latter case, the surfaces are seen to have zero thickness.

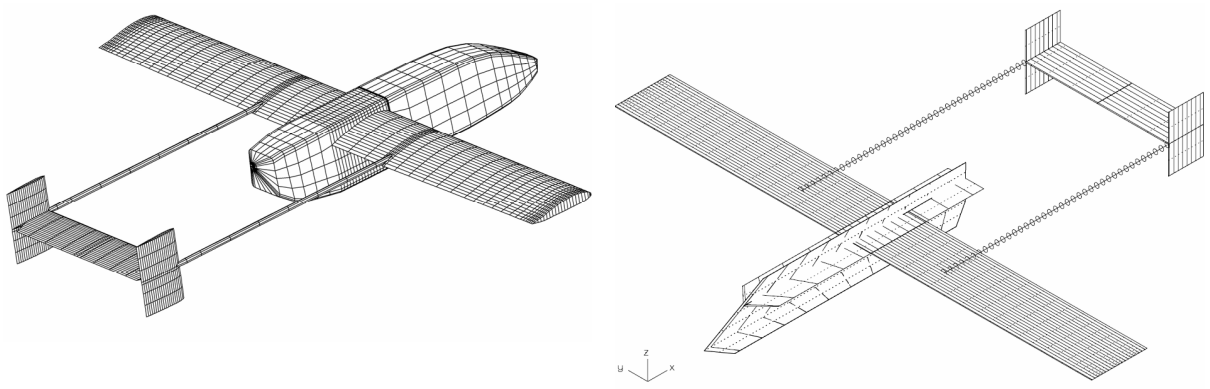


Figure 4.4: Comparison between geometric representations using a 3D panel method (PAN AIR, left) and a vortex lattice method (AVL, right), clearly indicating the lack of thickness in VLM representations (Boschetti et al., 2010, p. 5)

Boundary conditions

Regardless of a flow model being linear or not, boundary conditions are required to 'fix' the model (a differential equation, or set thereof) and its solution to a specific flow scenario (Cummings et al., 2015; Hirsch, 2007). There are far-field boundary conditions and surface boundary conditions. Far-field boundary conditions set requirements on the flow characteristics far away from the object under analysis. Often, free stream conditions are prescribed (Anderson, 2001; Bertin and Cummings, 2009).

Surface boundary conditions prescribe flow properties at the surface of the object. In case of viscous flow, this is the *no-slip* condition, which stipulates that the flow velocity at the surface is 0 – caused by viscous (shear force) effects at the surface. As heat transfer effects also come into play in viscous flow, a second boundary condition specifies the wall temperature or heat flux.

If viscosity is neglected, the *flow tangency* boundary condition is used. Contrary to the no-slip condition where all velocity components are 0, this only enforces the flow velocity normal to the surface to be 0. This essentially requires the surface to be a streamline of the flow. An exception to the flow tangency condition is made when the surface is porous or modelled as such (as is the case for an exhaust, for example). Then, a non-zero normal velocity is allowed.

4.1.3. Overview of solvers

An implementation of a particular flow model combined with a solution method is called an aerodynamic solver – or solver for short. Peerlings (2018) has reviewed 11 solvers, that indeed varied in terms of flow model and solution method – making the solvers suitable (or unsuitable) for a variety of flows. Figure 4.5 provides a concluding overview of the aforementioned review.

Besides flow model and solution method, the solvers vary in terms of their use (analysis, design or both), Mach regime, distribution or license (open source, academic or commercial) and the number of dimensions modelled. Two-dimensional methods are limited to analysis (or design) of airfoils. Often, there solvers are able to model viscous flows – as the viscous effects have a major influence on the airfoil performance and aerodynamic efficiency. Examples are XFOIL (Drela, 1989), VGK (Freestone, 2004), MSES (Drela, 1990) and ARC2D (Pulliam, 1984). Three-dimensional codes, such as AVL (Drela and Youngren, 2017a), Tornado (Melin, 2000), VSAERO (Maskew, 1982), MATRICS-V (van der Wees and van Muijden, 1992) and SU2 (Palacios et al., 2013), can model entire wings or bodies. Besides viscous codes, various inviscid models exist – a consequence of the fact that modelling viscous effects in three-dimensions is much more difficult (in case of three-dimensional boundary layer models), or computationally expensive (in case of RANS or other L3-simulations). 'Hybrid' or 2.5D models try to combine the best of both worlds by doing a two-dimensional viscous analysis (which yields the airfoil drag) and combining that with a three-dimensional inviscid analysis (or vice versa) . Often, these tools combine existing 2D- and 3D-packages. Examples are XFLR5 (Deperrois, 2011), which uses XFOIL for the 2D analysis, and Q3D (Mariens et al., 2014), combining 2D data from XFOIL, VGK or MSES (depending on the Mach number) with a 3D analysis in AVL.

4.1.4. Applicability to conceptual design

As discussed in the introduction of this section, various models have various applications. What models are best suited for conceptual aerospace design is a widely deliberated question – further stressing the relevance of this research (Roelofs and Vos, 2018b).

The question centres around the merits of using higher-fidelity models (such as RANS) in early design phases. Some scholars are in favour of this development, noting that these (more physics-based) models might be the only ones suitable for assessment of novel technologies (Ciampa et al., 2013), can prevent cost and schedule overruns (Kroo, 2004; Carty, 2002) and allow for earlier multidisciplinary design optimisation (Suwarantana and Rodriguez, 2011; McMasters and Cummings, 2004; Carty, 2002; Jameson, 1999; Torenbeek, 2013). Because of that, Gu et al. (2018) expects less redesign activities later on.

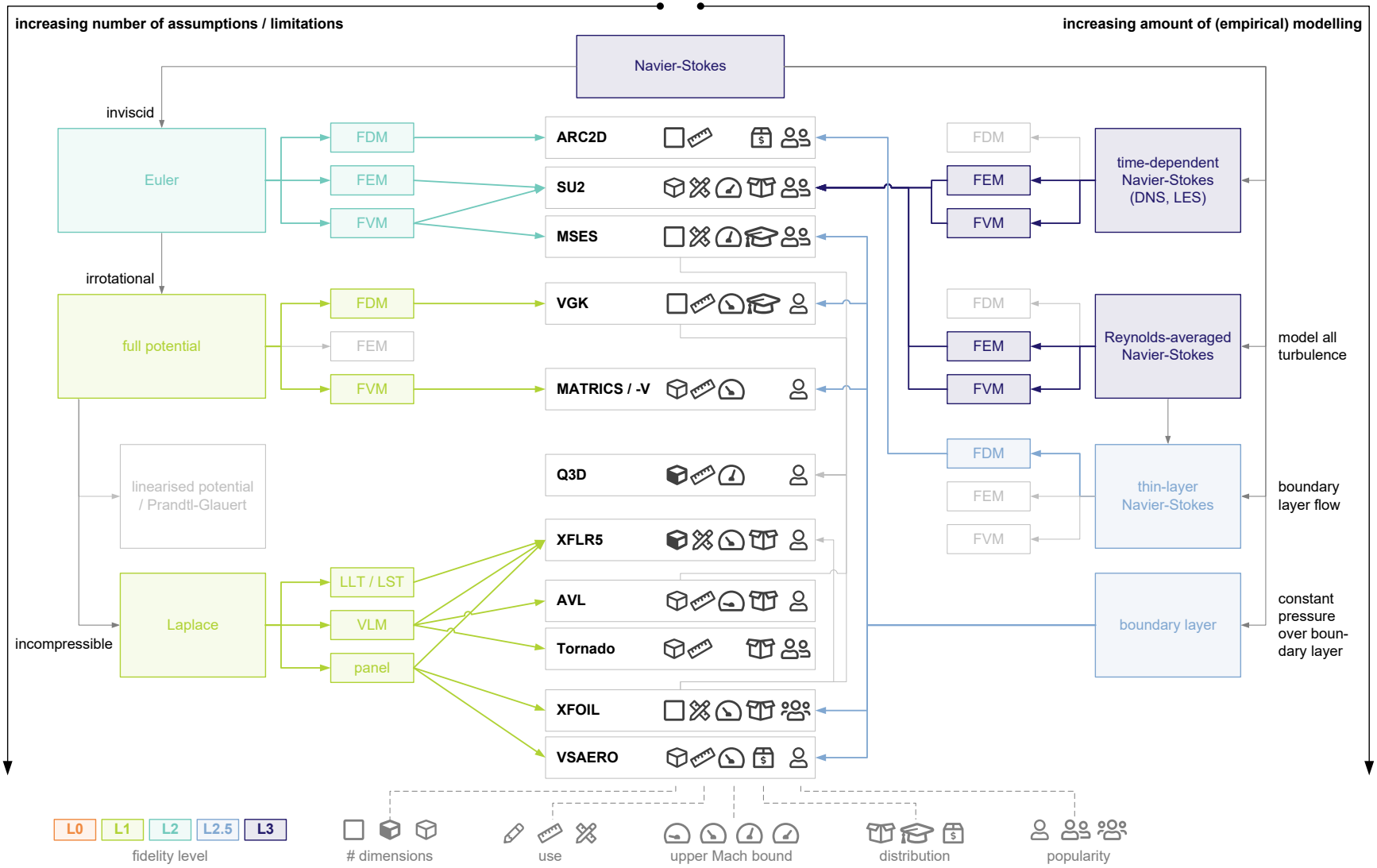
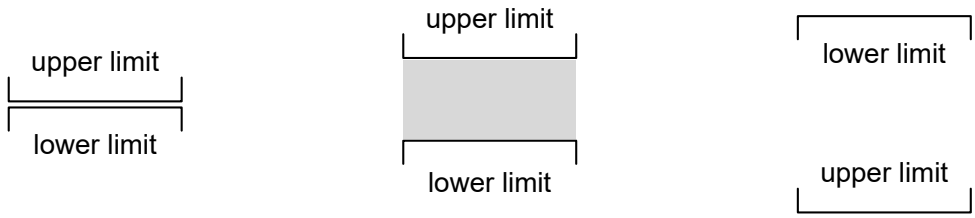


Figure 4.5: Hierarchical overview of aerodynamic solvers, copied from Peerlings (2018). Larger-size versions available through repository.tudelft.nl

That is completely opposite to the review presented by Raymer (2002, p. 35), who is arguing that if not all requirements are properly implemented in such an optimiser, substantial rework is required to create a feasible result, “probably worse than” what the optimiser proposed. Also, the detailed information (such as airfoil profiles) required by higher-fidelity models in his opinion has no place in conceptual design – which should focus on top-level requirements and geometry features (such as the wing planform). Raymer (2002, p. 17) furthermore feels that “everything-optimization” is not only infeasible, but also undesirable, given the time required. Additionally, Jameson (2003) has (in the context of high-fidelity models) warned that large volumes of data might be hard to interpret.

A last group of scholars appreciates the potential, but see practical limitations. Sinsay and Nuñez (2010) wonder if it will be cost effective to spend these resources on concepts, of which only very few will become reality. Generating a geometry of high enough accuracy is a prime cost driver (Sinsay and Nuñez, 2010; Ghosh et al., 2014; Gu et al., 2018; Suwarantana and Rodriguez, 2011; Haimes and Drela, 2012). Furthermore, current (drafting-based) computer aided design systems make it difficult to make even small changes to geometries (Suwarantana and Rodriguez, 2011) and grids (Raymer, 2002).

Based on these arguments and the introduction of the term *right-fidelity* (“where the band of uncertainty is small enough to definitively distinguish between concepts”) by Sinsay and Nuñez (2010, p. 4), Peerlings (2018) has defined limits to the fidelity level – lower bound given by right-fidelity; upper bound by time and cost available – that lead to the three scenarios visualised in Figure 4.6.



(a) Lower limit equal to upper limit: fidelity level clear

(b) Lower limit below upper limit: select lower fidelity level

(c) Lower limit above upper limit: postpone analysis or increase resources

Figure 4.6: Possible combinations of lower and upper fidelity limits (Peerlings, 2018, p. 75). The lower limit is defined by right-fidelity (Sinsay and Nuñez, 2010): the minimum level of detail required to distinguish between concepts. The upper limit is given by resource limitations.

In Figure 4.6a, the desired fidelity level is clear. In Figure 4.6b, it is argued to choose the lower limit as the relevant fidelity level. In Figure 4.6c, where the lower limit is higher than the upper limit, it is proposed to either postpone the analysis to a later design stage, to separate it from the main design process or increase resources. In all cases, more resources will become available either directly or indirectly, such that the upper limit is increased – surpassing the lower limit necessary to meet.

Concluding this section, it is proposed to define the upper limit for conceptual design at fidelity level L1 (i.e., full potential equation or simpler) in three dimensions or L2.5 (i.e., TLNS or boundary layer equations, or below) in two dimensions (Peerlings, 2018). The distinction between 2D and 3D models is drawn because of the higher computational cost and increased difficulties in modelling three dimensional flow.

4.1.5. Selected aerodynamic models

As time constraints do not allow for a comparison of all models and solvers presented in this section, a selection is made. Guided by the conclusions drawn regarding their applicability to conceptual design in Section 4.1.4 and the objective to make a fair comparison, a set of two-dimensional solvers is selected that spans fidelity levels L1 to L2:

- **XFOIL** (L1), a panel method using the incompressible Laplace equation;

- **VGK** (L1), a finite difference method using the (compressible) full potential equation;
- **MSES** (L2), a finite volume method using the (rotational) Euler equations;

Two-dimensional models were selected over three-dimensional solvers, as the latter are inherently more complicated (due to the inclusion of root and tip effects and various additional transition mechanisms), therefore providing more ways for the codes to differ. Furthermore, the present selection was found to be more easily available and (generally) better documented. Table 4.1 presents a testing matrix and shows which comparisons of solvers yield insights on the influence of particular flow model assumptions and solution methods.

Table 4.1: Testing matrix, showing which insights about flow model assumptions or solution method differences are gained from comparisons

	VGK	**MSES**
XFOIL	incompressible flow panel vs. FDM	incompressible, irrotational flow panel vs. FVM
VGK		irrotational flow FDM vs. FVM

ARC2D, a finite difference method using the (viscous) thin-layer Navier-Stokes equations, was originally also planned to be included in the comparative effort but removed from consideration due to time constraints. AVL, a (three-dimensional) vortex lattice method, is used as an intermediate step in the uncertainty propagation process, before evaluating the impact on the Aircraft Design Initiator. No direct comparisons to other three-dimensional aerodynamic solvers or aircraft design suites are made.

The selected solvers – as well as AVL and the Aircraft Design Initiator – are further described in Chapter 5. Additional details of the aerodynamic solvers are included in Peerlings (2018).

4.2. Criteria selection

Given the fact that the models selected in the previous section are all two-dimensional, the choice in comparison criteria is rather limited. The following characteristics are deemed relevant for conceptual design, focused on higher-level parameters:

- For each test case:
  - maximum lift coefficient $c_{l,max}$
  - maximum lift-to-drag-ratio l/d_{max}
  - angle of attack at maximum lift-to-drag ratio $\alpha_{l/d_{max}}$
  - lift coefficient at maximum lift-to-drag ratio $c_{l,l/d_{max}}$
  - drag coefficient at maximum lift-to-drag ratio $c_{d,l/d_{max}}$
- For each angle of attack:
  - lift coefficient c_l
  - drag coefficient c_d
  - quarter-chord pitching moment coefficient $c_{m,c/4}$
  - maximum local Mach number M
  - force and moment derivatives, such as $c_{l,\alpha}$ and $c_{m,\alpha}$

Besides the quantities of interest listed above, the derivatives of force and moment coefficients are relevant from a control and stability perspective. These, for example, influence tail sizing.

5

Solver description

This chapter treats the solvers – combinations of aerodynamic flow models and mathematical solution methods – that will be analysed and compared in this report in greater detail. As such, it aims to provide the reader with an understanding of the specifics of the tools under consideration and answer research question I-c: *What assumptions, simplifications and limitations are associated to these models, solution methods and solvers?*

The first three sections discuss the two-dimensional solvers compared in an effort to quantify the uncertainties associated to particular fundamental flow assumptions in Chapter 6: XFOIL in Section 5.1, VGK in Section 5.2 and MSES in Section 5.3. Subsequently, Section 5.4 discussed AVL, which is used in the uncertainty propagation study in chapter 7. Additionally, section 5.5 discusses the Aircraft Design Initiator – another component used for uncertainty propagation – in some greater detail, even though it does not fit the definition of solver given above.

Most of the sections that follow are largely based on the literature review report underlying this research (Peerlings, 2018), in which more details can be found. All sections start with a short introduction to the program and then go on to discuss the flow model (further treated in Section 4.1.1) and solution method (introduced in Section 4.1.2). Lastly, some words are spent on force and moment computations. Section 5.5 is structured slightly differently, as it is an aircraft design and analysis suite rather than an aerodynamic solver.

5.1. XFOIL

XFOIL was developed in 1986 by Mark Drela and Harold Youngren at MIT (Drela and Youngren, 2013, 2001). It is an "inviscid linear-vorticity panel method" with an optional boundary layer model based on source distributions in order to model viscous effects on the potential flow (Drela, 1989, p. 1). The code includes a Karman-Tsien compressibility correction to provide more accurate results at higher subsonic Mach numbers. Pressure coefficient estimations should be "reasonably accurate" and drag predictions are also "likely to be accurate" as long as local Mach numbers do not exceed $M = 1.05$ (Drela and Youngren, 2001). Of the solvers treated here, XFOIL is most popular. It is operated through a command-line interface and written in Fortran. Besides analysis of airfoils, the program features an inverse-design routine. Due to its focus on low Reynolds number flows, XFOIL is often used for the design or analysis of unmanned or micro aerial vehicles (e.g. Ahn and Lee (2012)).

The accuracy of XFOIL is well recognised (Morgado et al., 2016; Selig, 2003) and the program has proven its performance (Ben Mosbah et al., 2016; Madsen and Filippone, 1995; Coutu et al., 2010) as an "excellent airfoil design and analysis tool", which is substantially easier to use than more complex CFD-codes (Morgado et al., 2016, p. 212).

5.1.1. Flow model

Given the fact that XFOIL is a panel method, the program solves the incompressible Laplace flow equation. The inviscid flowfield is composed from a freestream flow, a vortex sheet (on the surface of the airfoil) and a source sheet (on both the surface of the airfoil and the wake). Vortex strengths vary linearly per panel; source strengths are constant on the airfoil and linearly varying in the wake. A Kutta condition is used to close the system of equations.

The viscous calculation is a two-equation integral formulation, combining the von Kármán momentum integral equation and the kinetic energy shape parameter equation (derived in Drela (1985)), based on dissipation closure. An earlier version of this method was used in the older ISES-code, also co-developed by Drela (Drela and Giles, 1987a; Giles and Drela, 1987). In laminar flows, straight-line approximations to the Falkner-Skan one-parameter profile family are used as closure relations (Drela and Giles, 1987b; Coder and Maughmer, 2014). In turbulent flows, these are replaced by relations based on Swafford (1980, Eqs. (12), (30)), which hold for a separated boundary layer and assume a smooth, impermeable and adiabatic wall. Transition from laminar to turbulent flow is predicted using a simplified version (the so-called *envelope method*) of the e^N method (van Ingen, 2008; Lasauskas and Naujokaitis, 2009; Morgado et al., 2016). XFOIL is also able to model separation, including separation bubbles (Drela, 1989; Fernandes et al., 2014).

This viscous and inviscid flow domains are coupled using the boundary layer edge velocity. A mass-influence matrix (determined by the geometry of the airfoil and wake, as well as freestream angle of attack) and the mass defect at each panel are added to the inviscid edge velocity to find the viscous edge velocity.

5.1.2. Solution method

Solving the viscous system of equations requires finding values for θ, δ^* and a third variable – C_τ in case of turbulent flows, $\tilde{n}$ in case of a laminar boundary layer. The corresponding three coupled and non-linear equations are the momentum equation, the kinetic energy shape parameter equation and either a lag equation (in case of turbulent flow) or an equation describing the growth of the Tollmien-Schlichting waves (in case of laminar flow).

Discretisation is done using two-point central differencing (Drela, 1989), or a hybrid between that and backward Euler, due to numerical difficulties otherwise coming into play (Drela and Giles, 1987b). The transition interval is treated as two sub-intervals, with the boundary layer variables obtained through interpolation of the values at neighbouring grid points. Right after transition, $\sqrt{C_\tau}$ is set to 70% of its equilibrium value. The viscous-inviscid interaction is solved by a full Newton method, which yields fast solution times given the regular grids used.

5.1.3. Force and moment computation

XFOIL determines the pressure coefficient from the freestream velocity and vortex strengths using Equation (5.1) and summing this over all panels (Drela and Youngren, 2013, `xfoil.f`, l. 1064).

$$C_p = 1 - \frac{\gamma_i}{V_\infty^2} \tag{5.1}$$

The pressure coefficient is subsequently corrected for compressibility effects using the Karman-Tsien compressibility correction, shown in Equation (5.2).

$$\beta = \sqrt{1 - M_\infty^2} \tag{5.2a}$$

$$\beta_f = \frac{0.5M_\infty^2}{1+\beta} \tag{5.2b}$$

$$d = \beta + \beta_f \cdot C_{p,0} \tag{5.2c}$$

$$C_p = \frac{C_{p,0}}{d} = \frac{C_{p,0}}{\sqrt{1-M_\infty^2} + \frac{0.5M_\infty^2}{1+\sqrt{1-M_\infty^2}} \cdot C_{p,0}} \tag{5.2d}$$

Lift and moment coefficients are subsequently determined from numerical integration of the pressure coefficient, using Equations (5.3) and (5.4) (Drela and Youngren, 2013, `xfoil.f`, ll. 1030 - 1110). c_m is computed about the quarter-chord point $(x_{ref}, y_{ref}) = (0.25, 0)$.

$$c_l = \sum_{i=1}^{N-1} \left(d_x \cos(\alpha) + d_y \sin(\alpha)\right) \cdot C_{p,avg} \tag{5.3}$$

$$\begin{aligned} c_m = \sum_{i=1}^{N-1} &- \left(d_x \cos(\alpha) + d_y \sin(\alpha)\right) \left[C_{p,avg}\left(r_x \cos(\alpha) + r_y \sin(\alpha)\right) + C_{p,diff} \cdot \frac{d_x \cos(\alpha) + d_y \sin(\alpha)}{12}\right] \\ &- \left(d_y \cos(\alpha) + d_x \sin(\alpha)\right) \left[C_{p,avg}\left(r_y \cos(\alpha) + r_x \sin(\alpha)\right) + C_{p,diff} \cdot \frac{d_y \cos(\alpha) + d_x \sin(\alpha)}{12}\right] \end{aligned} \tag{5.4}$$

In these equations, d_x and d_y represent the panel length on the x- and y-axes ($d_x = x_{i+1} - x_i$ and $d_y = y_{i+1} - y_i$) and r_x and r_y indicate the distance on the x- and y-axes from the panel midpoint to the reference position (x_{ref}, y_{ref}). $C_{p,avg}$, then, is the average pressure coefficient over the panel ($C_{p,avg} = (C_{p,i+1} + C_{p,i})/2$). $C_{p,diff}$ is the difference in pressure coefficient over two adjacent points, computed as $C_{p,i+1} - C_{p,i}$.

The total drag coefficient c_d is found by the Squire-Young formula (Squire and Young, 1939), shown in Equation (5.5), applied at the last point of the wake (typically one chord downstream of the trailing edge).

$$c_d = \frac{D}{q} = 2\Theta_i = 2\Theta\left(\frac{u_e}{V}\right)^{\frac{H+5}{2}} \tag{5.5}$$

Θ_i represents the momentum thickness at downstream infinity (i.e., at the last point of the wake), u_e the velocity at the edge of the boundary layer at the end of the wake, H is the shape parameter of the boundary layer and V the freestream velocity. Applying Equation (5.5) at the wake rather than at the trailing edge (which is often done) makes the computation more robust in case of separated flow (Drela and Youngren, 2001).

The friction and pressure drag components are computed separately. The friction drag $c_{d,f}$ is computed by integrating the skin friction coefficient (here defined based on the freestream dynamic pressure and not the dynamic pressure at the boundary layer edge), as in Equation (5.6) (Drela and Youngren, 2001):

$$c_{d,f} = \int c_f d\bar{x} \tag{5.6}$$

Rather than finding the pressure drag $c_{d,p}$ from surface pressure integration, it is computed by subtracting the friction drag from the total drag, as in Equation (5.7). This choice was made as the pressure integration method is “typically swamped by numerical noise” (Drela and Youngren, 2001).

$$c_{d,p} = c_d - c_{d,f} \tag{5.7}$$

5.2. VGK

VGK (short for *viscous Garabedian and Korn*, after Garabedian and Korn (1971)) is a “computational method for determining two-dimensional transonic attached flow past a lifting aerofoil immersed in a subsonic freestream” (Freestone, 2004, p. 6). It includes both inviscid and viscous formulations and although the program is limited to single-element airfoils, it can also be used for analysis of airfoils with deflected control surfaces. Furthermore, the code predicts the effects of shock waves. The program is an implementation of the full potential equations for steady, compressible and irrotational flow, which are solved using a finite difference method. As such, the program is able to solve flows with Mach numbers up to $M_{Lsh} = 1.3$, just upstream of the shock wave. VGK has been developed by the Royal Aircraft Establishment / Defence Evaluation and Research Agency (RAE / DERA), but is currently commercially licensed by QinetiQ (QinetiQ). First publications about the program stem from 1996 (Freestone, 2004), although Atkin and Gowree (2012) state development goes back to the late 1970s and reports from the 1980s indeed also mention the program (Blockley and Hodges, 1982). As XFOIL, the program is operated using a command-line interface.

Although the code is used substantially less than XFOIL in academic literature, Blockley and Hodges (1982, p. 7) described VGK as the “most accurate viscous transonic flow method currently available”. Although the method has been improved upon a number of times since then (Atkin and Gowree, 2012; Blockley and Hodges, 1982), results obtained using the original VGK method still have good accuracy, as long as the limitations are respected (Padulo et al., 2009; Freestone, 2004).

5.2.1. Flow model

The inviscid result is obtained by solving the full potential equation on the grid that is generated by the program. A non-zero normal velocity boundary condition is set at the inviscid surface, which allows for the growth of the (viscous) boundary layer (when the inviscid and viscous results are combined).

Similar to XFOIL, VGK uses different equations for describing the laminar and turbulent viscous flow. Laminar boundary layers are calculated using the method of Thwaites (1949), starting from the stagnation point, where the momentum thickness can be fixed. Thwaites focuses on an approximation of the skin friction and momentum or displacement thickness, rather than on the velocity distributions. Empirical relations provide the shear stress parameter and shape factor (Vos and Farokhi, 2015). To apply this essentially incompressible method to compressible problems, the compressible problem is transformed into an incompressible one using the Stewartson-Illingworth transformation (Stewartson, 1949). In case of a turbulent boundary layer, the ‘lag-entrainment’ method of Green is used (Green et al., 1977, 1973), which holds for two-dimensional, axisymmetric, adiabatic and compressible flow. This method consists of simultaneously solving three (ordinary) differential equations: the momentum-integral and entrainment equations are the same used in the method from which the current method was derived (Head, 1958); a new ‘lag’-equation is derived from the turbulent kinetic energy equation (which, in turn, follows from the Navier-Stokes equations (Green et al., 1977)). VGK does not include a transition prediction mechanism, except for a very simple measure that forces turbulent flow in case the local skin-friction coefficient is reduced below a certain threshold.

The viscous and inviscid flow methods are coupled using a so-called *direct method* (Lock and Williams, 1987). This viscous-inviscid interaction method is an iterative procedure. Starting with an estimation of the source strength at a particular grid point, a velocity gradient is found, which in turn is used to find a boundary layer growth rate. This starts another inviscid solution, with the boundary layer thickness

dictating the inviscid geometry. The boundary layer profile that is found when the viscous and inviscid methods have converged is accepted as solution.

5.2.2. Solution method

Rather than taking a rectangular grid, VGK maps the infinite flow region outside the profile conformally onto the inside of a circle (Catherall et al., 1969; Blockley and Hodges, 1982) using a x-coordinate spacing of $x = (1 - \cos\theta)/2$ with "approximately" equal intervals of the angle θ (Freestone, 2004, p. 10). The (angular) step size depends on the grid configuration. This mapping is not exact, as the grid points are an interpolation between the coordinates of the airfoil being analysed. Given enough grid points, the differences between the original geometry and the interpolation are small. Still, these differences might reduce accuracy of the boundary conditions at the airfoil surface. Figure 5.1 shows the input geometry in red and the mapping in cyan. Figures 5.1c and 5.1d show a close-up of the leading edge region for the same input geometry, represented using a cosine or linear spacing, respectively.

Because of this transformation, the velocity potential is expressed as a function of r and θ, as shown in Equation (5.8) (Lock, 1981, p. 118).

$$\left(a^2 - u^2\right)\Phi_{\theta\theta} - 2uvr\Phi_{r\theta} + \left(a^2 - v^2\right)r^2\Phi_{rr} \tag{5.8}$$

Defining $a^2 - u^2$ at location i, j ($\theta - i\Delta\theta$, $r = 1 - j\Delta r$) as A_{ij}, $\Phi_{\theta\theta}$ is computed using the central difference expression in Equation (5.9) (Lock, 1981, p. 118).

$$\left(\Phi_{\theta\theta}\right)_{ij} = \frac{\Phi_{i-1,j} - 2\Phi_{ij} + \Phi_{i+1,j}}{(\delta\theta)^2} \tag{5.9}$$

This is used for points where the flow is subsonic. At locations in the grid where the flow is supersonic, an upwind scheme is used, replacing $\left(\Phi_{\theta\theta}\right)_{ij}$ by $\left(\Phi_{\theta\theta}\right)_{i-1,j}$. For computing the potential at the so-called *shock point*, the first subsonic point behind the shock wave, various methods exist. The non-conservative approach, "which produces shock waves such that the downstream pressure is only just subsonic" (Lock, 1981, p. 117), uses the central difference expression and yield an underestimating of the shock strength. A quasi-conservative approach uses the sum of both, based on Murman's shock point operator (Murman, 1974; Jameson, 1976; Bauer et al., 1975), but thereby overestimates the strength of the shock. In the current version of VGK, a partially-conservative scheme is used, in which the upwind term is multiplied with a scaling factor λ, aptly named the partially-conservative parameter (Lock, 1981; Freestone, 2004), as shown in Equation (5.10).

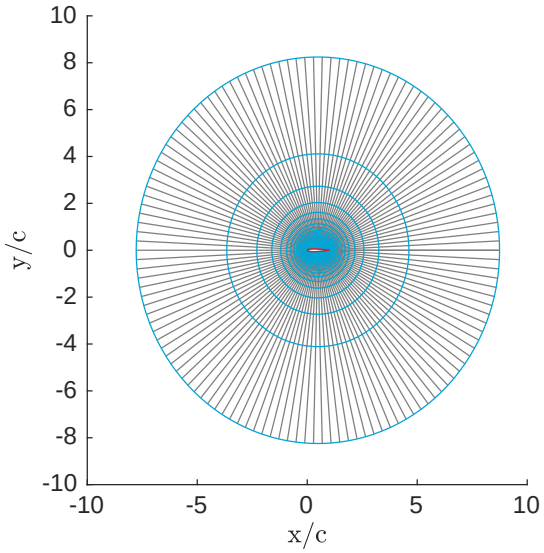
$$A_{ij}\left(\Phi_{\theta\theta}\right)_{ij} + \lambda A_{i-1,j}\left(\Phi_{\theta\theta}\right)_{i-1,j} \tag{5.10}$$

Naturally, with $0 \leq \lambda \leq 1$, setting $\lambda = 0$ reduces the code to a non-conservative scheme and $\lambda = 1$ yields the quasi-conservative scheme.

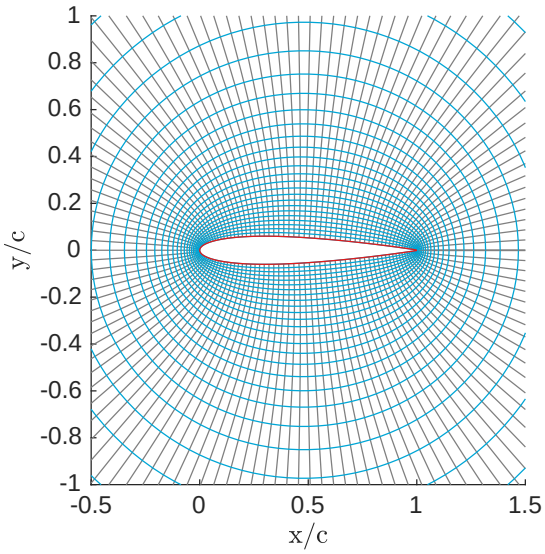
To counter the increased influence of the truncation errors introduced in the partially-conversative scheme (in comparison to the non-conservative scheme), an artificial viscosity parameter ϵ was introduced. This improves second order accuracy by slightly adjusting the artificial viscosity term, $-P_{ij} + P_{i-1,j}$, added to Equation (5.8). Whereas P_{ij} was formerly set to $\mu_{ij}\left(\Phi_{\theta\theta}\right)_{ij}$, with $\mu = f\left(A_{ij}\right)$, it is changed to the expression shown in Equation (5.11), including ϵ (Lock, 1981).

$$P_{ij} = \mu_{ij}\left[\left(\Phi_{\theta\theta}\right)_{ij} - \epsilon\left(\Phi_{\theta\theta}\right)_{i-1,j}\right] \tag{5.11}$$

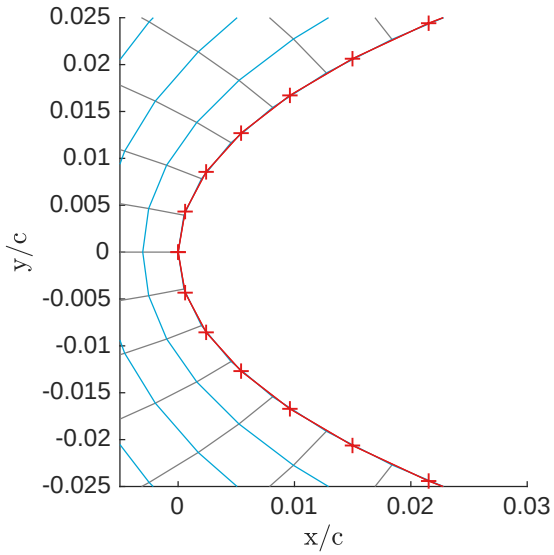
The finite difference equations are solved using a relaxation method (Collyer and Lock, 1978). In each new iteration, the potential at the grid points is recalculated and compared with the previous value, until



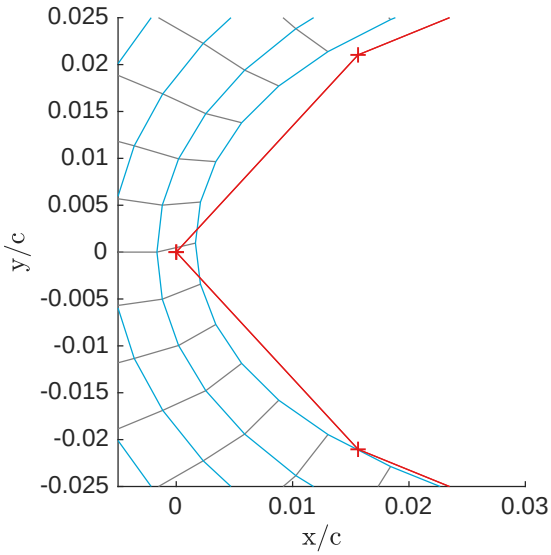
(a) Entire computational domain, geometry represented using a cosine spacing



(b) Zoomed in to $-0.5 \leq x/c \leq 1.5$, geometry represented using a cosine spacing



(c) Zoomed in to $-0.005 \leq x/c \leq 0.03$, geometry represented using a cosine spacing



(d) Zoomed in to $-0.005 \leq x/c \leq 0.03$, geometry represented using a linear spacing

Figure 5.1: Mapping of a NACA0012 airfoil in VGK at $Re = \infty$, $M_\infty = 0.150$ and $\alpha = 6°$

the difference is sufficiently small. An adjustable relaxation factor controls the convergence rate. The flow solution is deemed converged when the grid differences (or residuals) are so small that further updates to the grid values do not substantially impact the value of the flow parameters in the solution. Central differencing is used or subsonic regions; backward differencing for supersonic part of the flow.

5.2.3. Force and moment computation

Freestone (2004) does not explicitly specify the methods employed to compute lift and moment coefficients from the obtained pressure distribution. It is assumed that these are numerically integrated, as in case of XFOIL.

VGK includes two drag calculation methods: a *near-field approach* and a *far-field approach* (Freestone, 2004). The near-field approach (also known as *direct approach* (Lock, 1985)) finds the total drag coefficient by summation of pressure and friction contributions, in turn determined from surface pressure and surface shear stress integration, as in Equation (5.12). It is recommended for shock-free flows (Freestone, 2004).

$$c_d = c_{d,p} + c_{d,f} \tag{5.12}$$

The far-field approach sums the viscous and wave drag contributions to find the overall drag coefficient, as in Equation (5.13):

$$c_d = c_{d,v} + c_{d,w} \tag{5.13}$$

The viscous drag coefficient $c_{d,v}$ is computed based on the momentum thickness of the wake, far downstream. This is similar to the approach taken in XFOIL shown in Equation (5.5). For the computation of the wave drag coefficient $c_{d,w}$, a *first-order* (Lock, 1985) and an *improved* (Lock, 1995) method exist (Freestone, 2004). Both method use the same equation, shown in Equation (5.14) (Lock, 1995, 1985):

$$c_{d,w} = \frac{0.243}{\kappa} \left(\frac{\left(1 + 0.2M_\infty^2\right)}{M_\infty} \right)^3 \frac{\left(M_{Lsh} - 1\right)^4 \left(2 - M_{Lsh}\right)}{M_{Lsh} \left(1 + 0.2M_{Lsh}^2\right)} \tag{5.14}$$

M_∞ is the freestream Mach number and M_{Lsh} the local Mach number at the airfoil surface upstream of the shock. κ is the surface curvature and is the parameter in which the first-order and improved method differ. Whereas the first-order method uses $\kappa = \kappa_w$, the wing surface curvature at the foot of the shock, the improved method takes $\kappa = \bar{\kappa}$, a mean curvature determined over a particular section starting upstream of the shock wave and ending at its foot. This improves the accuracy of Equation (5.14) in case of "rapid variations of surface curvature in the region just ahead of the shock" (Lock, 1995, p. 12).

5.3. MSES

MSES (Analytical Methods, 2018; MIT Technology Licensing Office, 2018; Drela, 1994, 1990) is a 2D airfoil design and analysis tool that was developed from the earlier ISES code (Greer et al., 2000) and uses an Euler flow model, solved using a finite volume method, allowing it to perform computations at transonic Mach numbers so it can predict "transitional separation bubbles, shock waves, trailing edge and shock-induced separation" (Drela, 1994, p. 1). The code is built for the design and analysis of multi-element airfoils, but can also be used for single-element profiles. As XFOIL, MSES was developed by Mark Drela and Harold Youngren at the Massachusetts Institute of Technology (MIT) and has been around since at least 1994 (Drela, 1994), with methodological papers going back to 1990 (Drela, 1990). The program is available in both commercial and (open-source) academic licences[1].

MSES is not as popular and often-used as XFOIL, but still widely accepted (Chaparro et al., 2017) and described as an "excellent tool for the development of single and multi-element airfoil geometries" (Martin and Simpson, 2006, p. 374). Some authors note that higher-fidelity codes do not necessarily yield better $c_{l,max}$-predictions (Rumsey and Slotnick, 2014; Florjancic, 2015) and have noted excellent agreement in terms of predicted pressure distributions (Fujiwara et al., 2016), but others have found notable differences with respect to lift and drag prediction (Leifsson et al., 2014; Greer et al., 2000; Tatineni and Zhong, 1998).

[1] Delft University of Technology, in this case represented by R. Vos, holds an MSES-licence as of March 13th, 2019.

5.3.1. Flow model

The flow model closely follows the XFOIL code, described in Section 5.1, with the difference that MSES solves the Euler equations. It supports analysis using a Neumann boundary condition and design efforts using a Dirichlet boundary condition (Drela, 1994; Giles and Drela, 1987). Far-field boundary conditions follow from the method of characteristics and allow for representing an airfoil in a wind-tunnel (solid wall) or freejet (constant pressure outer surfaces), or in isolation (Drela, 1990; Giles and Drela, 1987). A conservative formulation of the flow model makes sure that shocks are treated properly in the inviscid scenario (Giles and Drela, 1987). The equations solved are the steady forms (i.e., partial derivatives with respect to t are zero) of the continuity equation, the momentum equation (without body forces, i.e. f_x, f_y and f_z equal to 0) and the inviscid form of the energy equation (van Craenenbroeck, 2016).

The viscous flow model is very similar – if not partially identical – to the one used in XFOIL and ISES (Drela and Youngren, 2001; Drela and Giles, 1987a). A viscous solution is obtained by solving the von Kármán momentum integral equation, a kinetic energy shape parameter and a rate equation depending on the flow domain (van Craenenbroeck, 2016; Merchant and Drela, 1996)[2]. As XFOIL, MSES uses the Falkner-Skan one-parameter profile family as closure relations (Drela, 1985) in laminar parts of the flow. In turbulent flows, a shear lag equation is used (van Craenenbroeck, 2016). This seems to be a combination of a rate equation used in XFOIL (Drela and Giles, 1987b, Eq. (22)) (derived from the stress-transport equation of Bradshaw and Ferriss (1971)) and the the lag equation from Green et al. (1977, Eq. (21)). Although the full e^N transition prediction method is computed in the background, it was not "deemed reliable enough" (Drela, 2013) to replace the e^N envelope method – which is therefore still used[3] (Coder et al., 2014; Drela, 2003; Lasauskas, 2005).

The viscous-inviscid interaction is achieved via the displacement thickness (Drela, 1994; van Craenenbroeck, 2016). The wall boundary condition is adjusted to allow for this (Giles and Drela, 1987). The viscous and inviscid flows are solved simultaneously in one set of equations, circumventing the need for back-and-forth iteration (Florjancic, 2015).

5.3.2. Solution method

MSES uses a finite volume discretisation on a grid that conforms to the inviscid streamlines of the flow (themselves computed using a 2D panel method) (Florjancic, 2015). Unsurprisingly given the more advanced analysis methods employed in MSES, a large number of settings is available for tuning the grid. The size of the computational domain can be specified in terms of the distance between the inlet and outlet planes and upper and lower streamlines and the geometry. Similarly, the number of streamlines in the upper and lower halves of the computational domain can be adjusted, as well as the number of normal lines upstream and downstream of the leading and trailing edges (number of *inlet* and *outlet points*). The spacing between two adjacent surface grid notes, then, is determined by Equation (5.15), in which Δs represents the local arc-length increment, κ the local surface curvature and a and b the two tuning variables, being the curvature coefficient and exponent, respectively:

$$\Delta s \sim \frac{1}{1 + a|\kappa|^b} \tag{5.15}$$

a is not set directly, but derived from the ratio $\Delta s / \Delta s_{avg}$, with $\Delta s_{avg} = s_{side}/N$ in which s_{side} is the length along the surface of half the airfoil and N the number of coordinates on that perimeter. After the grid is generated, it is smoothed to "clean up" (Drela, 2007, p. 23) the grid. This also ensures the gridlines in streamwise direction correspond to the streamlines of incompressible inviscid flow. Grid coarsening and refining can be used to speed up convergence.

[2] Merchant and Drela (1996, Eq. (3)) lack multiplication of $dH^*/d\xi$ with θ. Based on other references (e.g. van Craenenbroeck (2016) and Drela and Giles (1987b)) this is assumed to be a mistake.

[3] The developer's documentation, (Drela, 2013) in this case, is regarded as the leading source. Nevertheless, some authors (e.g. Driver and Zingg (2007), Maughmer and Coder (2010) and Coder et al. (2014)) report using MSES with the full e^N method.

The set of equations describing the flow is solved using the global Newton method, further described in Drela (1985) and summarised in van Craenenbroeck (2016).

5.3.3. Force and moment computation

Coefficients of pressure and friction forces in x and y direction are found using direct integration over the surface (Drela, 2007). Summation over all the elements (and taking the projection parallel and perpendicular to the freestream direction) then yields lift, skin friction drag and pitching moment. The total viscous drag is subsequently found by looking at the momentum defects in the wake, computed using Equation (5.16).

$$c_{d,v} = \frac{2}{\rho_\infty V_\infty^2} \sum \left[\rho_{e_{exit}} u_{e_{\text{exit}}}^2 \theta_{exit} \left(\frac{p_\infty}{p_{e_{exit}}} \right)^{H_{avg}/\gamma M_\infty^2} \right] \tag{5.16}$$

The elements with subscript $(\,)_{exit}$ are the wake exit quantities. H_{avg} is the average shape factor, taking the average of the shape factors at the end of the wake (H_{exit}) and at the freestream (H_∞).

The wave drag is found as the momentum defect of the streamtubes in the part of the flow that is inviscid. To this, the static and dynamic pressure at the wake exit are isentropically extrapolated to find their values at free-stream conditions. Integration over all streamtubes (with a mass flow $d\dot{m}$), as shown in Equation (5.17), yields the wave drag.

$$c_{d,w} = \frac{2}{\rho_\infty V_\infty^2} \int (V_\infty - q_{+\infty})\, d\dot{m} \tag{5.17}$$

The total drag is the sum of the viscous drag given by Equation (5.16) and the wake drag by Equation (5.17). Substraction of the skin friction drag (obtained from surface integration) then yields the pressure drag. This is deemed more accurate than finding the pressure drag directly from the surface pressures (Drela, 2007).

5.4. AVL

The Athena Vortex Lattice method (AVL[4]) is a VLM originally developed in 1988 by MIT's Mark Drela and Harold Youngren (Drela and Youngren, 2017a), based on codes developed for NASA (e.g. Lamar (1976) and Miranda et al. (1977)) (Drela and Youngren, 2010). The program is described in literature as an "extended" vortex lattice method (Jagdale et al., 2009; Raghunath et al., 2014; Thomas and Richardson, 2012) and indeed goes beyond the classical VLM realm in providing the capability of modelling slender bodies using a combination of a source and a doublet filament – the *slender-body* method (Rose et al., 2012; Katz and Plotkin, 1991). As it also allows to analyse flight dynamics characteristics (in the form of stability and control derivatives), AVL is widely used (Lee et al., 2017). This is especially the case for research to smaller air vehicles (Rose et al., 2012; Lykins et al., 2011; Thomas and Richardson, 2012), such as scale models (Thomas and Richardson, 2012) or UAVs or MAVs (Guo et al., 2011; Boschetti et al., 2010; Salichon and Tumer, 2013). The limited amount of validation data available notes lift and drag predictions are reasonably good, especially at smaller angles of attack (Dantsker and Vahora, 2018; Boschetti et al., 2010; Lee et al., 2017; Genco and Altman, 2009).

[4] Not to be confused with CFD and other simulation tools developed by the Austrian company of the same name (AVL LIST GmbH, 2018).

5.4.1. Flow model

As any VLM, AVL is an inviscid method. It assumes quasi-steady flow, therefore neglecting unsteady vorticity shedding. Also, small angles of attack and sideslip (roughly $15°$ (Thomas and Richardson, 2012)) are assumed (Dantsker and Vahora, 2018). Compressibility is taken into account using the Prandtl-Glauert correction ($\sqrt{1-M_\infty^2}$), deemed valid up to a wing-perpendicular Mach number of 0.6. Furthermore, AVL assumes thin airfoils and an associated lift slope of 2π. There are, however, a few options to include viscous 2D-data in AVL-analyses. For each section, a lift slope correction factor (limited to $[0, 2]$) and a c_l/c_d-polar can be set. Similarly, a profile drag coefficient can be set for the entire geometry Drela and Youngren (2010, 2017a).

5.4.2. Solution method

As with other discretised methods, the panelling has a substantial influence on the quality of the computational result. AVL allows for defining the number of panels in spanwise, chordwise and lengthwise (along the body-axis) direction, in a equidistant or (co)sine-spacing. Combinations thereof are also possible, but by default, cosine spacings are used for spanwise and chordwise panel distributions. This results in tighter spacing at the leading and trailing edges of a wing and at the wing tips.

The downstream legs of the horseshoe vortices extend parallel to the x-axis, regardless of possible sideslip. Drag can be predicted using surface force integration or a far-field Trefftz-plane analysis. In terms of boundary conditions, flow tangency is enforced on the airfoil camber line (Drela and Youngren, 2010) and zero mass flux through both the airfoil, wake and possible body surface (Miranda et al., 1977).

Given these boundary conditions, applied at the control point at $0.75c$, the vortex strengths can be found. Lift slope scaling factors affect the vortex strengths by shifting the control point in chordwise direction.

5.4.3. Force and moment computation

Drela and Youngren (2017b) does not provide detailed information about the methods used to compute force and moment coefficients. As such, a default vortex lattice implementation using horseshoe vortices is assumed (Katz and Plotkin, 1991; Bertin and Cummings, 2009; Margason and Lamar, 1971). Starting from the vortex strengths, the Kutta-Jouwkowski theorem is used to compute the contributions to the lift and pitching moment by each panel. Summing these yields the results corresponding to the complete wing.

The induced drag is found using the downwash velocity, which is in turn obtained from the wing loading. This changes the direction of the lift vector, giving rise to a drag component.

5.5. Aircraft Design Initiator

The Aircraft Design Initiator – used to investigate the influence of the two-dimensional uncertainties on aircraft-level parameters – is an aircraft design and analysis tool under continuous development since 2014 (Elmendorp, 2014). As such, it is a completely different type of program than XFOIL, VGK, MSES or even AVL. Whereas these codes compute solutions to an aerodynamic flow model, the Initiator combines a host of disciplines – from aerodynamics to structures and from stability and control to propulsion – into one tool. The fact that it uses empirical models as well as physical ones also discerns it from the other programmes treated in this chapter.

Given its different composition and use, the remainder of this section is also structured differently from the others in this chapter. Rather than discussing the flow model, solution method and fore and moment computation, the sections below provide an overview to the Initiator and show how all functions are combined (Section 5.5.1), and discuss how its iterative process works (Section 5.5.2). Finally, some

additional details are provided about aerodynamic module part of the Initiator, as well as other modules using the aerodynamic results.

5.5.1. Overview

The Initiator is built in MATLAB (The MathWorks, 2017), following an object-oriented approach. The program consists of various modules, grouped according to their function. Modules in the *sizing* group do the initial sizing based on the top-level requirements. This includes a preliminary weight estimation based on a database of reference aircraft and a module that configures the cabin layout, for example. *Analysis modules* analyse the aircraft considered. This includes modules evaluating the aerodynamics (lift, drag, stability and control derivatives), estimating the aircraft and subsystem weights and analysing the aircraft performance (e.g. in terms of a payload-range diagram). Then, there is a set of *design modules* that modify the aircraft design. Lastly, *workflow modules* assist in the program operation and handle things as the iterative process or generating reports.

Figure 5.2 shows an abstract overview of the aircraft design process as implemented in the Aircraft Design Initiator, largely for illustrative purposes.

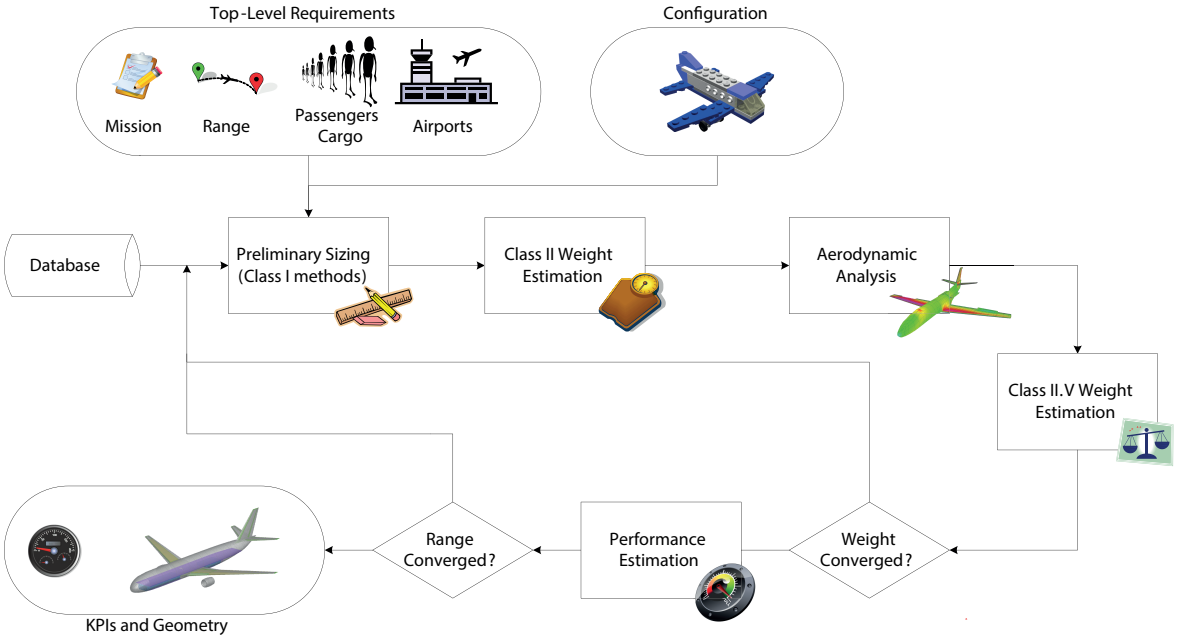


Figure 5.2: Abstract overview of the aircraft design process in the Aircraft Design Initiator (Elmendorp, 2014)

A more detailed representation of the latest version of the program (2.9) is shown in Figure 5.3. The grey blocks show (groups of) modules, with the values in the white cells defining (groups of) input (above or below a module) and output (to the left or to the right of a module) quantities.

As can be seen in Figure 5.2, there are two sets of information that can be used as input to the Initiator. When exploring new concepts, the program can be started using a set of top-level requirements. Examples of this are the required passenger and/or cargo capacity, the range and the type of airport the aircraft is supposed to be able to operate from[5].

Another way, more applicable in technology assessment uses, is the input of a pre-defined aircraft. Using an XML-file, more detailed information about the aircraft configuration can be submitted to the program.

[5]Airports can be categorised in various categories based on runway and taxiway dimensions. This especially has an impact on the wingspan of the aircraft, as well as on the (underwing) engine placement.

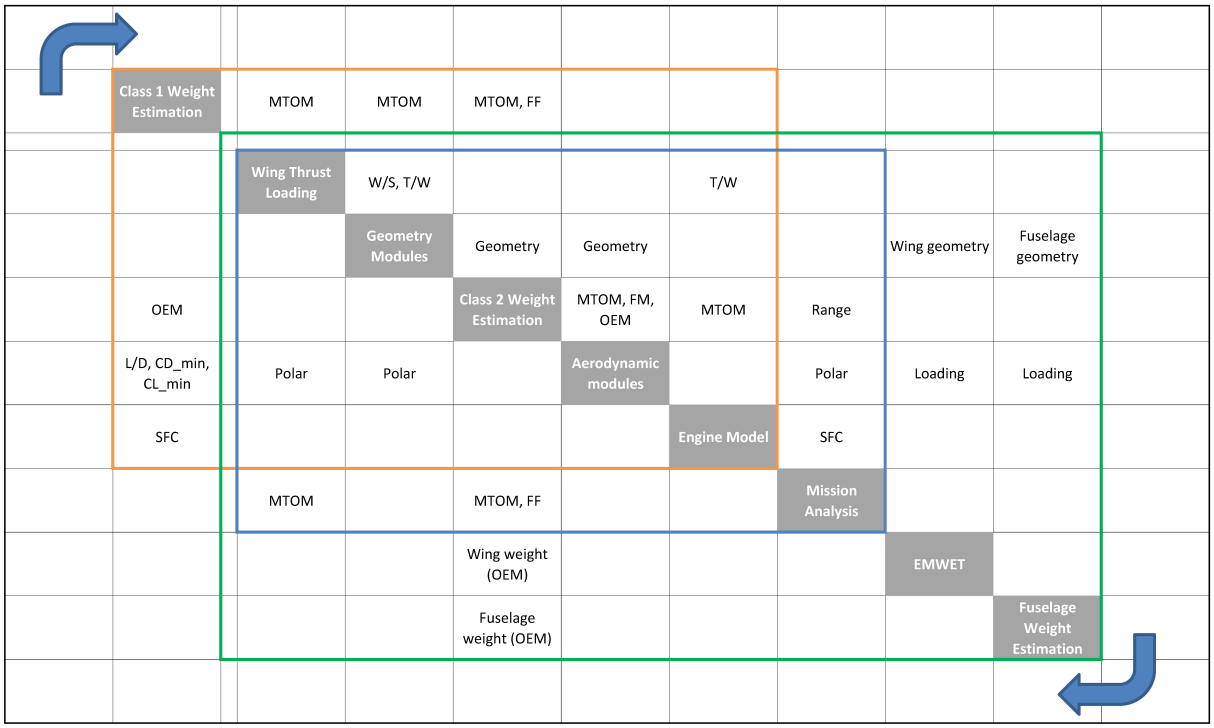


Figure 5.3: N^2-diagram of the Aircraft Design Initiator version 2.9 showing the process flow of information (Vos, 2016). Abbreviations are defined in the lists of abbreviations and symbols, on pages xxix and xxxi.

Examples of this are the cabin layout, various wing dimensions or airfoil coordinates, but also engine performance parameters or material specifications.

Although the Initiator keeps a detailed record of design and analysis results, its main output is limited to a few groups of high-level parameters:

- Design specification, including e.g. the number of passengers, range and altitude
- Operational performance, such as aerodynamic efficiency, cruise altitude and various ranges
- Mass summary, including maximum take-off mass, operational empty mass and total fuel mass
- Mass distribution, providing details about system masses (e.g. engines, wing, fuselage, interior and stabilisers)
- Aerodynamic properties, in terms of lift, drag and pitching moment coefficients
- Propulsion specifications
- Aircraft geometry, of the main wing, horizontal and vertical stabiliser and fuselage

5.5.2. Iteration

As stated in the introduction of this section, the Initiator follows an iterative process. There are three main iteration loops, as shown in Figure 5.3, which are partially nested.

The first loop performs the initial design, starting with empirical weight estimations based on reference data. Wing size and thrust requirements come from input requirements and/or regulations. Then, the geometry is sized, which provides input for a more detailed (physics-based) weight estimation and a set of aerodynamic computations. Finally, the engine model designs an engine that fits the previously set thrust requirements. The new information about the geometry is fed back to the Class I weight estimation module, which starts a new iteration. Once the Class I and Class II weight estimations have converged, the loop is terminated.

The second loop, shown in blue, takes the aircraft mission – a (number of) flight(s) the aircraft needs to successfully perform – into account. This generates new information about fuel use, so that the fuel weight estimation (previously determined using fuel fractions) can be updated. Also, more advanced methods for horizontal tail sizing (based on stability and controllability requirements) are used. Both, of course, influence on the weight of the aircraft. This loop is iterated until the (Class II) weight estimation at the end of the loop has converged to a specified tolerance from the weight estimation at the start of the loop.

In the third loop, empirical weight estimation methods for wing and fuselage mass are replaced by more advanced methods. These new weight estimations are based on the sizing of primary structural components required to cope the different loads seen by the fuselage and/or wing. For other (sub)systems and components, the previous Class II weight estimation is left untouched and carried over to this third loop. It iterates until convergence is obtained.

Typically, the Initiator requires between 10 and 15 iterations to reach a fully converged design. Figure 5.4 illustrates how various quantities of interest (maximum take-off mass, fuel fraction, maximum lift-over-drag) change throughout the iterative process.

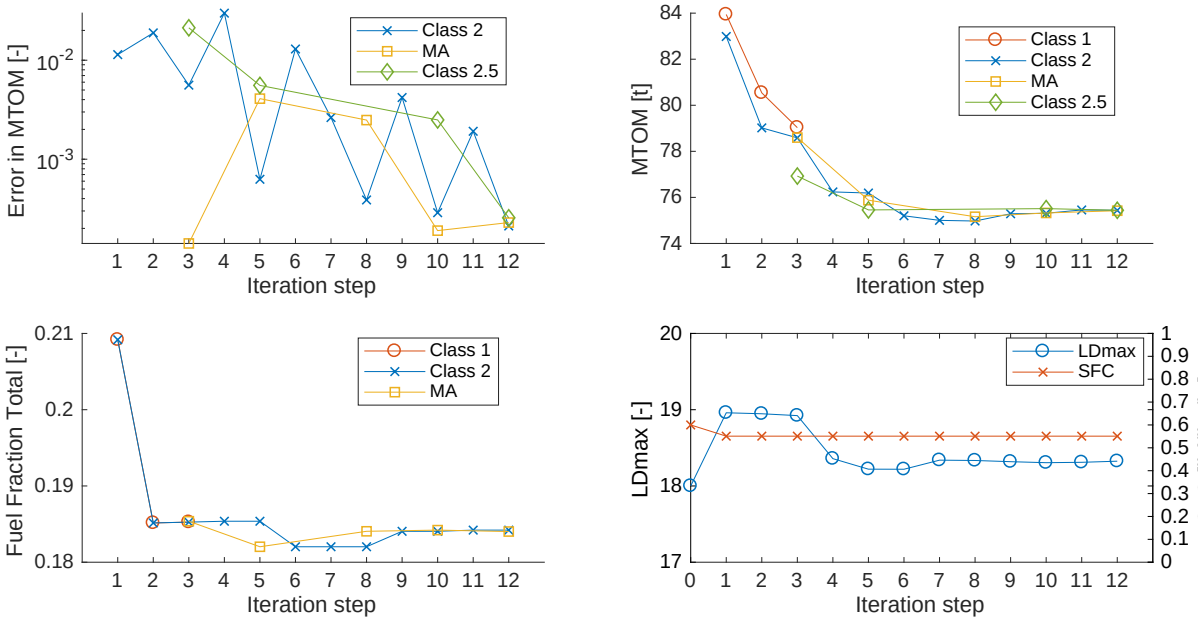


Figure 5.4: Diagrams showing the change in various quantities of interest throughout the iterative design convergence process

5.5.3. Aerodynamic modules

The Aircraft Design Initiatoruses AVL (discussed in Section 5.4) for its aerodynamic calculations. The program is used in C_L-mode, indicating that – rather than performing a flow analysis for a particular angle of attack – the lift coefficient is specified. Corresponding to various flight conditions, four different C_L-values are evaluated in the *DesignCruise*-analysis, listed below. Control surface deflections are set to zero in all cases.

- Low lift coefficient, equal to $C_L = 0.1$
- Cruise lift coefficient, determined from the lift force required for straight and level flight (i.e., a value for C_L derived from maximum take off mass, airspeed, altitude and geometry)
- High lift coefficient, equal to 75% of $C_{L,max}$
- Lift coefficient required for pull-up, based on maximum load factor and atmospheric properties

Based on lift coefficient and data about the aircraft design as it exists at the moment AVL is called is used to find an array of force and moment coefficients and derivatives. Over the iteration process of the Initiator, the AVL results are generated multiple times in order to reflect design changes in the aerodynamic characteristics. The output results are used without any modification by the Initiator-code, but are simply parsed and saved further analysis.

The modules listed below use (part of) the aerodynamic data generated by the solver. They are listed in the order of the first module call in a *DesignConvergence*-run.

- `ParasiteDragEstimation`, uses the lift coefficient to determine horizontal tail drag
- `WaveDragEstimation`, uses the design lift coefficient (obtained from the wing lift coefficient) to compute the wave drag
- `DragModule`, uses lift and drag coefficients to create a drag polar
- `HorizontalStabilityEstimation`, uses the lift slope to determine horizontal stability characteristics
- `FemWeight`, uses the results of the pull-up analysis

Although `FuselageWeightEstimation` does retrieve the AVL-results, it was not included in the previous list as the module does not seem to actually use the AVL-output. `ControlStabilityDerivativeEstimation` and `EMWETWeight` provide a reference to the output of the aerodynamic module, but are not called in the *DesignConvergence*-run.

6

Uncertainty quantification

With the models introduced in Section 4.1.1 and further detailed in Chapter 5, this chapter turns to one of the main topics of this research effort: uncertainty quantification. This current chapter treats the *quantification* and *assessment*-parts of the second research question (I-d): *What assumptions, simplifications and limitations are associated to these models, solution methods and solvers?* Uncertainty *propagation* (research question I-e) is the topic of Chapter 7.

The remainder of this chapter is split up into three sections. Section 6.1 presents the approach taken, followed by a more detailed discussion of the methodology employed in Section 6.2. The results are then presented and analysed in Section 6.3. More specifically, Section 6.3.1 shows the results of a grid refinement study conducted, Section 6.3.2 presents the influence of the solution method, Section 6.3.3 treats the influence of the flow model and Section 6.3.4 shows how these compare.

6.1. Approach

The uncertainties associated to particular solution method or flow model characteristics were assessed separately. The impact of the solution method – most notably in terms of discretisation – was determined first, using a grid refinement study. In this effort, *multiple representations of a test geometry* were analysed by *the same solver* and their results were compared.

Once the uncertainty associated to the solution method was quantified at various settings, a *reference result* for each solver was determined. These reference results are independent of the solution method and thereby form an excellent basis for comparing the results obtained from *different solvers*. This provides insight into the influence of particular flow model assumptions – incompressible flow (through comparison of XFOIL and VGK, described in Section 5.1 and Section 5.2, respectively) and irrotational flow (through comparison of VGK and MSES, described in Section 5.2 and Section 5.3). Last, two compressibility corrections (Prandtl-Glauert and Karman-Tsien) were evaluated, to determine to what extent these reduce the uncertainties introduced by assuming incompressible flow.

6.2. Methodology

Having explained the approach of the current research in Section 6.1, this section turns to a much more detailed description of the methodology through which the results presented in Section 6.3 were obtained. It starts with a description of the toolkit developed to perform the assessments presented in this thesis. This is the topic of Section 6.2.1. The sections that follow are concerned with the content of the analysis and present which geometries (Section 6.2.2) were analysed, how these were represented (Section 6.2.3), what flow cases were investigated (Section 6.2.4) and how the solvers were configured

(Section 6.2.5). Section 6.2.6 elaborates how the aforementioned reference results, the basis for flow model assumption impact analysis, were obtained. Lastly, Section 6.2.7 discusses the application of compressibility corrections.

6.2.1. Toolkit

In order to ease the manual workload, improve data consistency and provide a basis for future analyses of the same sort, the process of performing simulations and extracting and analysing data was largely automated using a combination of MATLAB and Tableau (The MathWorks, 2017; Tableau Software, Inc., 2019). A more detailed reference to code listings is included in Appendix C; the current section shares the most important characteristics.

Execution

The MATLAB-toolkit that was developed is highly modular and consists of three main components: a *RunSuite*, an *AnalysisSuite* and a number of *Export*-scripts. The former is concerned with execution of the different solvers, as well as for reformatting the solver output to a set of consistent data structures. Separate wrapper-programmes interface with the external flow solvers and associated pre- or post-processing software. These are subsequently called by the RunSuite, which can loop over a variety of parameters:

- solver;
- airfoil geometry and representation, in terms of coordinate amount and distribution;
- Mach number;
- Reynolds number; and
- angle of attack.

Computations can be automatically run multiple times in order to verify the consistency of solver output. Following from the fact that the RunSuite controls the angle of attack, any parameter sweep features built in to the individual solvers (XFOIL and MSES) are not used. The same holds for the possibility of re-using grids (VGK), which are not used. Although this increases computational cost in the solver, it enabled (partial) parallel execution of the RunSuite – reducing computation time. Similarly, geometries are generated in MATLAB (despite the fact that, for example, some solvers are able to generate a set of NACA 4-digit airfoil coordinates itself), to make sure all solvers receive identical input. Airfoils are defined normalised to the chord length, with the leading edge positioned at $(0, 0)$. Various solver-independent tasks (such as generating geometry input files, loading plot settings and saving results) are stored in separate scripts and functions to limit code duplicity. Solver settings (e.g., grid parameters and iteration limits) can be specified directly in the RunSuite-script to further harmonise the workflow.

All original files used for and output by the analysis are stored in labelled folders combined with a date-timestamp, the solver settings used and a copy of the wrapper-program used to control that particular analysis. The output is then read from the relevant files using MATLAB and subsequently saved in two data structures: `brief` contains the results for each test case, `full` contains the results for each angle of attack. Their contents are listed in Appendix C.1.2, but the most important output is listed below:

- lift coefficient;
- drag coefficient, split up in various components;
- pitching moment coefficient;
- minimum pressure coefficient;
- chordwise location of the minimum pressure coefficient;
- transition location on upper and lower surface; and
- various derivative quantities, such as lift-to-drag ratio, maximum lift coefficient and stall angle of attack.

Analysis

After generating results, the data can be analysed in a variety of ways. The AnalysisSuite is used for simpler evaluation. Comparing a maximum of two parameters (such as solver and airfoil, or Mach number and number of coordinate points) at a time, it generates graphs showing the relation between particular quantities of interest (such as lift coefficient and angle of attack, lift coefficient and drag coefficient, or pressure coefficient and chordwise location for a particular α). Another part of the AnalysisSuite can analyse the consistency of multiple sets of identical results.

For more elaborate comparisons, data is exported to Excel-files for further processing in Tableau, a software suite developed for data analysis and visualisation. Differences between parameters as computed by different solvers are determined by Tableau in a number of ways:

- **Difference**: the difference between the result and the reference, computed as $\text{result} - \text{reference}$. This value is also referred to as *true* difference.
- **Difference, normalised to reference**: the difference between the result and the reference, normalised with respect to the reference. This indicates the difference with respect to the 'truth'.
- **Difference, normalised to result**: the difference between the result and the reference, normalised with respect to the result. This shows what correction factor needs to be applied to the result in order to arrive at the 'truth'.

In case of assessments of the influence of the solution method, the reference values found using the method in Section 6.2.6. For the analyses concerned with the influence of the flow model, the higher-fidelity solver (i.e., the solver *not* making the assumption investigated) determines the reference.

6.2.2. Geometries

Two different types of airfoil – the symmetrical NACA0012 and the supercritical RAE2822 – were analysed in order to investigate whether model uncertainty depends on the geometry under investigation or not. These particular geometries are selected as they are well-known and well-researched and often used as standard cases[1] (Holst, 1987; Abbott and von Doenhoff, 1959; Vos and Farokhi, 2015).

NACA0012

The NACA0012 is a symmetrical airfoil of the NACA 4-digit airfoil series, introduced in 1933 by the National Advisory Committee for Aeronautics (Jacobs et al., 1933), with a maximum thickness of $0.12c$ at 30% of the chord and a nose radius of $0.01584c$. Given a chord from $x = 0$ to $x = 1$, the airfoil y-coordinates are given by Equation (6.1), with t the maximum thickness expressed as percentage of the chord length. The NACA0012 has a finite thickness at the trailing edge equal to $0.0026c$ and a zero-lift angle of attack equal to $\alpha_{L=0} = 0°$. The geometry is shown in Figure 6.1.

$$y(x) = \pm\frac{t}{0.20}\left(0.29690\sqrt{x} - 0.12600x - 0.35160x^2 + 0.28430x^3 - 0.10150x^4\right) \tag{6.1}$$

RAE2822

The RAE2822 is a supercritical airfoil with a maximum thickness of $0.121c$ at approximately 38% chord and a nose radius of $0.00827c$ (Cook et al., 1979), designed using the method presented in Blockley and Hodges (1973). The maximum camber is found at approximately 0.765% of the chord and the non-symmetrical geometry yields a zero-lift angle of attack of $\alpha_{L=0} \approx -2°$. Rather than being derived from an equation (as is the case for the NACA0012 profile), Cook et al. (1979) provide 130[2] coordinate points describing the airfoil. The geometry is shown in Figure 6.1.

[1] Searching Scopus for `TITLE-ABS-KEY ( "NACA0012" OR "NACA 0012" )` yields almost 3.500 results, `TITLE-ABS-KEY ( "RAE2822" OR "RAE 2822" )` almost 400 (February 15th, 2019). By comparison, `TITLE-ABS-KEY ( "NACA0009" OR "NACA 0009" )` shows less than 100 results, and the RAE5212, 5213, 5214 and 5215 are not mentioned in any title, abstract or keyword.

[2] Cook et al. (1979) actually list 129 coordinates points, but defines the trailing edge as a single point. Consistent with other geometry definitions, this text defines the upper and lower trailing edge coordinate as different points – even if they are identical.

The geometry was retrieved from Cook et al. (1979) and Holst (1987) using optical character recognition (OCR) software. The results were compared and inaccuracies were manually corrected.

As it is impossible to change the amount of coordinate points of the airfoil using the original definition, a parametric representation, generated using the class function/shape function transformation method (CST-method, Kulfan (2008)) was found. Using class function parameters $N_1 = 0.5$ (round leading edge) and $N_2 = 1$ (sharp trailing edge) (Kulfan, 2008, p. 143) and 11 shape function parameters (La Rocca et al., 2014, p. 37) on the upper and lower surface, an optimisation procedure was used to obtain a CST-representation with a mean error (relative to the original geometry obtained from Cook et al. (1979)) of $1.9434 \cdot 10^{-5}$. The parameters used are shown in Equation (6.2), with the upper surface parameters in the first column and the lower surface in the second.

$$\begin{matrix} 0.1285 & -0.1290 \\ 0.1262 & -0.1336 \\ 0.1557 & -0.1559 \\ 0.1494 & -0.1133 \\ 0.1543 & -0.2198 \\ 0.1844 & -0.1617 \\ 0.2018 & -0.0971 \\ 0.1718 & -0.1199 \\ 0.2088 & -0.0608 \\ 0.1865 & -0.0223 \\ 0.2112 & 0.0614 \end{matrix} \tag{6.2}$$

Comparison
Figure 6.1 shows the two geometries combined in one figure, highlighting the differences. Besides the camber, the difference in leading edge radius and trailing edge thickness can be clearly seen.

6.2.3. Geometry representation

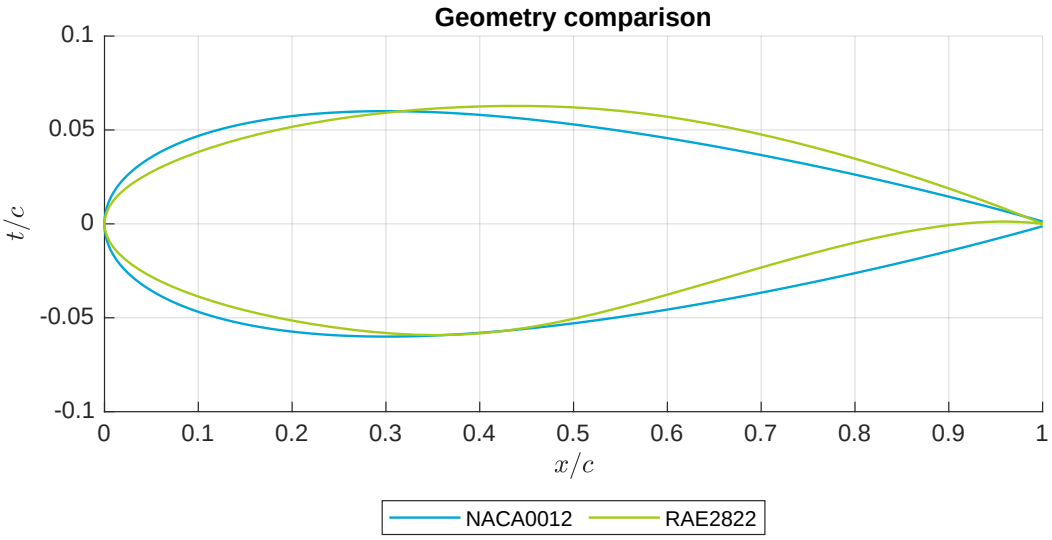
In order to allow the solvers to analyse the geometries shown in Section 6.2.2, they have to be discretised: translated into a set of discrete coordinates. The accuracy with which a geometry is represented depends on the amount and spacing of the coordinate points used.

Both geometries were analysed with 112, 130, 160, 200 and 250 coordinate points, meaning 56, 66, 80, 100 and 125 for each surface. They were distributed over the x-axis using a linear spacing (i.e., constant distances between successive coordinates) or a cosine spacing (using Equation (6.3), with θ varying between 0 and π at constant intervals).

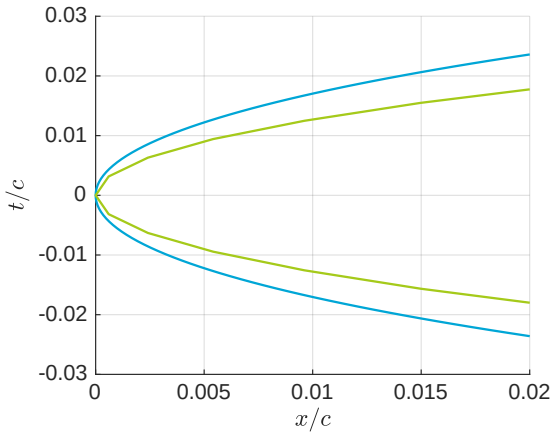
$$x = 0.5 \cdot \frac{1 - \cos\theta}{2} \tag{6.3}$$

Figure 6.2 and Figure 6.3 show the influence of the amount and spacing of coordinate points on the NACA0012 (evaluating Equation (6.1)) and RAE2822 (using the CST-representation) geometries, respectively.

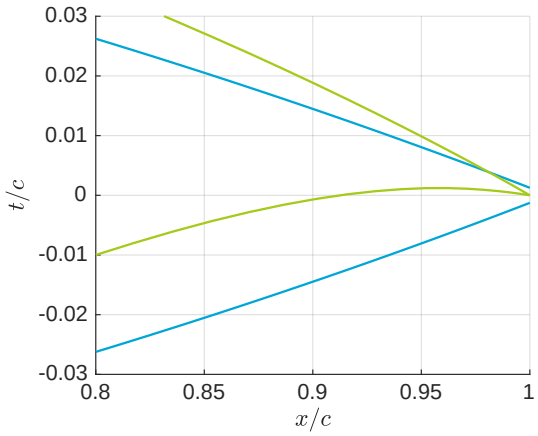
For both airfoils, less coordinate points are required to accurately describe the geometry when using a cosine distribution as compared to a linear one.



(a) Complete chord



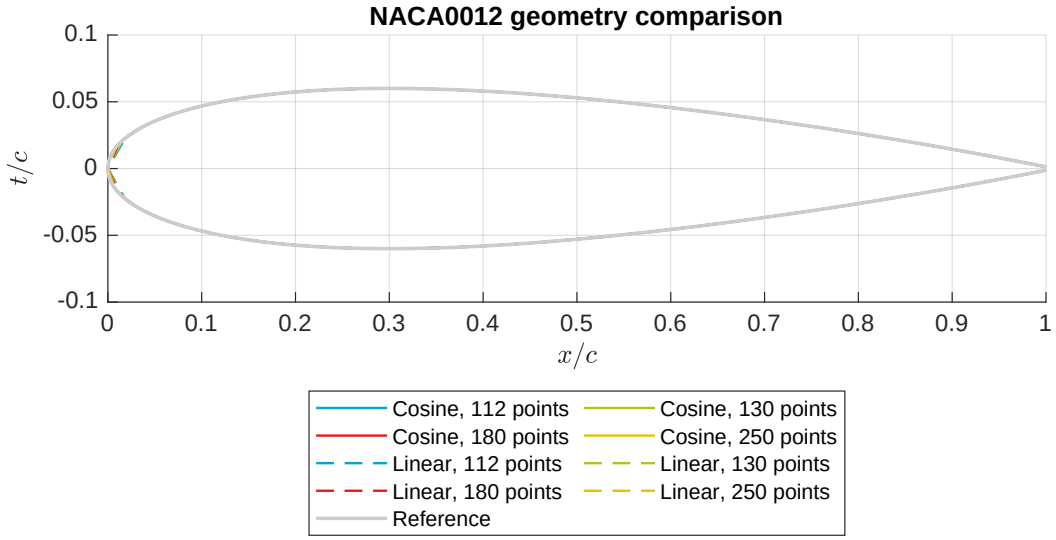
(b) Leading edge



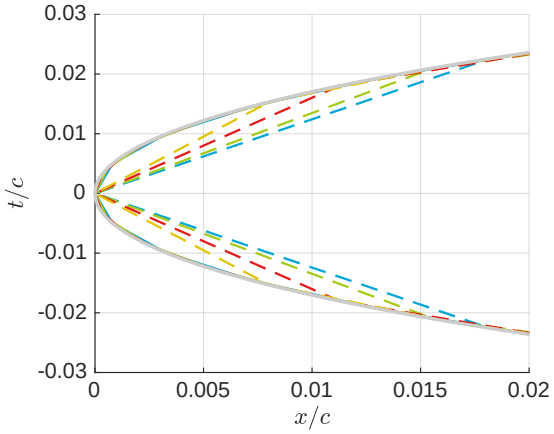
(c) Trailing edge

Figure 6.1: Comparison of NACA0012 (generated from 1000 coordinates using cosine-spacing) and RAE2822 (as defined in Cook et al. (1979) and Holst (1987)) geometries

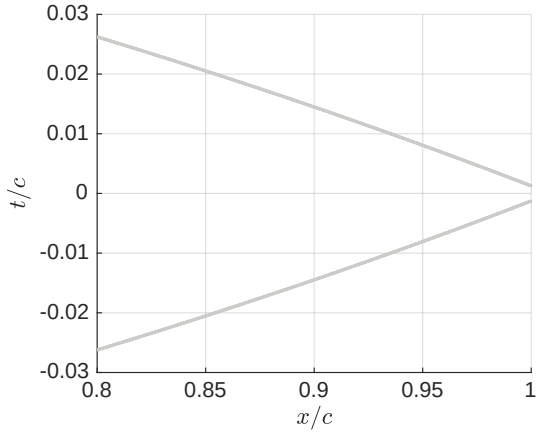
The VGK-generated cosine spacing (discussed in Section 5.2.2) was not evaluated separately. Although Freestone (2004, p. 10) states it is also generated using Equation (6.3), the intervals of θ are only "approximately" equal. As these intervals are not specified, it is difficult to replicate. Also, the difference was found to be relatively small (as shown in Figure 6.4) and Freestone (2004, p. 10) notes that "[c]]hoosing the values of the input x-coordinates so as to correspond to equal intervals of θ is the optimum way of specifying the aerofoil geometry with a given number of coordinates".



(a) Complete chord

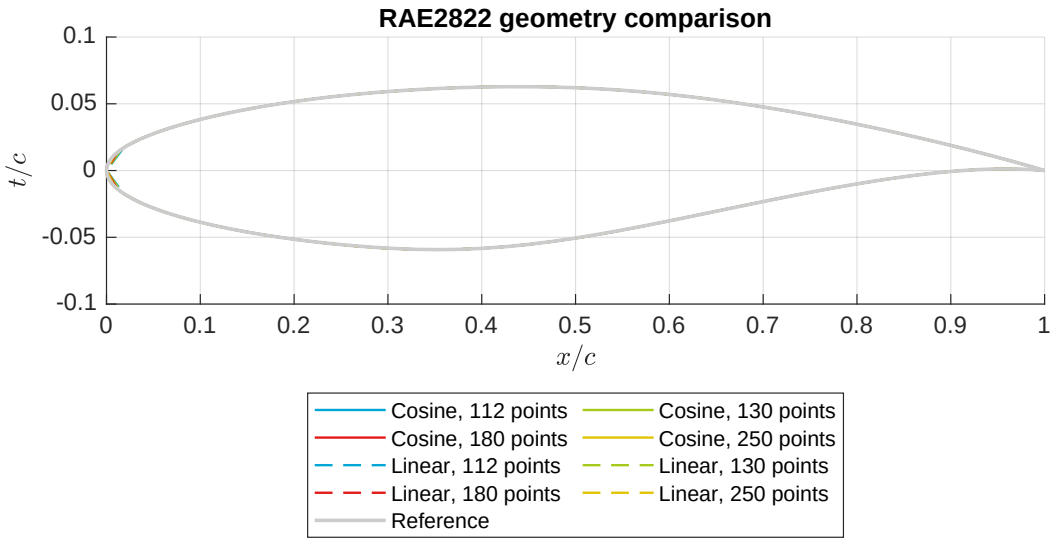


(b) Leading edge

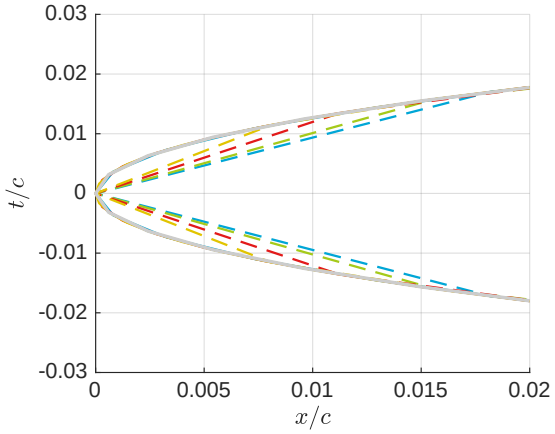


(c) Trailing edge

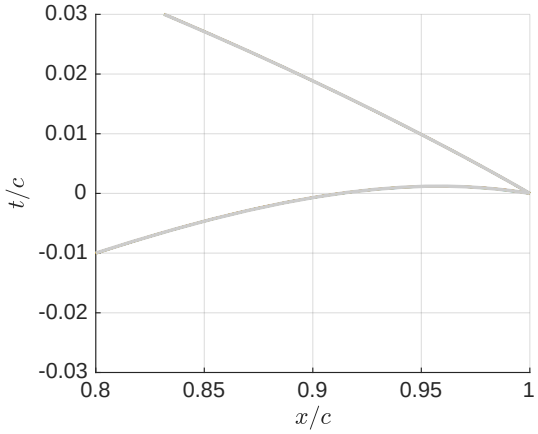
Figure 6.2: Comparison of NACA0012 geometries, showing the influence of spacing (constant or linear) and amount of coordinate points (112, 130, 180 and 250) in different line styles and colours, compared to the reference case (1000 coordinate points, cosine spacing).



(a) Complete chord



(b) Leading edge



(c) Trailing edge

Figure 6.3: Comparison of RAE2822 geometries, showing the influence of spacing (constant or linear) and amount of coordinate points (112, 130, 180 and 250) in different line styles and colours, compared to the reference case (1000 coordinate points, cosine spacing).

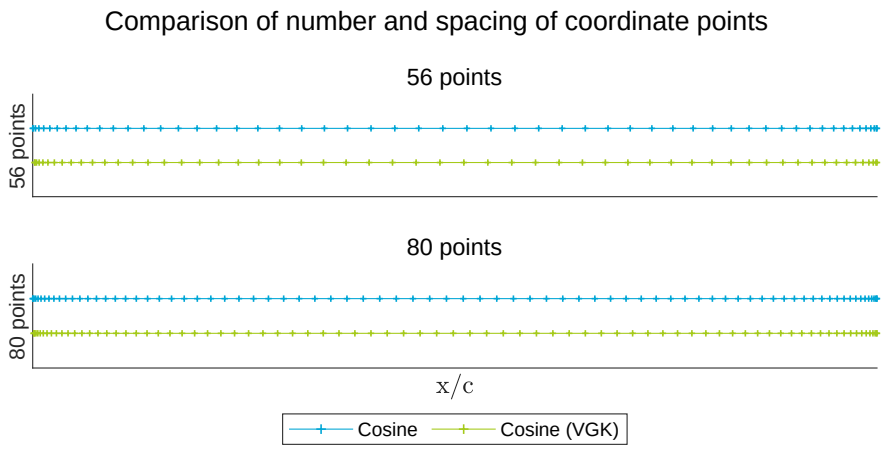


Figure 6.4: Comparison of cosine and VGK-cosine spacings for 56 and 80 coordinate points (per surface)

6.2.4. Flow cases

Simulations were executed at various flow cases to investigate how the effect of solution method and flow model changes (or remains constant) over a variety of scenarios.

- **Mach number,** M_∞
  Freestream Mach numbers of 0.05, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.65, 0.70, 0.75 and 0.80 were analysed in order to evaluate the effect for low subsonic up to transonic speeds. $M_\infty = 0.30$ and $M_\infty = 0.60$ are generally used as the limits of the incompressible flow assumption and the Prandtl-Glauert assumptions. The transonic range matches typical flight conditions of transport aircraft: with sweep angles of $25° \leq \Lambda \leq 35°$ and cruise Mach numbers of $0.80 \leq M_\infty \leq 0.85$, Mach numbers in chordwise direction between 0.65 and 0.80 are found.
- **Reynolds number,** Re
  Even though the toolkit developed for the current research (as described in Section 6.2.1, only inviscid flow (i.e., $Re = \infty$) was analysed at this time. This choice was made for two reasons:
  - For assessing the influence of the solution method, computational cost tremendously increases with viscosity – as it requires the (iterative) viscous-inviscid interaction system to run.
  - For assessing the influence of the flow model assumptions considered here (incompressible and irrotational flow), Chapter 5 has indicated too many differences (in terms of boundary layer model, but also drag computation method) exist between the solvers. This differences would make it impossible to attribute the differences found to the flow model assumption.
- **Angle of attack,** α
  Angles of attack between $-6°$ and $16°$, with intervals of $\Delta\alpha = 0.25°$, were analysed. In case convergence at a particular angle of attack was not obtained, a new analysis was started at an progressively higher or lower angle of attack ($|\Delta\alpha_{step}| = 0.001°$). This searching algorithm was terminated if convergence was not obtained after a set number of analyses (10 by default, yielding a maximum of 5 analyses at a slightly higher α and 5 at a slightly lower α). As $\Delta\alpha$ indicates, the seeker-algorithm is mostly intended to work around potential problems related to numerical stability.

Analysing all possible combinations of geometry representations and flow cases, a total of 23 (geometries and geometry representations) $\times$ 12 (Mach numbers) $\times$ 89 (angles of attack) $= 24.564$ simulations (excluding α-searching in case of non-convergence at the initial angle of attack) was run for each solver.

6.2.5. Solver settings

Although this research is concerned with quantifying and assessing the uncertainty of (numerical) solution methods and (mathematical) aerodynamic flow models, the data was obtained using aerodynamic solvers: software implementations of these flow models. This section presents the approach taken with regard to tuning the various solver settings. Overall, options were set in order to minimise the difference between the solvers – apart from the flow model. Furthermore, the settings were kept constant over the set of simulation runs (geometries and flow cases) to allow for proper comparisons.

XFOIL

The grid size used by XFOIL was determined by the number and spacing of coordinate points of the input geometry. The number of iterations was kept at its default value of 10.

VGK

Contrary to XFOIL, VGK generates a fine grid (using spline interpolations of the input airfoil geometry, as discussed in Section 5.2.2) with a user-specified number of radial mesh lines N_{SG} (between 96 and 160). In this study, N_{SG} was set equal to the number of coordinate points. For geometries with more than 160 coordinate points, N_{SG} was set to that upper limit. In these situations, any differences in simulation outcome is caused by the spline interpolation. In all cases, a fixed amount of 30 circumferential grid lines was used. A coarse grid, which is first evaluated and used to reduce computational cost, is formed by removing half the lines from the fine grid (Freestone, 2004, p. 10) by VGK.

In order to increase the convergence rate, especially at higher Mach numbers, the recommended settings for "difficult flows" (Freestone, 2004, p. 13) were used. These parameters do not have a "significant influence on the converged flow solution", but "only [affect] the convergence process" (Freestone, 2004, p. 11). This means the number of iterations using the coarse and fine grids were set to 200 and 400, respectively.

Simulations were performed at two combinations of λ (partially-conservative parameter) and ϵ (artificial viscosity parameter) to assess their influence: $\lambda = 0.25$ and $\epsilon = 0.8$, as recommended by Freestone (2004), and $\lambda = \epsilon = 0$. The latter case corresponds to a non-conservative scheme, as detailed in Section 5.2.2. Because these changes impact the system of equations that is being solved (rather than the way they are solved), they were classified as flow model difference.

MSES

Different from both XFOIL and VGK, MSES generates a largely rectangular grid – as discussed in Section 5.3. The size of the computational domain was kept constant over all flow cases, to prevent these parameters influencing the results. The input and output planes were positioned $2.14c$ from the leading and trailing edges, respectively. Drela (2007, p. 4) recommends $1.75c$, scaled with $\sqrt{c_l}$ in case of high lift coefficients. $c_l = 1.5$ is used as scaling value. The top- and bottom-most streamlines were located at ± 5.1, derived from a recommended value of 2.5 and scaled for c_l- (again using $c_l = 1.5$) and Mach-effects (using Prandtl-Glauert scaling, with $M_\infty = 0.8$, yielding a correction factor of 1.667). Identical values were used for upper and lower streamline location to make sure the grid is suitable for both positive and negative lift analyses.

Sixty streamlines were split over the top and bottom of the domain, corresponding with the 30 circumferential grid lines used by VGK. Similarly, the number of inlet and outlet points was set at 30 each. The number of airfoil side points was set at half the number of coordinate points to define the geometry, consistent with the approach taken in VGK. Lastly, the "X-spacing parameter", which "controls how much the quasi-normal grid lines spread out from the airfoil" and the cell aspect ratio at the stagnation point were left at their default values of 0.85 and 2.5 (Drela, 2007, p. 24). Two settings specifically applicable to multi-element airfoils (one controlling the distribution of airfoil side points of the elements; another setting the maximum number of streamlines between two elements) were left unaltered. Furthermore, grid coarsening and refining features were not used, as these could not be automated.

Although MSES provides options to change the spacing, it was found very difficult to approximate a linear or cosine distribution. This is due to the fact that spacing settings cannot be changed directly, but only through spacing ratios. Furthermore, the solver modifies all spacings in order to prevent errors in the grid. As such, default settings were used. This means that the grid spacing inversely depends on local curvature (i.e., smaller spacing in regions of high curvature). This is – in principle – comparable to the cosine distribution of coordinate points.

6.2.6. Reference values

As outlined in Section 6.1, grid refinement studies were used to determine reference values of all quantities of interest. The resulting reference values are independent of solution method, and thereby provide a basis for further comparisons. When compared to results from the same solver at different grid settings, the influence of the solution method is obtained. When comparing the reference values of different solvers amongst each other, the effect of flow model is found. The current section shows the methodology used for obtaining these reference results.

The grid refinement studies were conducted using both geometries represented by 50 to 448 coordinate points using both distributions (linear and cosine), for all combinations of Mach number and angle of attack. The grid refinement study is based on the observation that the quantity of interest (such as the lift coefficient) levels off to an asymptote as the number of coordinate points is increased.

The value of the asymptote is set as the reference value. Depending on the solver, slightly different approaches were used to find that asymptote. These approaches were based on visual inspection of simulation results and discussion with an expert in the field.

XFOIL

For XFOIL, the number of coordinate points required for convergence was found by computing the change in quantity of interest Q_i and Q_{i+1} (with i a particular amount of coordinate points) for all pairs, and determining the $i+1$ at which a change in sign of the quantity of interest was observed. Labelling this number of coordinate points c, the reference value was subsequently computed by averaging Q_i ($i : i \in N, i \leq c$, N the total amount of coordinate points). As geometry representations generated using a cosine spacing showed substantially faster convergence, only these results were used. In case no change in sign was detected, the value for the quantity of interest obtained from the largest number of coordinate points was used.

Figure 6.5 illustrates the results obtained using the procedure described, for the NACA0012 geometry at $M_\infty = 0.15$ and $\alpha = 6°$. In addition to the average value, the upper and lower bounds are also shown. These were stored as well, in order to provide an uncertainty estimate of the reference value. Furthermore, the vertical line in grey indicates the number of coordinate points c at which convergence was found (in this example, $c = 125$).

VGK

For VGK, which is severely limited in grid size, reference values were obtained from simulations at all possible grids ($96 \leq N_{SG} \leq 160$) using both geometries represented by 500 coordinate points (the maximum amount possible (Freestone, 2010)), distributed in a cosine spacing (following solver documentation recommendations (Freestone, 2004)). Visual inspection indicated notable outliers at the three lowest values for N_{SG} and much lower dependence of grid size than the dependence of XFOIL on the number of coordinate points: for the NACA0012 at $M_\infty = 0.15$ and $\alpha = 6°$, the spread in c_l is $\mathcal{O}(-3)$ in XFOIL and $\mathcal{O}(-4)$ in VGK. As such, the reference value was computed as the average value of the quantity of interest as found from simulations with $N_{SG} \geq 102$ using a cosine-spaced geometry representation.

The result obtained is visualised in Figure 6.6. Figure 6.6a shows the case for $M_\infty = 0.15$ and $\alpha = 6°$ (equal to Figure 6.5). Figure 6.6b shows the case for $M_\infty = 0.55$ and $\alpha = 4°$, more clearly showing the outliers at 96, 98 and 100 radial grid lines.

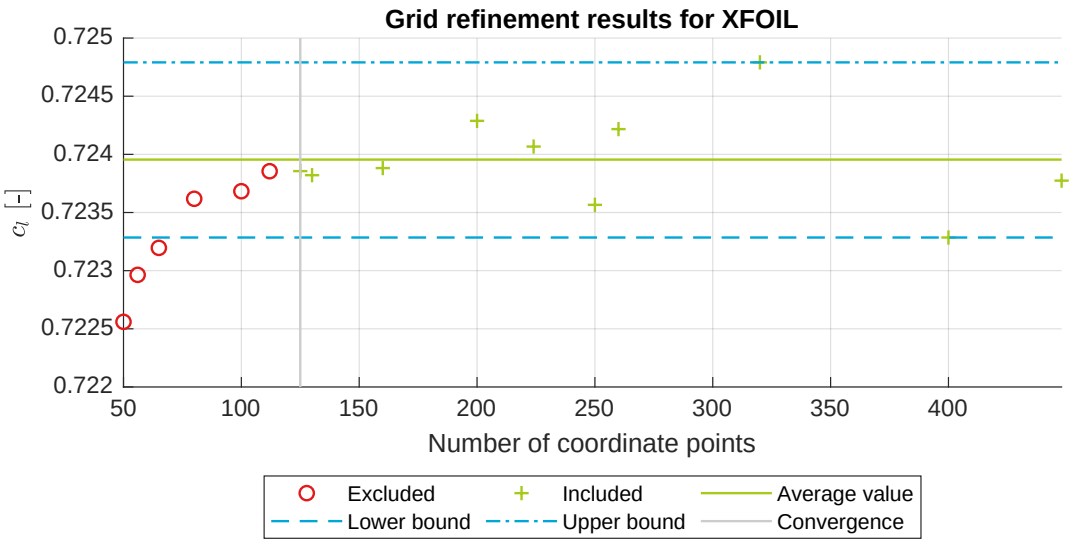


Figure 6.5: Lift coefficient values obtained with XFOIL (NACA0012, cosine spacing, $M_\infty = 0.15$, $\alpha = 6°$), showing the results used for determining the (averaged) reference value and bounds

MSES

For MSES, the same procedure as for XFOIL was used, with the difference that the analyses only involved geometries represented with linearly-spaced coordinate points. Input geometries using cosine spacing did not converge at higher coordinate point counts and associated grid settings due to memory limitations of MSES.

6.2.7. Compressibility corrections

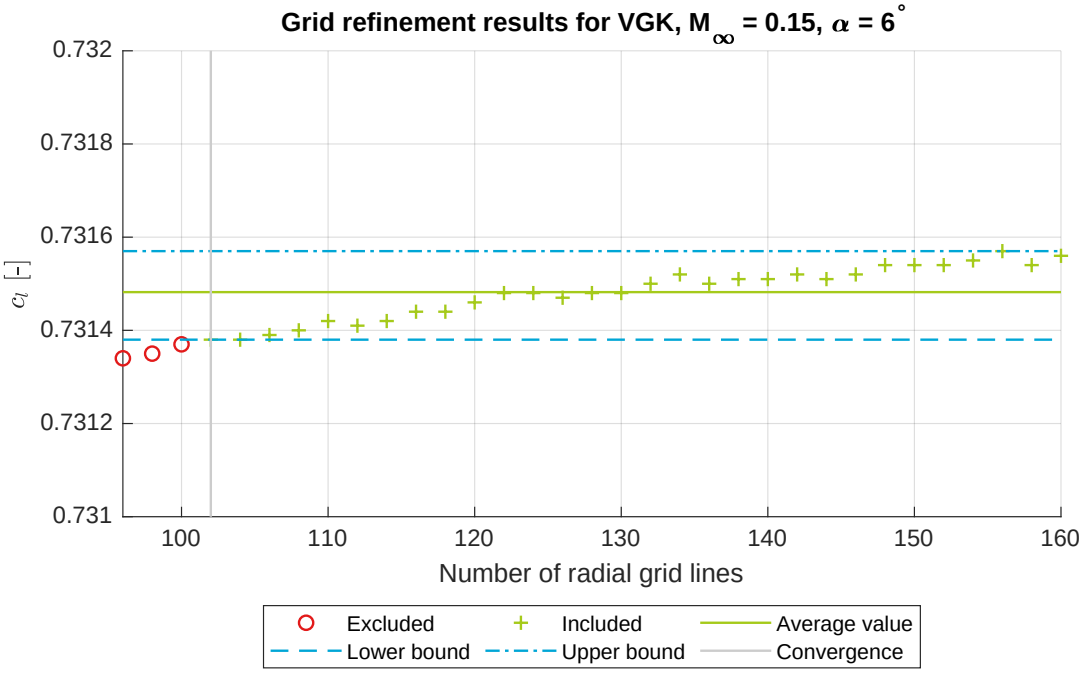
The Karman-Tsien compressibility correction, applied by default in XFOIL, was removed in order to allow for making a fair assessment of the influence of the incompressible flow assumption. To this effect, Equation (6.4) was applied. These uncorrected pressure coefficient values were subsequently numerically integrated to find the updated lift and pitching moment coefficient. The drag coefficient was found to be independent of the pressure coefficient (Drela and Youngren, 2013, `xfoilf`, ll. 1114–1150, `xoper.f`, l. 2542). Identical integration algorithms as originally used by XFOIL were employed, shown in algebraic form in Equation (5.3) and Equation (5.4), and as pseudo-code in Appendix D.1

$$C_{p,0} = \frac{C_p \sqrt{1 - M_\infty^2}}{1 - \frac{1}{2} C_p \frac{M_\infty^2}{\sqrt{1 - M_\infty^2}}} \tag{6.4}$$

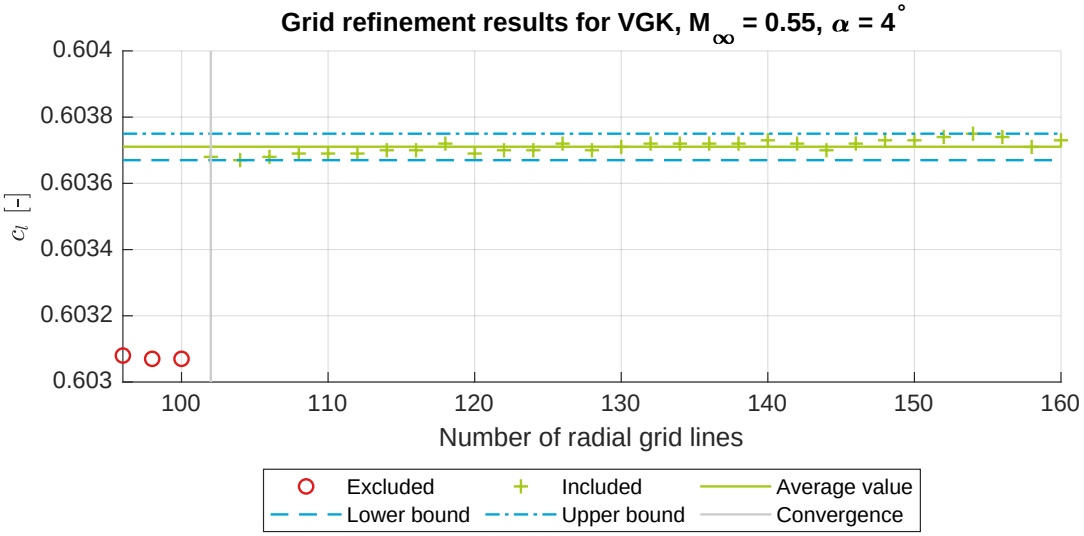
To assess the influence of the Prandtl-Glauert and Karman-Tsien compressibility corrections, the uncorrected XFOIL dataset was duplicated to which these corrections (as shown in Equation (6.5) and Equation (6.6), respectively) were applied (Vos and Farokhi, 2015). Again, numerical integration was performed using the algorithm presented in Appendix D.1.

$$C_p = \frac{C_{p,0}}{\sqrt{1 - M_\infty^2}} \tag{6.5}$$

$$C_p = \frac{C_{p,0}}{\sqrt{1 - M_\infty^2} + \left(\frac{M_\infty^2}{1 + \sqrt{1 - M_\infty^2}} \right) \frac{C_{p,0}}{2}} \tag{6.6}$$



(a) $M_\infty = 0.15$, $\alpha = 6°$



(b) $M_\infty = 0.55$, $\alpha = 4°$ clearly showing the outliers at 96, 98 and 100 coordinate points

Figure 6.6: Lift coefficient values obtained with VGK (NACA0012, cosine spacing, 500 coordinate points), showing the results used for determining the (averaged) reference value and bounds

The Karman-Tsien compressibility correction was removed first and subsequently re-applied in order to remove any (minor) effects introduced by the integration results from XFOIL compared to MATLAB (e.g. related to numerical precision). Averaged over all results, the average relative difference in lift coefficient is limited to 0.0012% (NACA0012) and 0.0667% (RAE2822). Excluding outliers (most notably at or near the zero-lift angle of attack), standard deviations are 0.08% (NACA0012) and 0.461% (RAE2822). Other comparative results are shown in Appendix D.2.

6.3. Results

Having extensively treated the methodology in Section 6.2, the current section presents the results obtained. Consistent with the approach outlined in Section 6.1, the results of the grid refinement study are shown and discussed first (in Section 6.3.1), before moving on to the uncertainty quantification of solution method (Section 6.3.2) and flow model (Section 6.3.3). The last section, Section 6.3.4, compares the effects of solution method and flow model.

In the remainder of the text, abbreviations are used to discern between various solver variants. These are listed in Table 6.1.

Table 6.1: Solver abbreviations

Abbreviation	Solver	Remarks
XFOIL-U	XFOIL, uncorrected	XFOIL results, minus Karman-Tsien compressibility correction
XFOIL-PG	XFOIL, Prandtl-Glauert	XFOIL-U, plus Prandtl-Glauert compressibility correction
XFOIL-KT	XFOIL, Karman-Tsien	XFOIL-U, plus Karman-Tsien compressibility correction
VGK-NC	VGK	VGK results of non-conservative scheme ($\lambda = \epsilon = 0$)
VGK	VGK	VGK results of partially-conservative scheme ($\lambda = 0.25$, $\epsilon = 0.8$)
MSES	MSES	

Results only discussed and not shown in this section can be found in Appendix F.1. The extensive amount of graphs included in that appendix can also be used to gather initial estimates of the uncertainty associated to using a particular flow model to compute different quantities of interest, depending on geometry and flow case. This can be helpful when determining which flow model can best be used for a particular analysis.

6.3.1. Grid refinement

This section presents the results of the grid refinement study, conducted to find the reference values used in the impact assessment of solution method and flow model differences.

The results are presented in the form of heat maps, such as the one shown in Figure 6.7. The vertical axis shows the airfoil and Mach number, the horizontal axis shows the angle of attack. The colours, defined in the legend below the graph, indicate the number of coordinate points (and corresponding grid size) at which convergence was obtained, determined as indicated in Section 6.2.6. The shape is a measure for the size of the domain used to find the asymptote: diamonds indicate the reference value is based on one result, squares show the reference value is an average of more than one result. Finally, blank cells indicate the solver could not find a solution, for example due to numerical overflow of pressure coefficient values.

Figure 6.7 shows the results for lift coefficient for XFOIL-U. There are some slight differences with respect to angle of attack and a number of cases showing a Mach dependency. Those variations with Mach number can be attributed to slight numerical differences in the original XFOIL results form which these results were derived. The dependence on angle of attack follows from the increased values for $|C_p|$ at higher α. Differences in leading edge radius and (most notably) camber (yielding a difference in zero-lift angle of attack) explain the variance between geometries. Asymmetry in the NACA0012-data is caused by minute numerical differences. As the scale is discrete, these differences appear more pronounced.

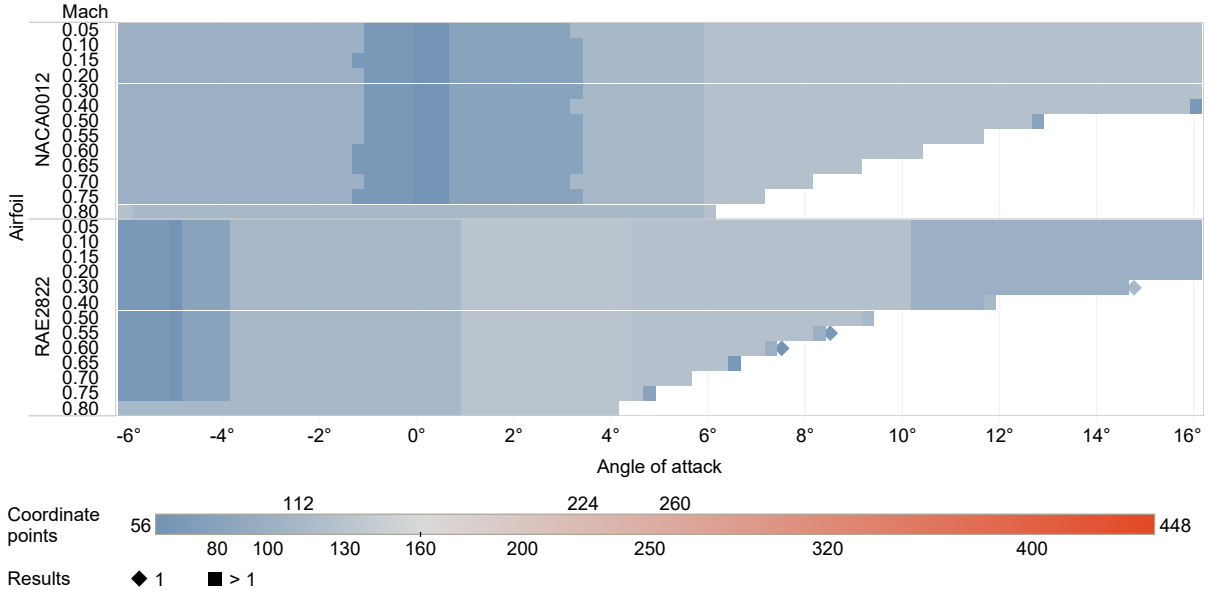


Figure 6.7: Number of coordinate points required for convergence of lift coefficient (XFOIL-U, cosine spacing)

The results for XFOIL-PG are exactly the same, due to the fact that the Prandtl-Glauert correction depends linearly on C_p. As the Karman-Tsien compressibility correction is non-linear, this is not the case for XFOIL-KT. These results are shown in Figure 6.8. In this case, there is a notable variation with M_∞. Interestingly, the direction of this variation depends slightly on angle of attack, and somewhat more on geometry. The latter is explained by the fact that the asymptote is approached monotonically in case of the NACA0012, but not for the RAE2822. The fact that C_p varies with M_∞ in the Karman-Tsien corrected data also explains the lack of solutions at combinations of higher angles of attack and Mach. In these regions (the lower right of the figures), the magnitude of the leading edge suction peak is larger than can be represented in XFOIL-output, yielding overflow errors.

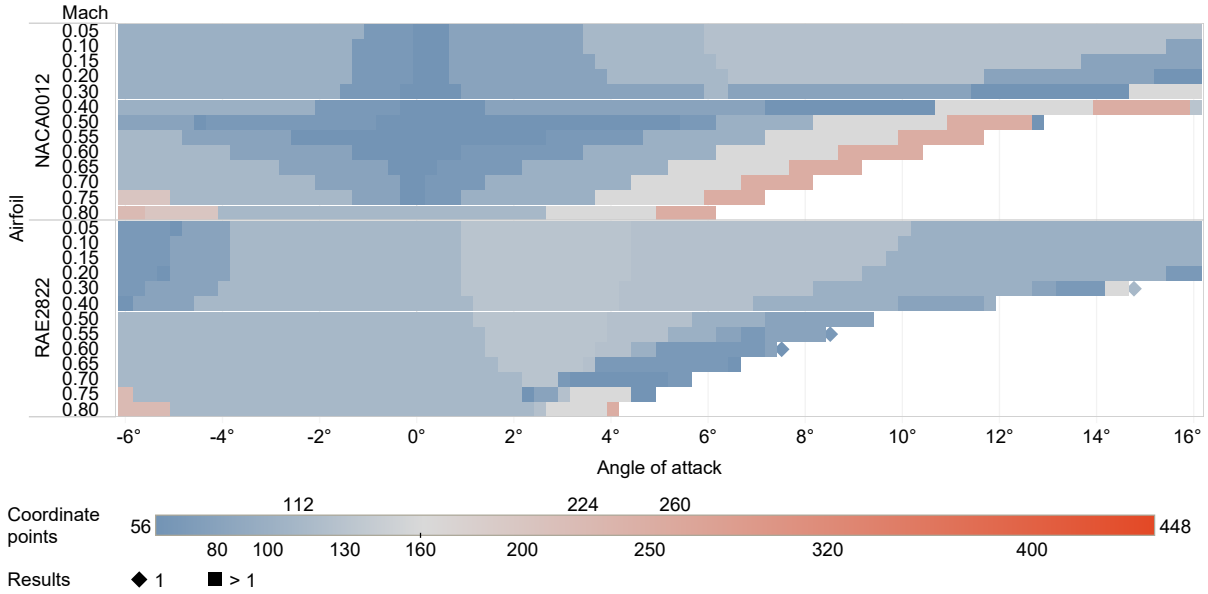


Figure 6.8: Number of coordinate points required for convergence of lift coefficient (XFOIL-KT, cosine spacing)

Results for VGK and VGK-NC are not shown, as the reference data is consistently determined from the same set of results. For MSES, they are depicted in Figure 6.9. These are rather different, when compared to the earlier XFOIL-set. The much more erratic behaviour is striking. Furthermore, the de-

pendence on Mach number is reduced substantially: especially at lower and moderate angles of attack, Figure 6.9 shows a more pronounced vertical pattern. This is explained by the fact that $|C_p|$-values computed by XFOIL rise indefinitely with Mach number, whereas the shock-capturing capabilities of the Euler code prevent this from happening in MSES. This, in turn, prevents the overflow problem observed in the panel code.

Also, there is a much larger contrast between the two airfoils. At a lot of instances at lower angles of attack, the reference value of the supercritical airfoil is determined from a single point. For a subset of these (the most brightly coloured orange diamonds), the lift coefficient of the RAE2822 did not definitively reach the asymptote at even the finest grid analysed. Given the fact that progressively smaller differences were observed, the values determined as reference are nevertheless accepted. The fact that a substantial amount of diamonds have a lighter or more blue hue shows that increasing the number of coordinate points and grid lines does not necessarily improve the probability of obtaining a solution.

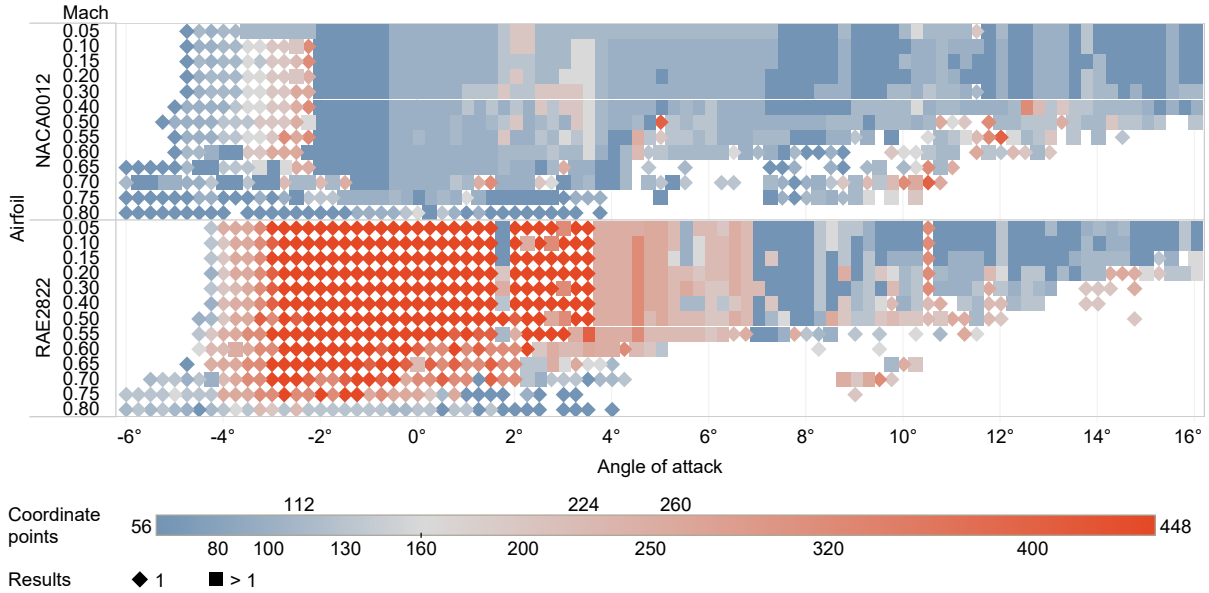


Figure 6.9: Number of coordinate points required for convergence of lift coefficient (MSES, linear spacing)

An identical analysis of pitching moment coefficient data (included in Appendix F.1.1) shows the same trends. For the various XFOIL-cases, the number of coordinate points after which a c_m-asymptote was reached is slightly higher than for c_l in case of the NACA0012. The reverse is true for the RAE2822. This is mostly likely a consequence of the notably different pressure distribution generated by the supercritical airfoil. As the pressure difference between upper and lower surfaces on the aft portion of the airfoil is much larger for the RAE2822 than for the NACA0012, inaccurate representation of the leading edge (and the associated suction peak) has a smaller effect on the force distribution along the chord line and thereby on the pitching moment coefficient.

Having determined the convergence point, Table 6.3 shows descriptive statistical data of the spread of the data. The data is expressed as the absolute difference between the upper and lower bound and the reference value, normalised to that reference value. Results obtained at or close to the zero-lift angle of attack ($\alpha = 0°$ for the NACA0012; $-2.25° \leq \alpha \leq -2°$ for the RAE2822) have been excluded, as relative differences would be unjustly magnified due to the low nominal value in the denominator. For the same reason, the table is limited to the lift coefficient, as c_m-values are small over the entire α-range.

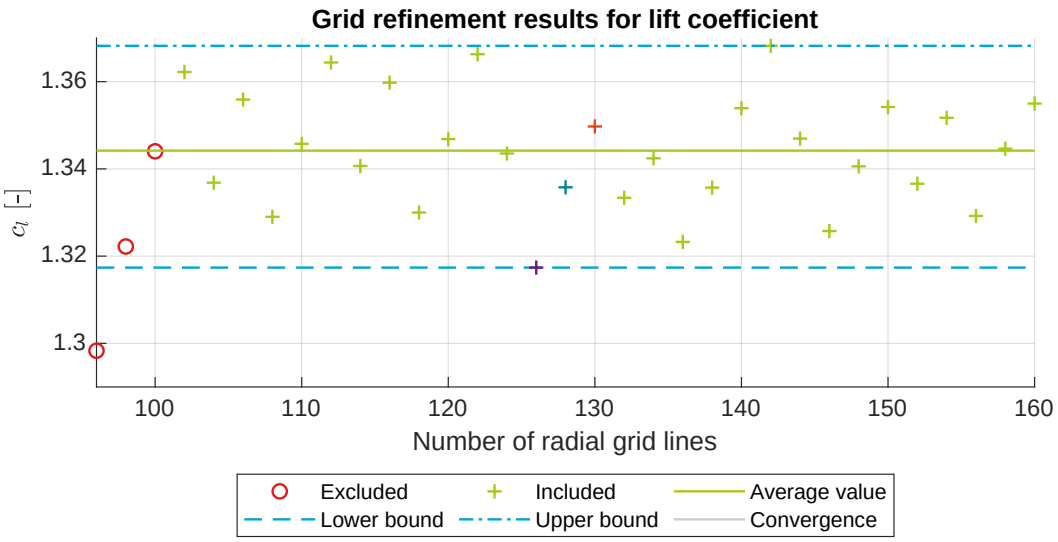
The table shows the spread is low, even more so for the symmetrical than for the supercritical airfoil: 95% of the data is within 2.5% of the reference value. The relatively high minimum and maximum values obtained from VGK-NC and VGK (up to 22%) are a consequence of the limitations of the computational grid. The maximum of 80 radial grid lines per surface and cosine distribution substantially reduce the resolution over the middle portion of the chord. The grid is therefore unable to accurately capture the shock location, resulting in the fact that the pressure change caused by the shock 'jumps' back and

Table 6.3: Descriptive statistical data of the data-spread underlying the reference values, showing median (Med), standard deviation (StD), 75th and 95th percentile (P75 and P95), minimum (Min) and maximum (Max) for the lower and upper bounds of NACA0012 (NACA) and RAE2822 (RAE) data

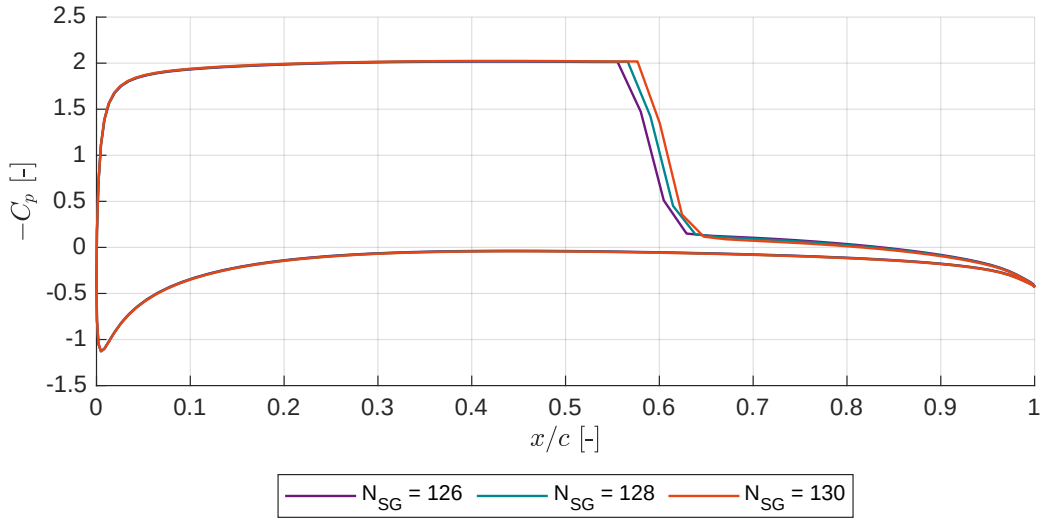
	Solver	Airfoil	Med	StD	P75	P95	Min	Max
Upper	XFOIL-U	NACA0012	0.08%	0.42%	0.14%	0.54%	-1.95%	2.05%
		RAE2822	0.12%	0.94%	0.29%	1.22%	-4.18%	3.61%
	XFOIL-PG	NACA0012	0.08%	0.42%	0.14%	0.54%	-1.95%	2.05%
		RAE2822	0.12%	0.94%	0.29%	1.22%	-4.18%	3.61%
	XFOIL-KT	NACA0012	0.08%	0.42%	0.14%	0.51%	-1.95%	2.40%
		RAE2822	0.13%	1.00%	0.33%	1.58%	-4.18%	6.76%
	VGK-NC	NACA0012	0.01%	1.07%	0.04%	2.03%	-13.17%	11.89%
		RAE2822	0.05%	0.87%	0.12%	1.00%	-12.32%	9.56%
	VGK	NACA0012	0.01%	1.07%	0.04%	1.71%	-11.44%	12.85%
		RAE2822	0.06%	1.19%	0.18%	1.60%	-13.71%	13.50%
	MSES	NACA0012	0.25%	1.27%	1.61%	3.05%	-1.82%	5.86%
		RAE2822	0.00%	0.49%	0.23%	1.26%	-2.65%	5.45%
Lower	XFOIL-U	NACA0012	-0.06%	0.39%	0.10%	0.46%	-1.88%	1.85%
		RAE2822	-0.29%	1.44%	-0.09%	2.11%	-5.96%	6.68%
	XFOIL-PG	NACA0012	-0.06%	0.39%	0.10%	0.46%	-1.88%	1.85%
		RAE2822	-0.29%	1.44%	-0.09%	2.11%	-5.96%	6.68%
	XFOIL-KT	NACA0012	-0.08%	0.38%	0.10%	0.41%	-1.83%	1.84%
		RAE2822	-0.31%	1.57%	-0.11%	2.38%	-8.30%	6.95%
	VGK-NC	NACA0012	-0.01%	0.97%	0.01%	1.11%	-8.27%	12.63%
		RAE2822	-0.11%	1.24%	-0.06%	0.99%	-8.73%	22.08%
	VGK	NACA0012	-0.01%	1.12%	0.01%	0.98%	-11.70%	12.07%
		RAE2822	-0.11%	1.39%	-0.07%	0.99%	-20.26%	18.34%
	MSES	NACA0012	-0.36%	1.61%	0.00%	0.48%	-15.60%	1.70%
		RAE2822	0.00%	0.90%	0.00%	0.00%	-9.85%	1.16%

forth over a relatively wide x/c-range. Figure 6.10 illustrates this behaviour. The highlighted c_l-values in Figure 6.10a correspond to $N_{SG} = 126$, $N_{SG} = 128$ and $N_{SG} = 130$, of which the pressure distributions are shown in Figure 6.10b. As the shock location moves downstream, the computed lift coefficient is logically affected.

Concluding the grid refinement study, reference values were obtained that can be used for assessing the impact of solution method and flow model in the upcoming sections. Convergence was obtained by XFOIL (both in uncorrected as in corrected form) for both geometries in nearly all combinations of Mach number and angle of attack, establishing the accuracy of the resulting reference values. VGK was found to notably depend on grid size, especially as the larger spacing over the middle portion of the chord influences the shock location. Nevertheless, the variance in the data was explained by this behaviour and subsequently removed by averaging, resulting in reference values that are mostly unaffected by this numerical problem. MSES showed the least amount of converged results, even at the maximum amount of coordinate points and grid lines – most notably for the RAE2822. As such, the largest uncertainty is associated to the reference values established for MSES.



(a) Lift coefficient, at different numbers of radial grid lines N_{SG}



(b) Pressure distribution at $N_{SG} = 126$, 128 and 130

Figure 6.10: Lift coefficient values obtained with VGK (NACA0012, cosine spacing, 160 coordinate points, $M_\infty = 0.70$, $\alpha = 6°$), showing the impact of N_{SG} on shock location, pressure distribution and lift coefficient

6.3.2. Influence of solution method

This section presents the results of the comparison of individual solution runs with the reference values determined by the grid refinement study. The figures and analyses presented here thereby indicate the influence of the solution method on the final result, for different quantities of interest.

As in the previous section, the data is displayed using heat maps, such as the one shown in Figure 6.11. The vertical axis shows the spacing, number of coordinate points and Mach number. The horizontal axis distinguishes between the true difference (left two columns) and the difference normalised to the reference value (right two columns), the airfoil and the angle of attack (shown in bins 2° wide). The difference itself is shown using a colour scale, in which blue indicates the quantity is underestimated and

orange shows it is overestimated. Cells in the shape of a diamond signify that that particular value is outside the range shown by the colour bar. Lastly, the size of the symbol is a measure for the relative amount of angles of attack for which a solution could be obtained. In all figures, the results obtained at or around the zero-lift angles of attack ($\alpha = 0°$ for the NACA0012; $-2.25° \leq \alpha \leq -2°$ for the RAE2822) have been excluded.

Appendix F.1.2 shows the same figures, with the difference that the relative differences are normalised with respect to the computed result. Those heat maps thereby provide an indication of the correction necessary, once a particular result has been obtained. The appendix (more specifically, Appendix F.1.2) also includes line graphs that present the isolated relations between the number of coordinate points, Mach number and angle of attack and a particular quantity of interest.

The results from the incompressible panel method, XFOIL-U, are shown in Figure 6.11. The independence of Mach number is clear, and the fact that the solver could not obtain results at combinations of high α and M_∞ – already discussed in the previous section – is evident as well. Further inspection immediately shows the rapid convergence of cosine-spaced geometries, consistent with Figure 6.7: only a few very light spots of blue and orange appear, but normalised differences never exceed $\pm 0.6\%$. Contrary to these cosine-results, the geometries represented using linearly spaced coordinates show a clear dependence on the number of coordinate points as well as angle of attack. In case of 112 coordinate points and a Mach number equal to 0.05, these range from approximately $\Delta c_l = 0.02$ to $\Delta c_l = -0.05$ (NACA0012) or $\Delta c_l = -0.08$ (RAE2822). When the differences are normalised, the variance is mostly removed (to roughly -4%). This is a direct effect of the size of the panels (i.e., the distance between adjacent coordinate points) in the leading edge region, which are too large to accurately resolve the LE suction peak and pressure recovery. The effects are slightly more pronounced for the supercritical airfoil than for the symmetrical profile, due to the smaller leading edge radius of the former (Anderson, 2001).

When a compressibility correction is applied to the incompressible results, a dependency on Mach number is observed. This is shown in Figure 6.12 for airfoil representations with 112 coordinate points and a linear spacing. For XFOIL-PG-results, variation in true difference with $\overline{M_\infty}$ can hardly be noticed: in the depicted case, $\Delta c_l \approx 0.01$ between lower and higher Mach numbers. In the normalised situation, the discrepancies between are even smaller. The effect is larger in case of the Karman-Tsien correction, which also amplifies the relation with angle of attack. In the $0°$-degree α-bin the variance with M_∞ is about 3%, growing to 5% at higher values for $\overline{\alpha}$. As with the uncorrected results, the influence of solution method decreases with increasing number of coordinate points and are for all intents and purposes absent if coordinates are distributed in a cosine fashion.

The results obtained from VGK, shown in Figure 6.13, are much less colourful – a testament to the good convergence at low panel counts and relatively sparse grids displayed by the solver. Additionally, the cell size – indicating the number of converged results – shows VGKs ability to find a solution is reduced at higher α and M_∞. Nevertheless, it outperforms XFOIL as well as VGK-NC, which could not produce output for some the highest angles of attack at $\overline{M_\infty} = 0.3$. As VGK interpolates any geometry analysed in the solver to a cosine-distributed grid, clear differences between linear and cosine spacings are largely absent, although the influence of the solution method on the lift coefficient as predicted for the supercritical airfoil shows a slight dependence on the number of coordinate points, visible as a downward colour gradient in Figure 6.13. Excluding the zero-lift regions, relative differences are limited to 1.2% (NACA0012) and $+3/-6\%$ (RAE2822). As before, larger differences are generally observed at higher (absolute) angles of attack, especially in case of higher Mach numbers. Compared to the various data sets obtained from XFOIL, the influence of geometry is more clearly seen in the VGK results. At lower coordinate point counts distributed in a linear fashion, the lift coefficient of the RAE2822 is consistently overpredicted 0.01 to 0.02, increasing to 0.06 at higher α and M_∞. This can only be attributed to the geometry interpolation algorithm and is consistent with remarks in Freestone (2004)[3].

The results in Figure 6.14 were found from MSES. The missing data at the bottom of the figure (cosine distributions of higher amounts of coordinate points) is caused by memory limitations in the solver. In

[3] "Choosing the values of the input x-coordinates so as to correspond to equal intervals of θ is the optimum way of specifying the aerofoil geometry with a given number of coordinates." (Freestone, 2004, p. 10)

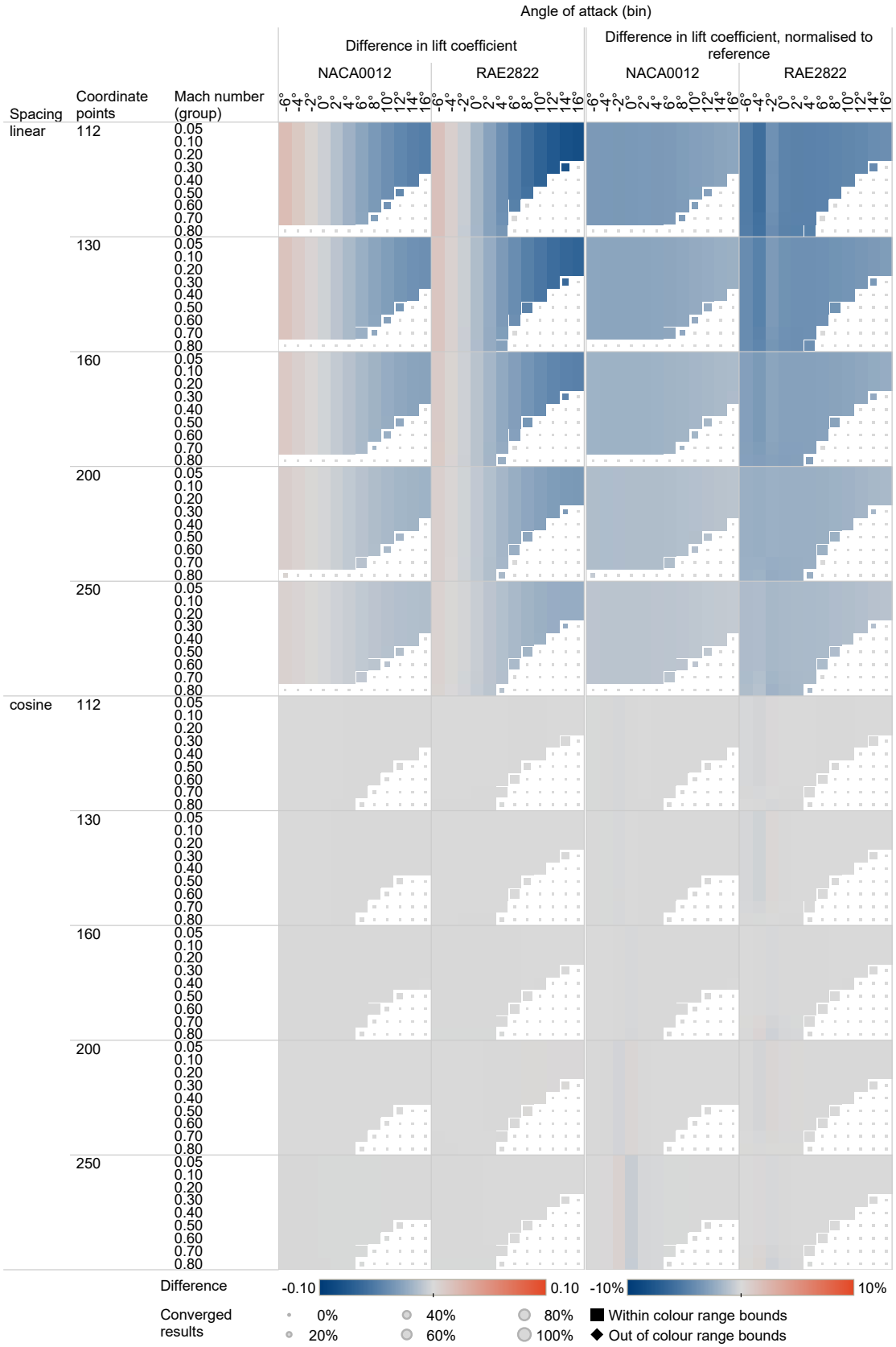
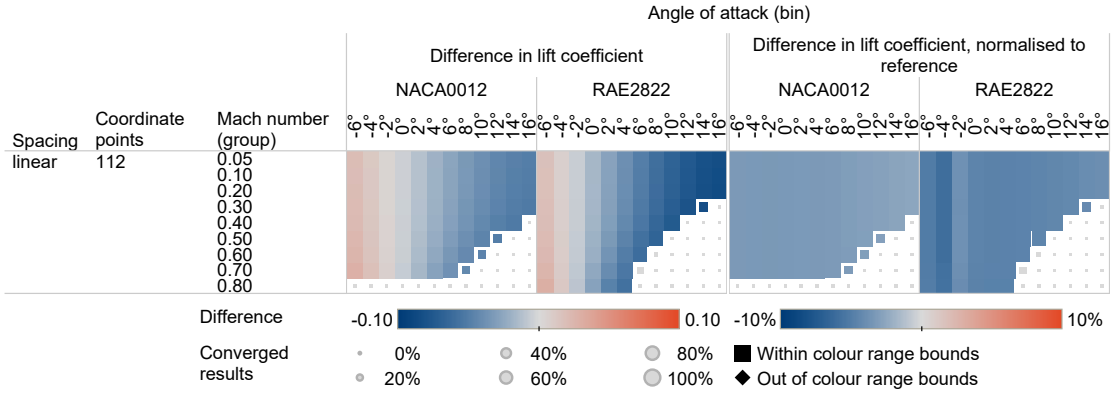
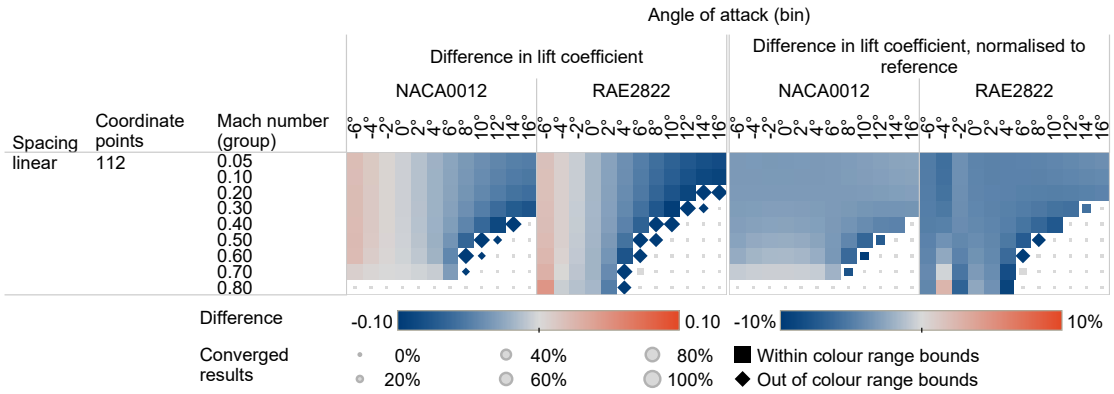


Figure 6.11: Difference in lift coefficient (true and normalised w.r.t. reference) observed in XFOIL-U results for different geometries, geometric representations, Mach numbers and (binned) angles of attack



(a) XFOIL-PG



(b) XFOIL-KT

Figure 6.12: Difference in lift coefficient (true and normalised w.r.t. reference) observed in XFOIL-PG and XFOIL-KT results for different geometries represented using 112 linearly spaced coordinate points, Mach numbers and (binned) angles of attack

comparison to the two other solvers, it clearly has – on average – more difficulties with finding a solution (most likely due to numerical instabilities), but does manage to obtain results in a number of flow conditions (higher α and M_∞) where XFOIL and VGK could not. The differences between individual and reference values are notably larger than in previous figures. This is especially true for low-resolution cosine representations of the RAE2822 at higher angles of attack (indicated by the diamond shapes). When the geometry is represented using linearly spaced coordinates, the influence of the solution method is small. (This also confirms earlier remarks in Section 6.3.1, noting that although reference values were based on single data points, these were accepted as the differences became progressively smaller with increasing grid size.) The large relative differences (between 10% and 20% in magnitude) and sign switch observed for the supercritical airfoil – especially at 112 coordinate points – are caused by normalisation. They were also seen in the VGK-results, but were not found in the XFOIL data. Focusing on the MSES-results obtained from linearly spaced input geometries, the lift coefficient is regularly under-estimated by 1% (NACA0012) to 2% (RAE2822), increasing to some 5% higher angles of attack.

For the pitching moment coefficient, c_m, similar results are found across all solvers (shown in Appendix F.1.2). Normalised differences are larger than for c_l and larger for the NACA0012 than for the RAE2822. Both facts are explained by the smaller magnitude of the moment coefficients (even more so for the symmetrical airfoil than for the cambered one) to which the differences are normalised. Discrepancies furthermore reduce when the grid is refined or additional points are used to represent the geometry, consistent with observations regarding lift coefficient. Some instabilities observed in the results from (especially) VGK and MSES are most likely related to the larger spread in c_m-data on which the reference values were based. Interestingly enough, the pitching moment coefficient is often overpredicted by XFOIL whereas these solutions underestimated c_l. MSES follows this trend to a lesser extent:

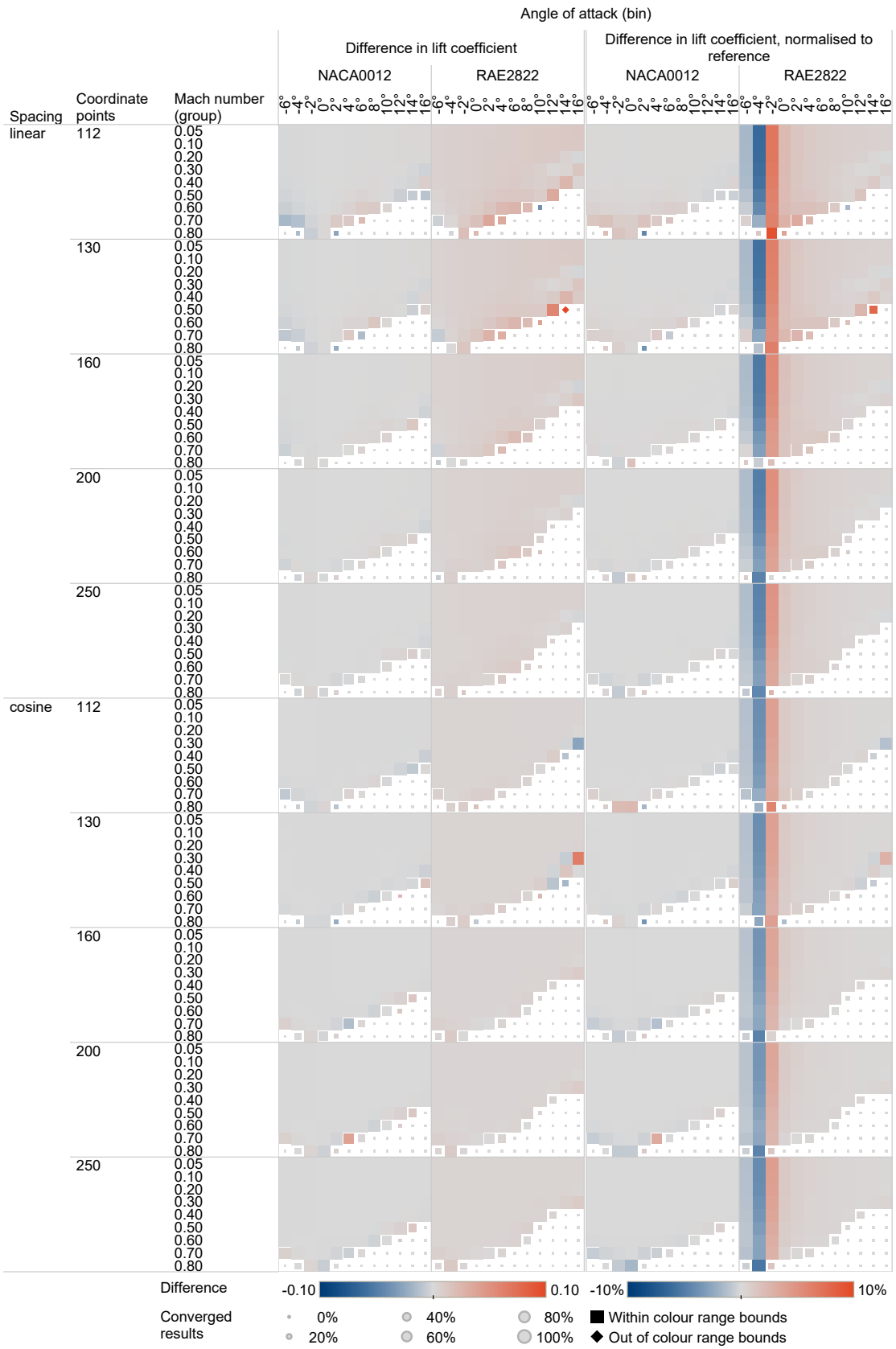


Figure 6.13: Difference in lift coefficient (true and normalised w.r.t. reference) observed in VGK results for different geometries, geometric representations, Mach numbers and (binned) angles of attack

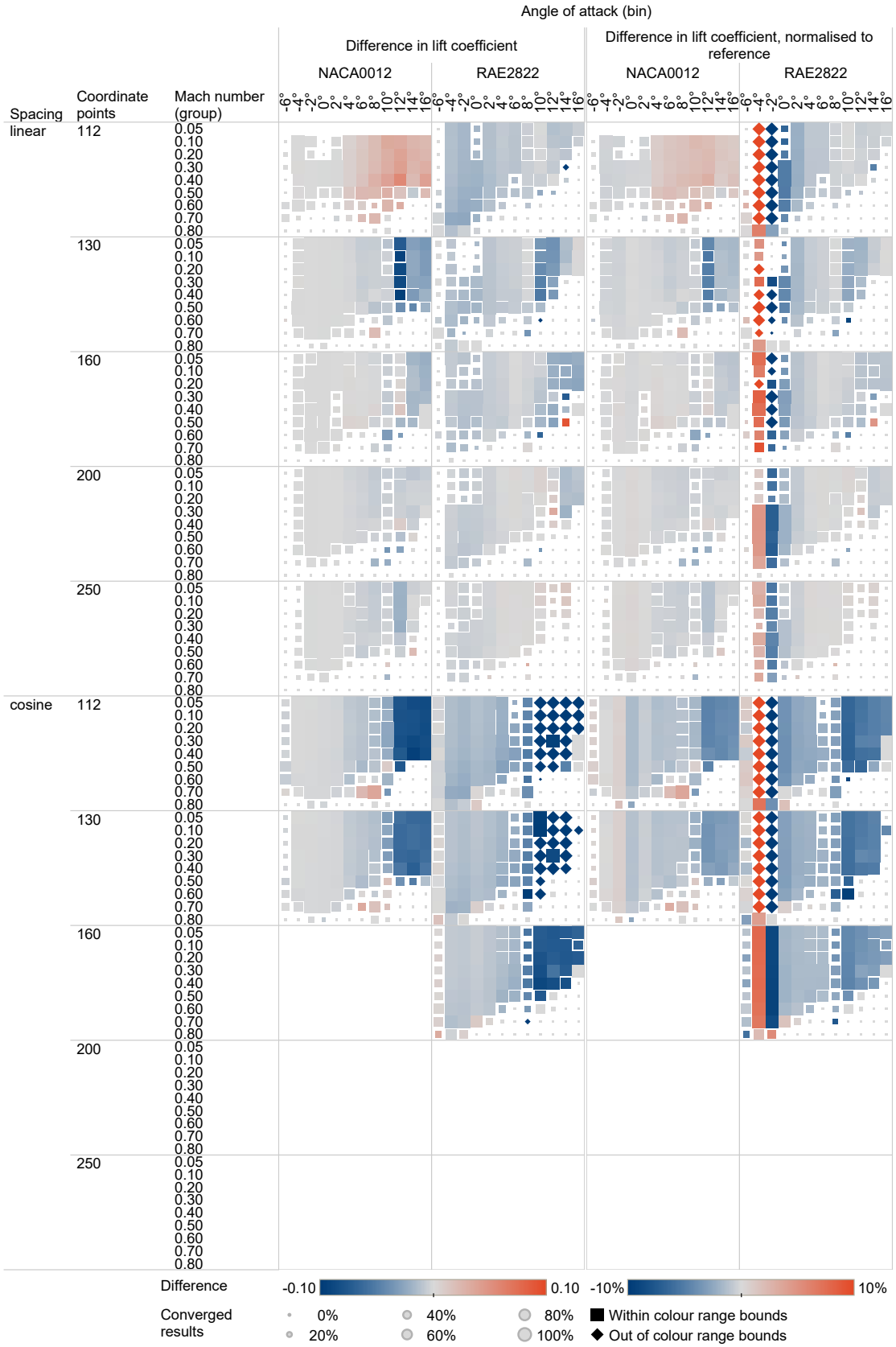


Figure 6.14: Difference in lift coefficient (true and normalised w.r.t. reference) observed in MSES results for different geometries, geometric representations, Mach numbers and (binned) angles of attack

although results do not change in sign, the entire heat map colours less blue and more orange. For VGK, the reverse is true.

Results of the minimum C_p-value are consistent with the observations of the variables that have been derived from that quantity. Larger leading edge panels (or wider grid spacing) result in difficulties with resolving the suction peak. Whereas VGK was found to be relatively unaffected by this in terms of c_l, the differences in terms of $C_{p,min}$ are substantial, showing differences up to 20% (NACA) or even 50% (RAE). MSES shows smaller discrepancies between individual solution runs and the reference value when the geometry is represented using a linear spacing.

Comparing between the various results discussed, it is noted that difference are relatively limited. The influence on the lift coefficient is smaller than on the pitching moment coefficient. The solution method generally does not affect the Mach number, but does influence the angle of attack. Whereas both VGK and MSES interpolate coordinate and/or redistribute the grid points in order to increase the resolution at the leading edge, XFOIL does not do so. This causes XFOIL-results to be notably influenced by the way its input geometry is defined.

6.3.3. Influence of flow model

Having treated the influence of the solution method, this section investigates the influence of the flow model of the quantities of interest defined before by comparing the reference values of the various solvers, in which the influence of the solution method is negligible. Most attention is paid to the influence of the incompressible flow assumption and the irrotational flow assumption, but some words are spent on the effectiveness of compressibility corrections.

As on previous pages, most data is displayed using heat maps. Although the colour bar scales have been adjusted to fit the results shown here, other elements of the visualisation (axes, icons denoting out of bound data and the size-indicator showing the percentage of converged results in a single data point) have been left unchanged. One exception to that rule is that, per the approach used to assess the influence of the flow model, axes concerning the representation of a geometry (number of coordinate points and spacing) have been removed.

Again, Appendices F.1.3 and F.1.4 show the results normalised with respect to the computed result, reformulating the data to allow use as a correction factor to lower-fidelity results.

Incompressible flow assumption

In order to determine the influence of the incompressible flow assumption, results from an incompressible panel code and a compressible full potential model are compared: XFOIL-U and VGK. At the end of the analysis of each assumption, the effect of the Prandtl-Glauert (XFOIL-PG) and Karman-Tsien (XFOIL-KT) compressibility corrections is shortly discussed, as well as the influence of mass conservation in case of the potential model (VGK versus VGK-NC).

The lift coefficients as computed by XFOIL-U and VGK are shown in Figure 6.15. The Mach-independence of the compressible solver is immediately clear from that figure, in which the line corresponding to $M_\infty = 0.05$ hides all others from sight. The compressible coefficients especially show the lack of convergence at combinations of higher M_∞ and α, as was also observed in Section 6.3.2. As the results are inviscid, flow separation and stall are not observed.

Lift coefficient

Figure 6.16 shows the difference in lift coefficient between the incompressible and compressible solvers using the familiar heat map. As before, angles of attack at or near the zero lift α have been excluded. Fitting with expectations, the influence of the incompressible flow assumption is clearly dependent on Mach number: the effects are mostly absent at $\overline{M_\infty} = 0.05$ (also shown in Figure 6.15), but increase towards higher Mach numbers. At $\overline{M_\infty} = 0.60$, neglecting compressibility results in an under-representation of

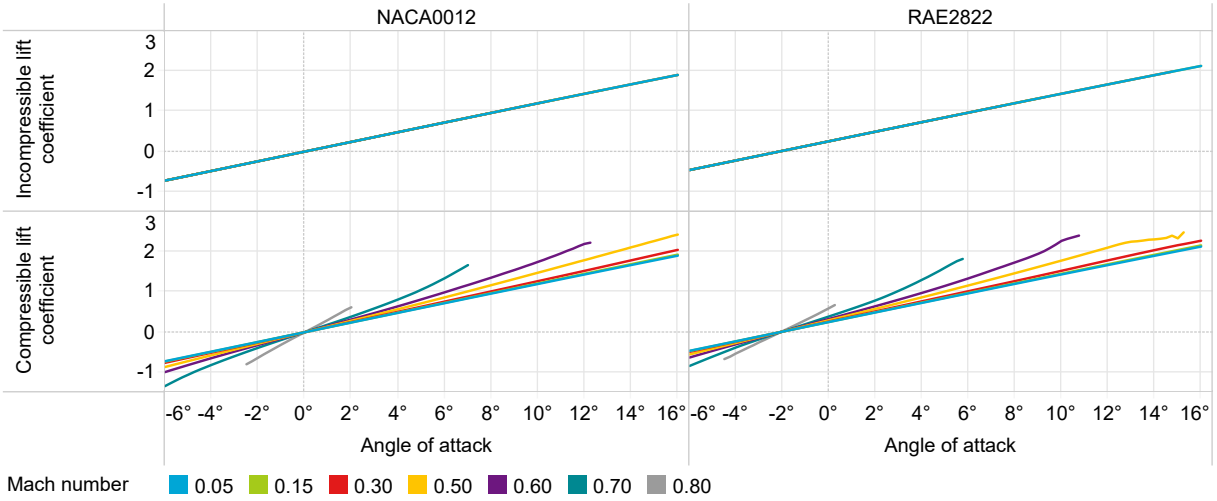


Figure 6.15: Incompressible (XFOIL-U) and compressible (VGK) lift coefficient for different geometries, Mach numbers and angles of attack

lift coefficient by approximately 25% to 30%, growing to 45% to 50% and circa 60% at $\overline{M_\infty} = 0.70$ and $\overline{M_\infty} = 0.80$, respectively. Differences grow beyond 10% for the first time at $\overline{M_\infty} = 0.40$. The normalised differences vary little between the symmetric and supercritical airfoil are small. This also holds between different angles of attack. When the differences are not normalised, the dependency on α can be clearly observed. The change in colour at lower angles of attack is a result of the incompressible and compressible lift curves intersecting at the zero-lift angle of attack.

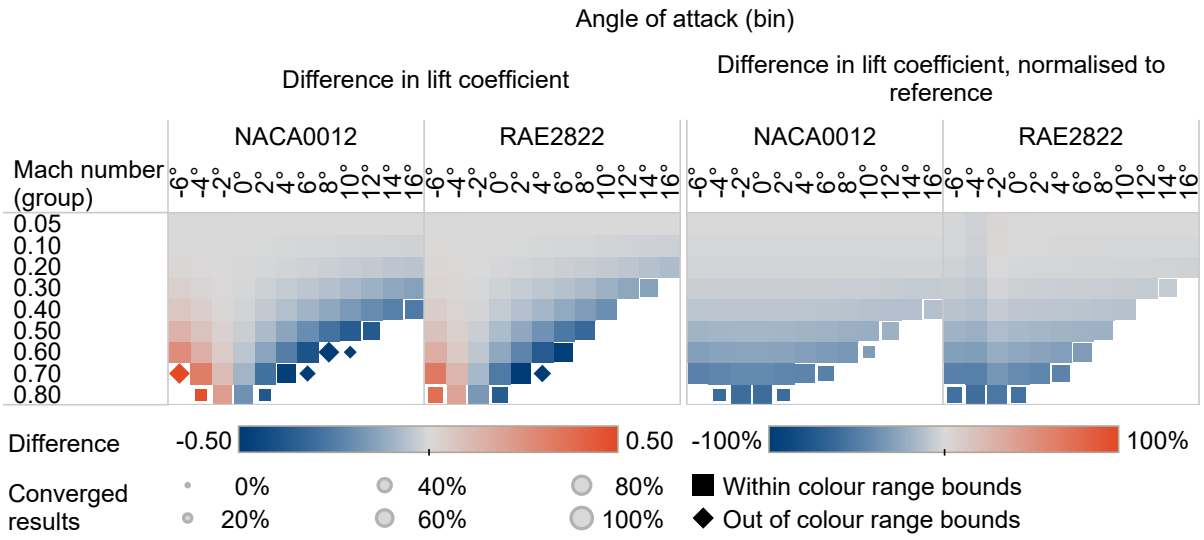


Figure 6.16: Difference between incompressible (XFOIL-U) and compressible (VGK) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Pitching moment coefficient

Figure 6.17 shows the influence of the incompressible flow assumption on the pitching moment coefficient. As for c_l, the influence of the incompressible flow assumption on the pitching moment coefficient at low Mach numbers is low. For the RAE2822, normalised differences only grow beyond (an absolute value of) 10% from $\overline{M_\infty} \geq 0.5$, with the exception of a few cases at higher α. In absolute terms, true differences in that domain are limited to $|\Delta c_m| < 0.01$. The fact that the trend with α – overestimated at lower values, underestimated at higher angles – is reversed between the true and normalised difference is caused by the negative pitching moment coefficient of the supercritical airfoil.

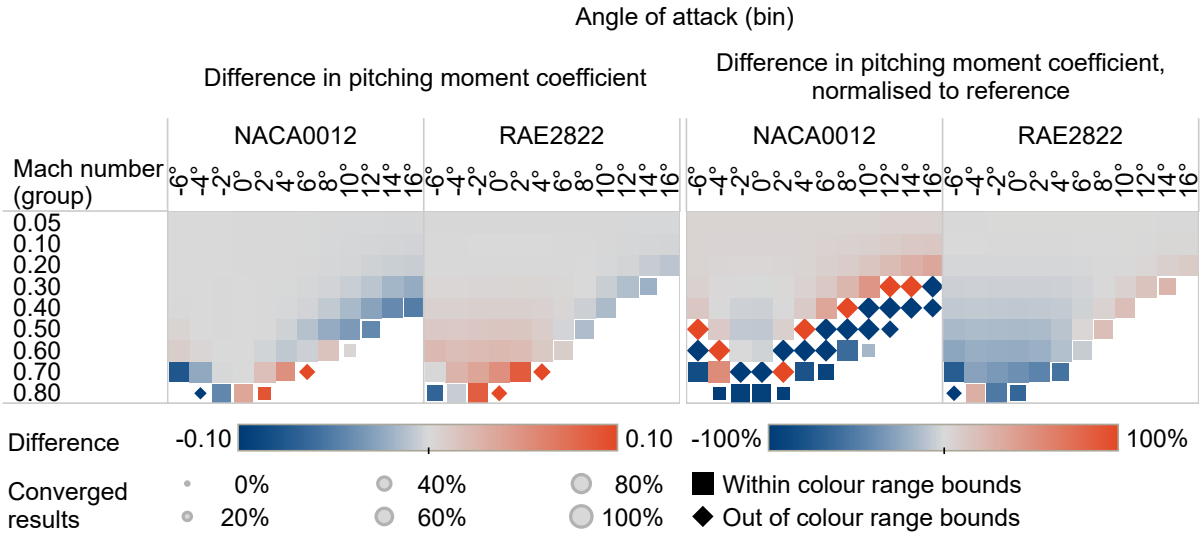


Figure 6.17: Difference between incompressible (XFOIL-U) and compressible (VGK) pitching moment coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

As the c_m of the NACA0012 is much smaller in magnitude (on average over all data points underlying Figure 6.17, c_m as estimated by VGK is equal to -0.00317), the normalised differences are substantially larger, fairly rapidly growing to values outside the bounds of the colour range (indicated by the diamond-shaped markers). In terms of the true difference, the overall influence of the incompressible flow assumption does not distinctly vary between the two geometries. For smaller angles of attack and higher Mach numbers, a smaller effect is observed in case of the NACA0012 than for the RAE2822, whereas the opposite is true at higher angles of attack and moderate Mach numbers. Overall, average differences over the combination of Mach numbers and angles of attack are $|\Delta c_{m,avg}| < 0.01$. Another difference between the two flow models, observed in Figure 6.18, is the fact that the pitching moment as predicted by incompressible flow solver is not only constant with M_∞, but also shows little variance with α. This is notably different from the compressible results, which shows the c_m-curves 'breaking away' from the incompressible line as angles of attack and Mach numbers increase.

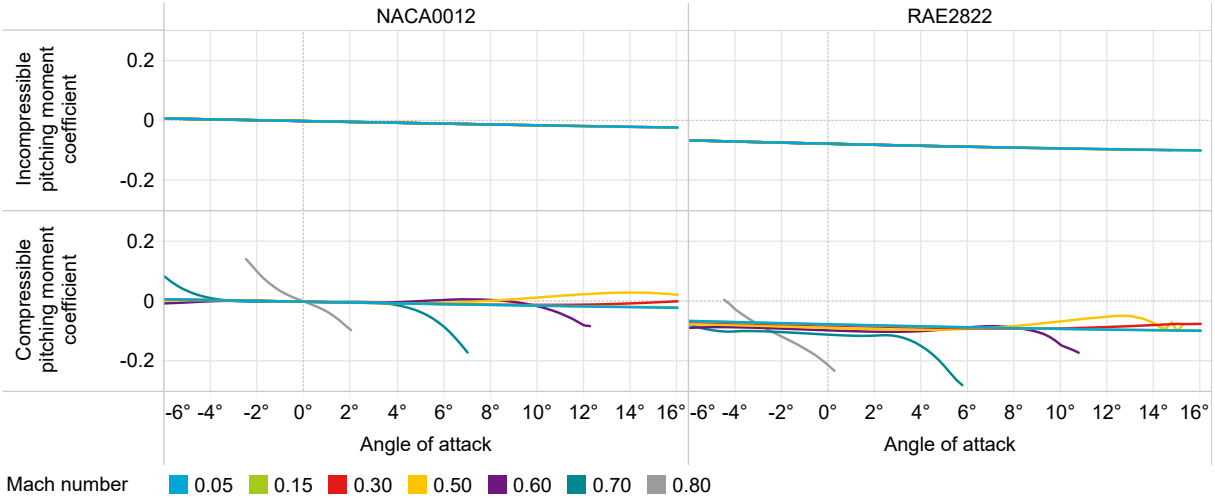


Figure 6.18: Incompressible (XFOIL-U) and compressible (VGK) pitching moment coefficient for different geometries, Mach numbers and angles of attack

Minimum pressure coefficient

The observed influences with respect to c_l and c_m are consistent with findings regarding the minimum pressure coefficient, $C_{p,min}$, as shown in Figure 6.19. Especially in situations where the angle of attack is limited to approximately $|\overline{\alpha}| \leq 6°$, the influence is small for low Mach numbers. Beyond $M_\infty \approx 0.3$, the effect grows. Compared to the result from the potential code, the incompressible solution slightly overestimates the pressure coefficient at the leading edge, thereby underestimating the magnitude of the suction peak. As Figure 6.19 clearly shows, this changes at higher angles of attack and higher Mach numbers. Whereas VGK models a shock wave and associated pressure recovery, XFOIL-U predicts the magnitude of the suction peak to keep increasing. In the most extreme situations (e.g. RAE2822 at $\overline{M_\infty} = 0.50$ and $\overline{\alpha} = 12°$), this results in differences of over 300%. Matching its lower maximum lift coefficient (shown previously in Figure 6.15), the results for the symmetrical case do not grow this large.

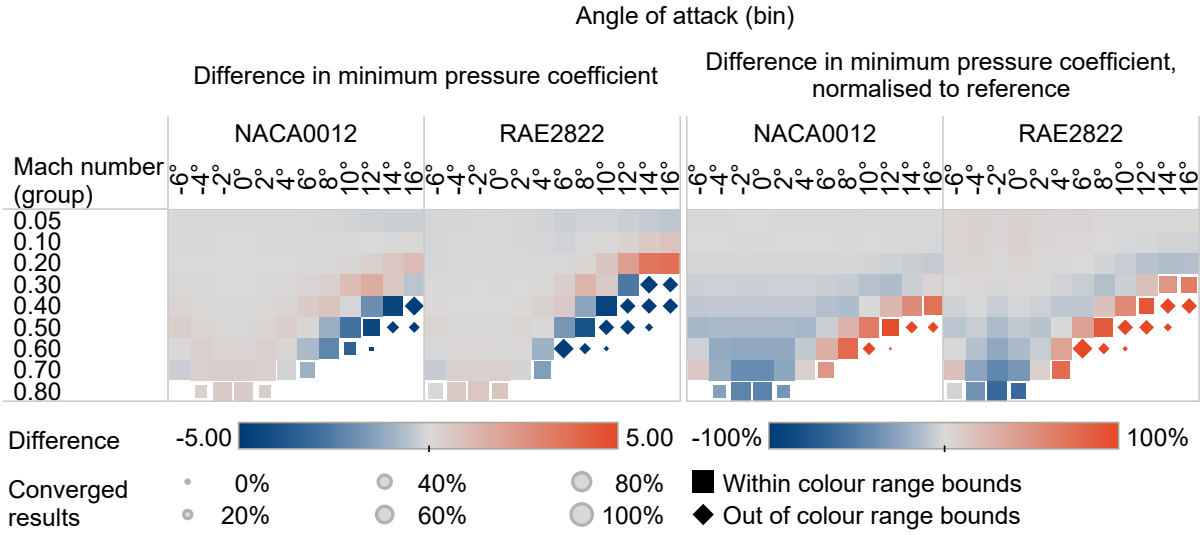


Figure 6.19: Difference between incompressible (XFOIL-U) and compressible (VGK) minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Chordwise location of minimum pressure coefficient

The chordwise location of the minimum pressure point, too, is influenced by shocks. The differences are visualised in Figure 6.20. Because the minimum pressure coefficient is found close to the leading edge, the normalised difference values grow large quickly. The difference itself is caused by $(x/c)_{c_{p,min}}$ tending to 0 with increasing α in the incompressible model, whereas the shocks captured by VGK keep it at a larger distance from the stagnation point – increasingly so with increasing Mach number. Compared to the NACA0012, the RAE2822 shows the same effects at a slightly lower M_∞ and α due to its different geometry.

Supporting arguments

The results and explanations presented previously are supported by Figure 6.21. For the NACA0012, represented using 250 cosine-spaced coordinate points[4], pressure distributions for $\alpha = 4°$, $6°$, $8°$, $10°$ and $12°$ are shown – as computed by the incompressible and the compressible solver. Figure 6.21a shows the case for $M_\infty = 0.30$, where local Mach numbers are below 1. In Figure 6.21b, $M_\infty = 0.50$. From $\alpha = 6°$, but more clearly visible from $\alpha = 8°$, VGK predicts a shock wave on the upper surface, whereas the incompressible flow solver does not.

Inspection of the pressure distributions of the compressible solver also provides insight in the non-linear variation of c_m with α and M_∞. Figure 6.22a shows the pressure distribution for $M_\infty = 0.60$ and $M_\infty =$

[4]Values of one particular geometry representation are used, as no reference values were computed for pressure distributions. Given the fact that the influence of the solution method was determined (in Section 6.3.2, specifically Figure 6.11 and Figure 6.13) to be low at the selected representation, this choice does not affect the illustrative qualities of the figures shown.

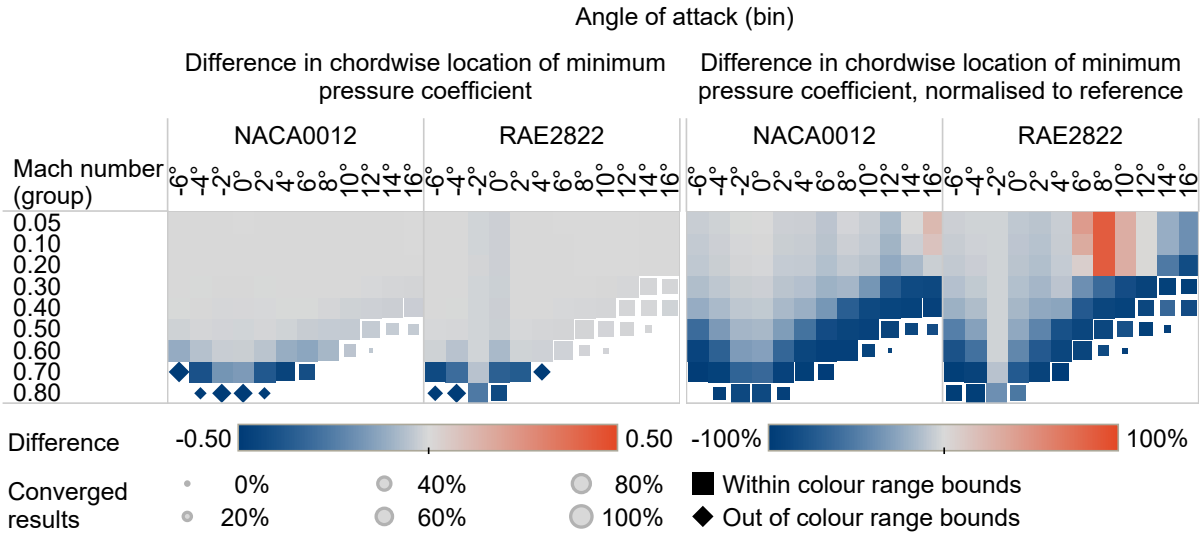


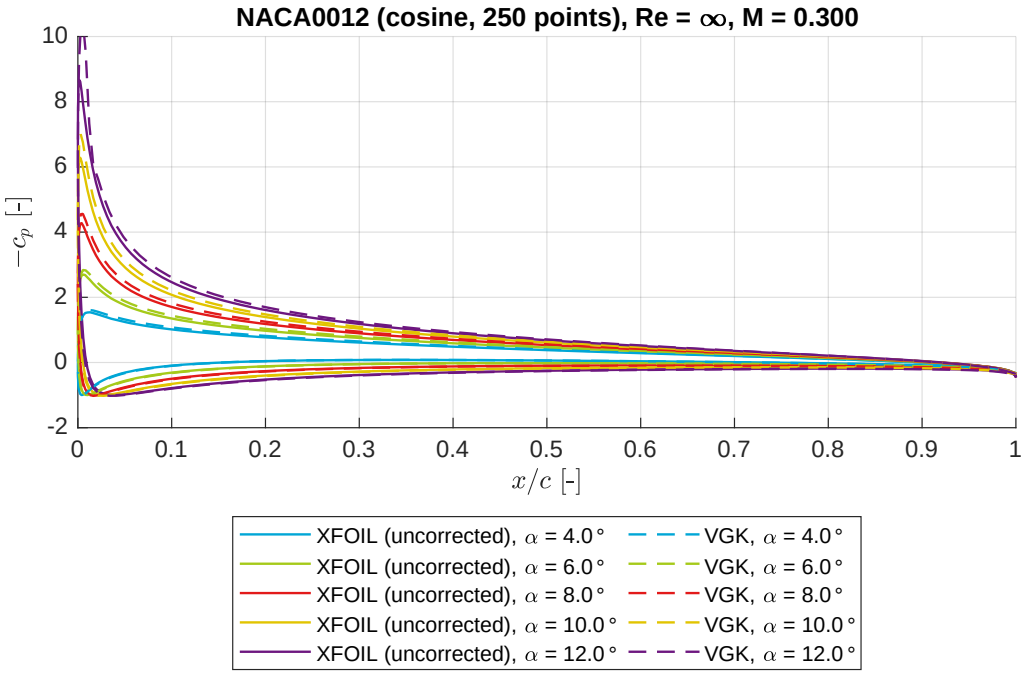
Figure 6.20: Difference between incompressible (XFOIL-U) and compressible (VGK) chordwise location of minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

0.70, for a variety of angles of attack. In case of $M_\infty = 0.60$ (represented with the solid lines), a shock starts to form at $\alpha = 4°$, which increases the pressure difference over the first 10% of the chord. When the angle of attack grows, the shock increases in strength and moves further downstream. This results in an increase in pitching moment coefficient, indicated using the blue line in Figure 6.22b, which continues up to $\alpha \approx 9°$. At that point, the centre of pressure coincides with the quarter-chord point and $c_m = 0$. As the angle of attack continues to increase, the shock moves further downstream and the centre of pressure moves aft of the aerodynamic centre, resulting in another sign change of $c_{m,\alpha}$. At $M_\infty = 0.70$ (shown using a dashed line in Figure 6.22a and the green line in Figure 6.22b), these effects are magnified to such an extent that $c_m < 0$ for all $\alpha \geq 0°$.

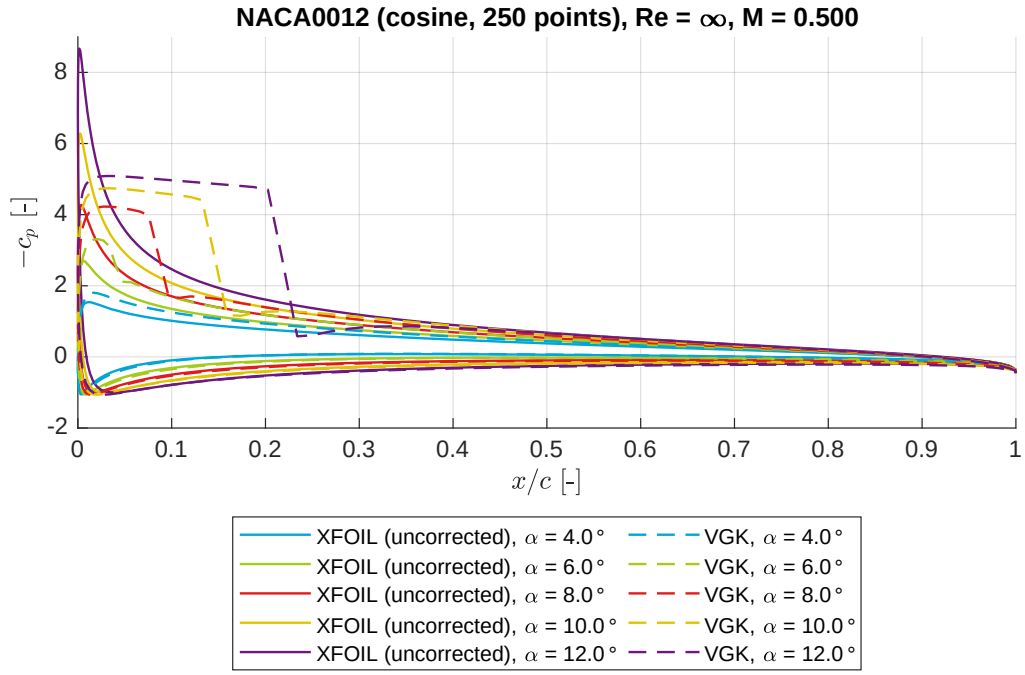
Compressibility corrections

The influence of the two compressibility corrections tested – Prandtl-Glauert and Karman-Tsien – is as expected. Effects concentrate at higher Mach numbers and higher angles of attack, and as Figure 6.23 shows, the underestimation of the lift coefficient at higher angles of attack seen in the incompressible case reduces after application of the Prandtl-Glauert correction factor and even results in c_l being overestimated in case of the Karman-Tsien corrected data. Taking $\overline{M_\infty} = 0.60$ and $\overline{\alpha} = 6°$ for the NACA0012, for example, XFOIL-U shows an underestimation of $\Delta c_l = -0.4$, which reduces in magnitude to $\Delta c_l = -0.16$ in case of XFOIL-PG and then increases to $\Delta c_l = 0.06$ when the Karman-Tsien correction is applied. Normalised, these values changes from -32% to -13% to $+5\%$. In more extreme situations, the Karman-Tsien correction however over-compensates the lack of compressibility: when the angle of attack is increased to $\overline{\alpha} = 10°$, XFOIL-KT shows a difference of $\Delta c_l = 0.44$ (25%) with respect to the compressible solver, whereas XFOIL-PG only deviates -0.26 (-14%).

Similar effects are seen for the pitching moment, although the effect of the Prandtl-Glauert correction is not as clear as for c_l when comparing true differences. The largest impact of the two compressibility corrections is seen in case of the supercritical airfoil. For smaller angles of attack, the difference between XFOIL-PG and XFOIL-KT and the compressible solver is largely absent up to $\overline{M_\infty} \approx 0.7$. The chordwise location of the minimum pressure coefficient is hardly affected, whereas the value of the minimum pressure coefficient is drastically scaled. The corrected results correspond better with the higher fidelity potential code at lower angles of attack, but beyond $\overline{\alpha} = 6°$ (RAE2822) or $\overline{\alpha} = 8°$ (NACA0012), the lowest (true and normalised) differences are found between the potential code and the uncorrected incompressible results.

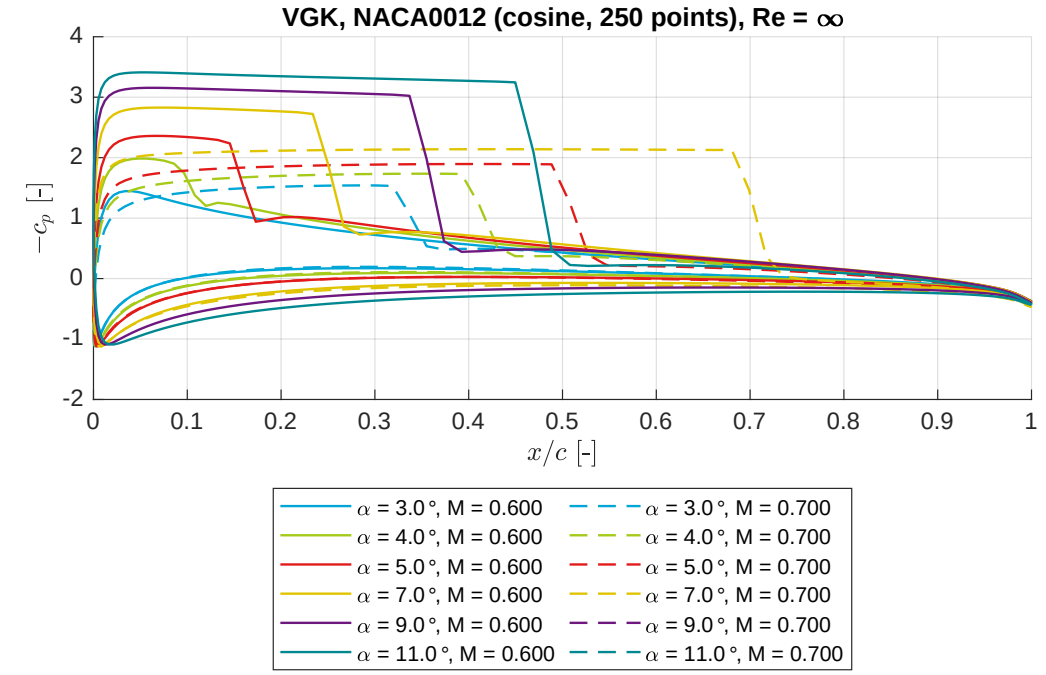


(a) $M_\infty = 0.30$, $4° \leq \alpha \leq 12°$, $\Delta\alpha = 2°$

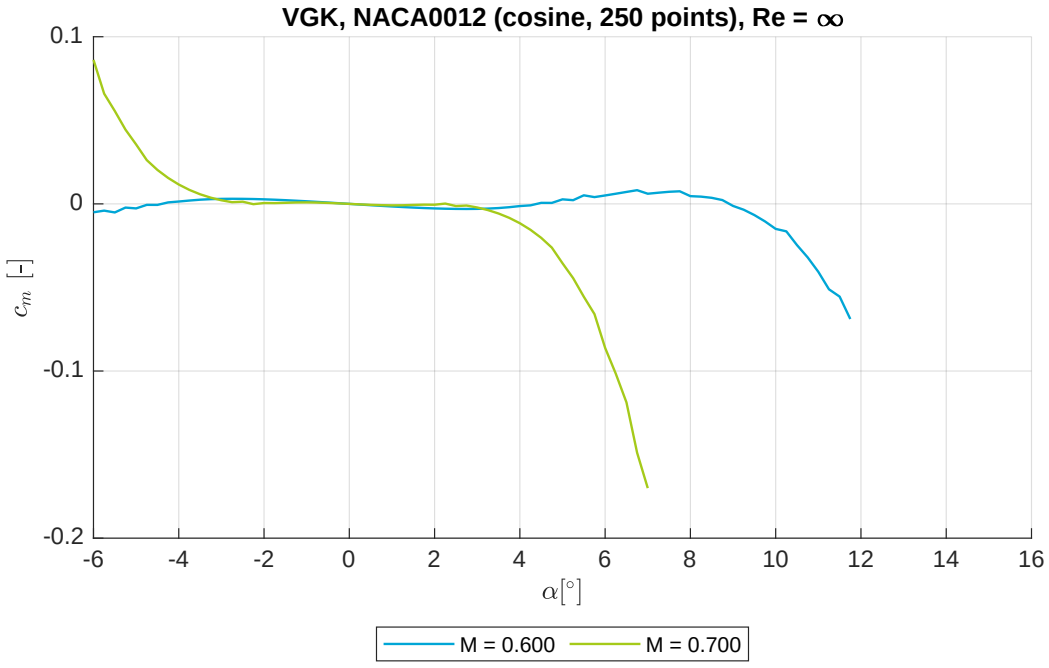


(b) $M_\infty = 0.50$, $4° \leq \alpha \leq 12°$, $\Delta\alpha = 2°$

Figure 6.21: Pressure distributions of a NACA0012 airfoil, represented using 250 cosine-spaced coordinate points, computed by an incompressible (XFOIL-U) and a compressible (VGK) solver at various Mach numbers and angles of attack

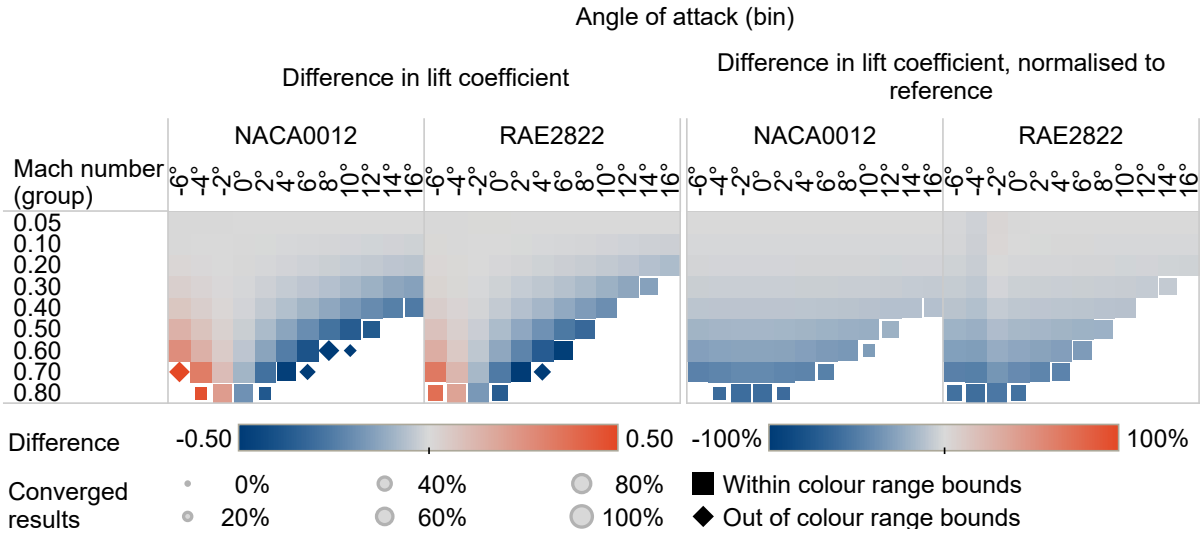


(a) Pressure distribution

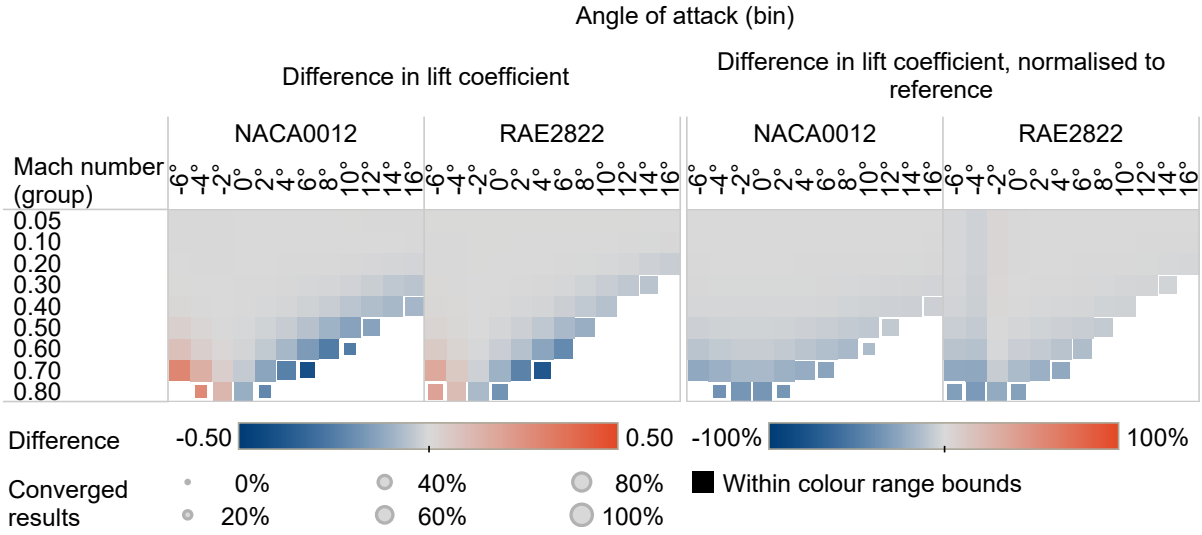


(b) Pitching moment coefficient

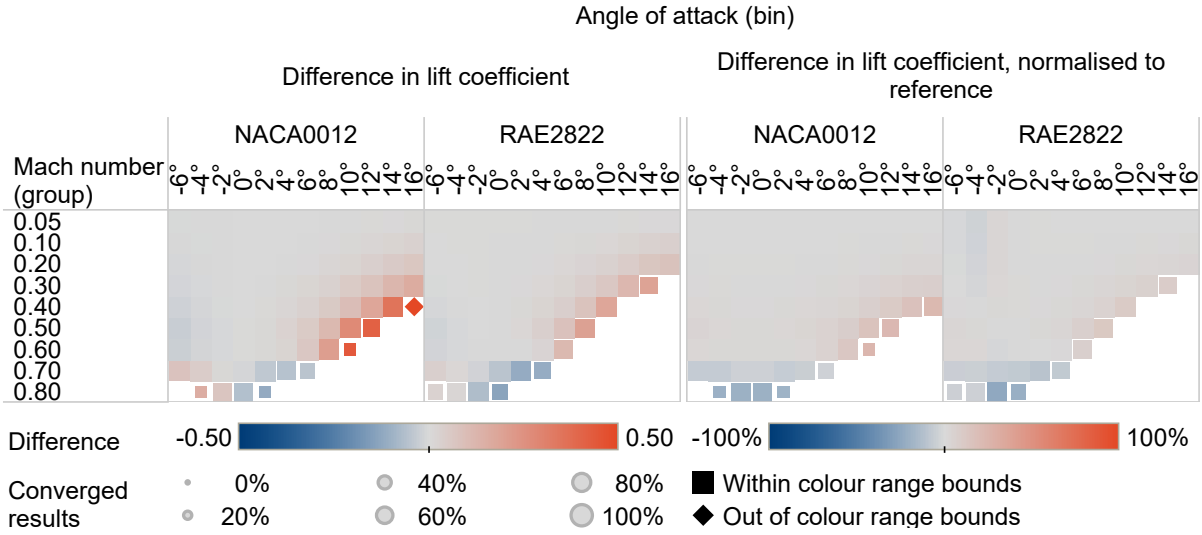
Figure 6.22: Pressure distributions and pitching moment of a NACA0012 airfoil, represented using 250 cosine-spaced coordinate points, computed by a compressible (VGK) solver, at $M_\infty = 0.60$ and $M_\infty = 0.70$ and various angles of attack



(a) Without compressibility correction (XFOIL-U) (repeated from Figure 6.16)



(b) With Prandtl-Glauert compressibility (XFOIL-PG)

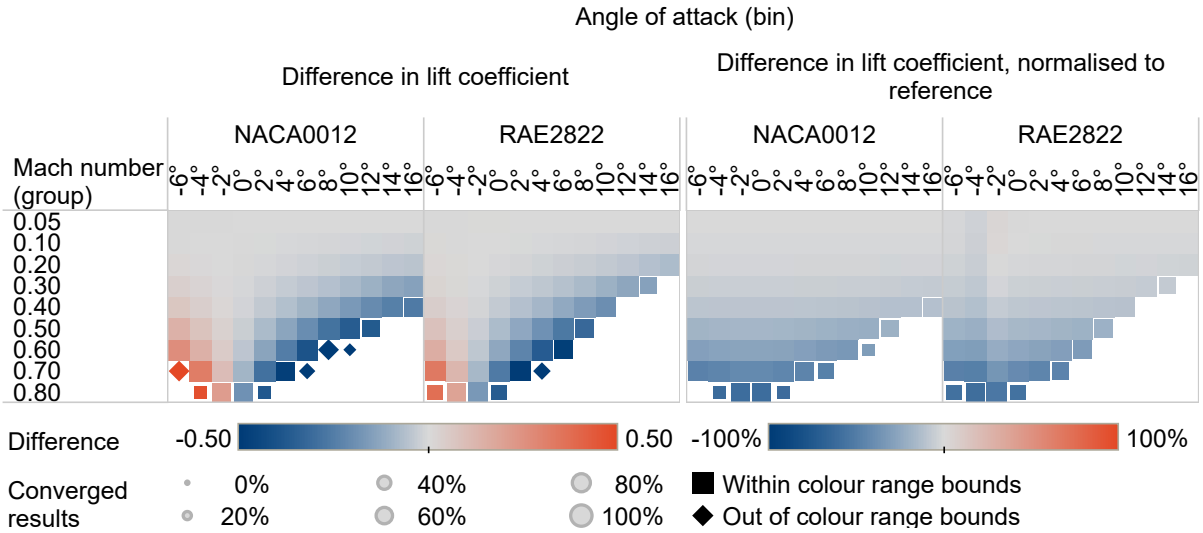


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

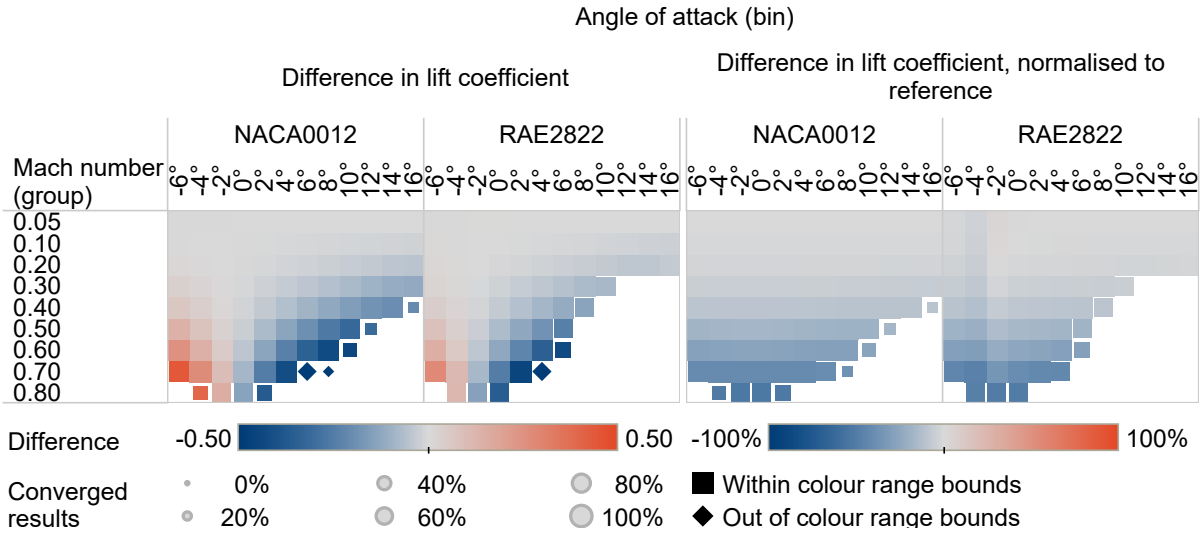
Figure 6.23: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Mass conservation

The previous analysis compared XFOIL-results with results obtained from the partially-conservative output from VGK. When the non-conservative scheme of the potential flow model (VGK-NC) is used, little changes. Besides the fact that convergence is poorer (especially in case of the RAE2822 analysed at $\alpha \geq 8°$), the minimum pressure coefficient and its location are unaffected, and differences between Figure 6.24a (XFOIL-U versus VGK) and Figure 6.24b (XFOIL-U versus VGK-NC) with respect to c_l and c_m were only observed at $\overline{M_\infty} \geq 0.7$. This is shown in Figure 6.24.



(a) Partially-conservative (VGK) (repeated from Figure 6.16)



(b) Non-conservative (VGK-NC)

Figure 6.24: Difference between uncorrected incompressible (XFOIL-U) and partially-conservative and non-conservative compressible (VGK and VGK-NC) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Irrotational flow assumption

The influence of the irrotational flow assumption is assessed through the comparison of results obtained using an irrotational partially-conservative full potential code (VGK) and a rotational Euler method (MSES). In contrast to previous results, the current analysis is limited to a smaller range of angles of attack: $|\alpha| < 3.50°$ for the NACA0012 and $-4.00° < \alpha < 2.00°$ for the RAE2822. This is due to the fact that at higher angles of attack, a discrepancy between the geometry and the inner-most streamline was found in MSES. Described in more detail in Appendix E, it mimics a long separation bubble, yielding a

spontaneous increase in lift curve slope which could not be attributed to the difference between rotational and irrotational flow. In order to prevent unfair comparisons, these results were excluded from the analysis.

Lift coefficient

Within these previously defined α-bounds, Figure 6.25 shows the effect of the irrotational flow assumption on lift coefficient. As the differences are notably smaller than those following from the irrotational flow assumptions, the colour scales are adjusted accordingly.

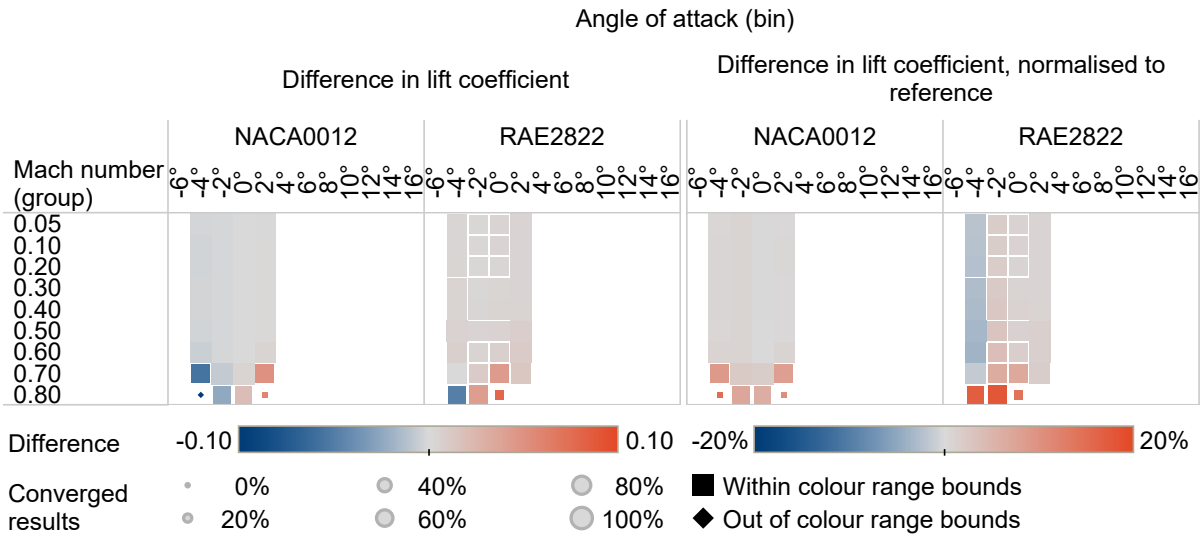


Figure 6.25: Difference between irrotational (VGK) and rotational (MSES) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Especially for the symmetrical NACA0012, the difference in lift coefficient below $\overline{M_\infty} \leq 0.60$ is negligible: for the data shown, the average difference is $\mathcal{O}(-4)$. In case of the supercritical RAE2822 differences are somewhat larger, but nonetheless limited to $\mathcal{O}(-2)$. As seen previously, the normalised differences of the latter geometry are larger (up to $\pm 7\%$ for $-4° \leq \overline{\alpha} \leq -2°$), which is caused by the normalisation procedure. Beyond $\overline{M_\infty} = 0.7$, the magnitude of the difference grows larger for both geometries.

Pitching moment coefficient

For the pitching moment coefficient, of which the difference is shown in the heat map in Figure 6.26, similar observations can be made. The influence is small at lower Mach numbers and depends slightly on geometry. Contrary to the lift coefficient, the pitching moment coefficient for the RAE2822 as computed by MSES is larger than the same quantity found by VGK. Due to the inherently negative c_m of that profile, the underestimation is reversed to an overestimation when normalised. The influence of the irrotational flow assumption manifests itself more notably at larger Mach numbers and angles of attack, in which true differences grow to $\Delta c_m = -0.025$ and $\Delta c_m = 0.039$ for the NACA0012 – equivalent to approximately 40%. In case of the RAE2822, extremes between $\Delta c_m = -0.0057$ and $\Delta c_m = -0.032$ are recorded, corresponding to -11% and -16%.

Supporting arguments

The results showing the influence of the irrotational flow assumption are explained through analysis of the pressure distributions, shown for the NACA0012 represented using 250 linearly spaced coordinate points at $\alpha = 2°$ for various Mach numbers in Figure 6.27. Besides the uneven pressure distributions as computed by MSES (physically unexplained, therefore most likely a numerical artefact), the difference in predicted shock strength and location at $M_\infty = 0.70$ between the two solvers is clear: the latter code predicts a stronger shock and shows a slight increase in the magnitude of C_p right after the shock. The fact that the two codes deviate noticeably when supersonic flow is analysed matches expectations

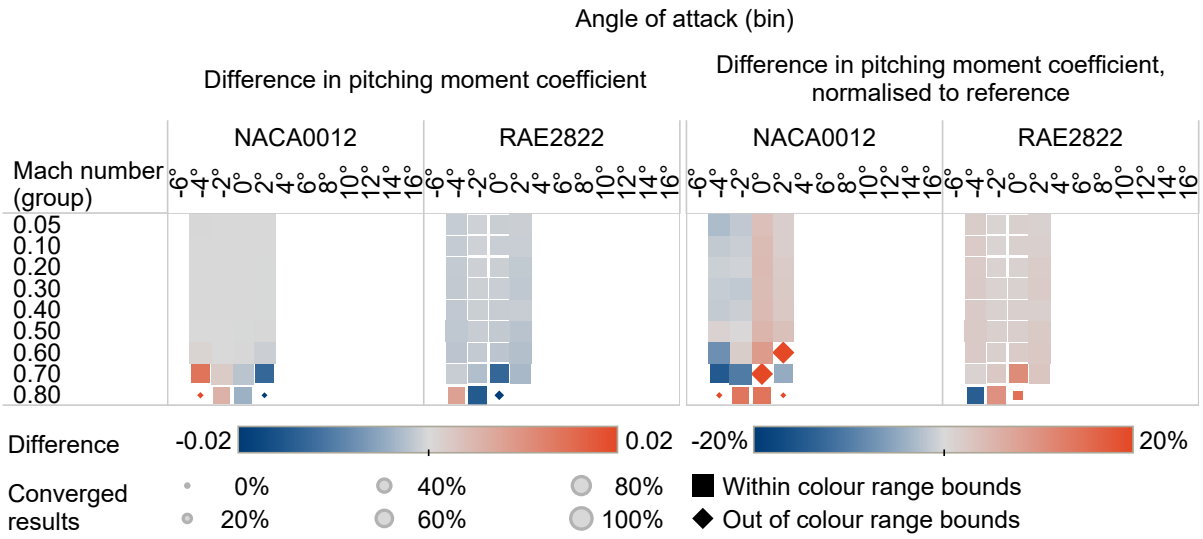


Figure 6.26: Difference between irrotational (VGK) and rotational (MSES) pitching moment (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

regarding the impact of the irrotational flow assumption. Besides, the maximum local Mach number found at $M_\infty = 0.70$ ($M \approx 1.25$) corresponds well with remarks in Freestone (2004), noting $M = 1.3$ as upper limit for VGK.

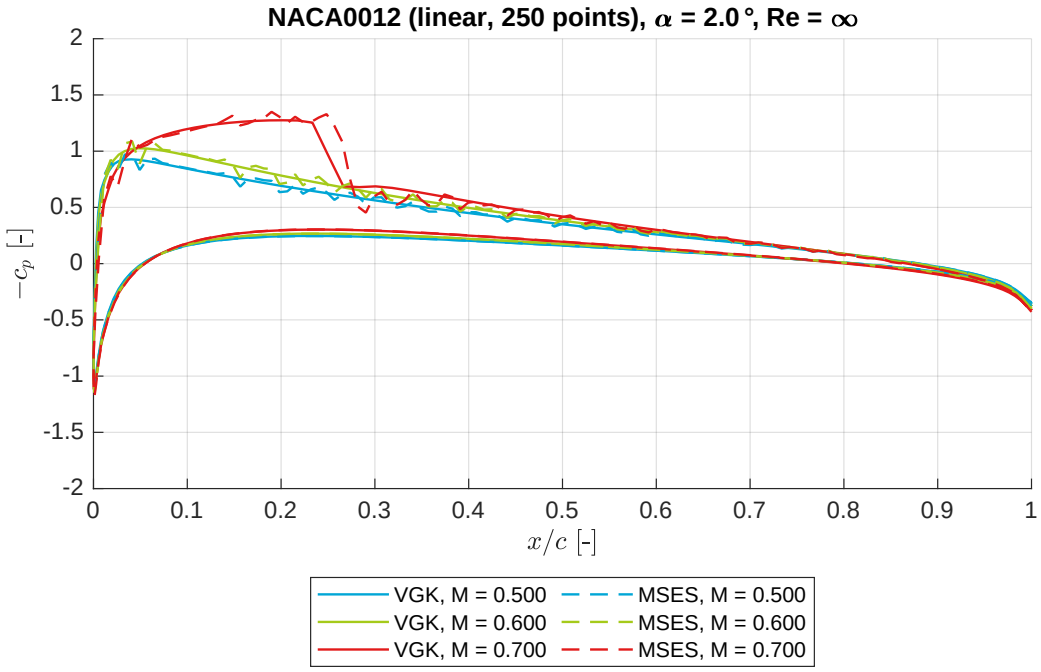
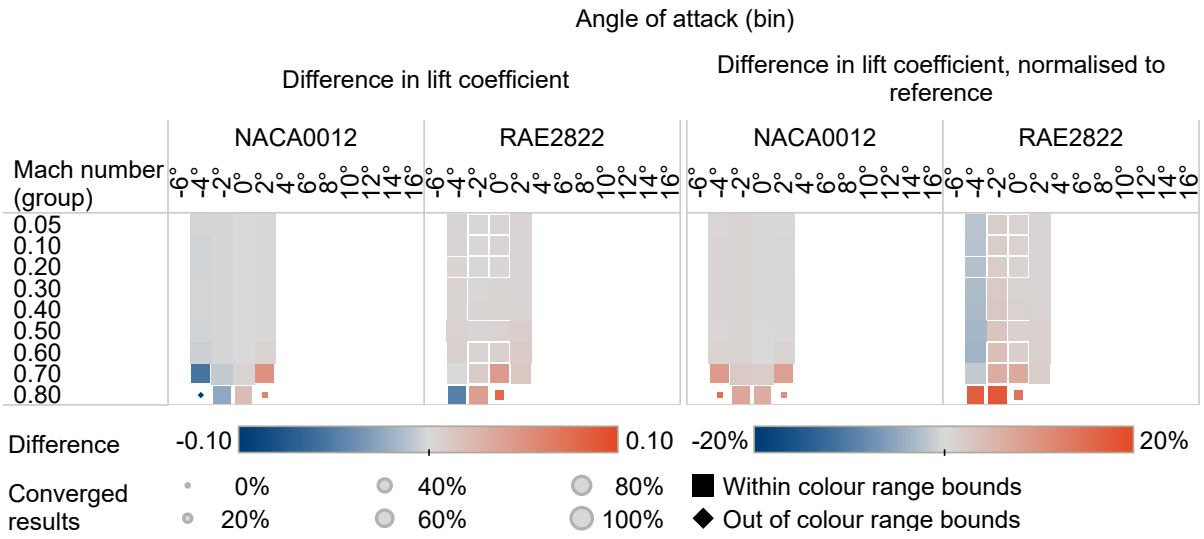


Figure 6.27: Pressure distributions and pitching moment of a NACA0012 airfoil, represented using 250 cosine-spaced coordinate points, computed by a irrotational (VGK) and rotational (MSES) solver, at $\alpha = 2°$ and various Mach numbers

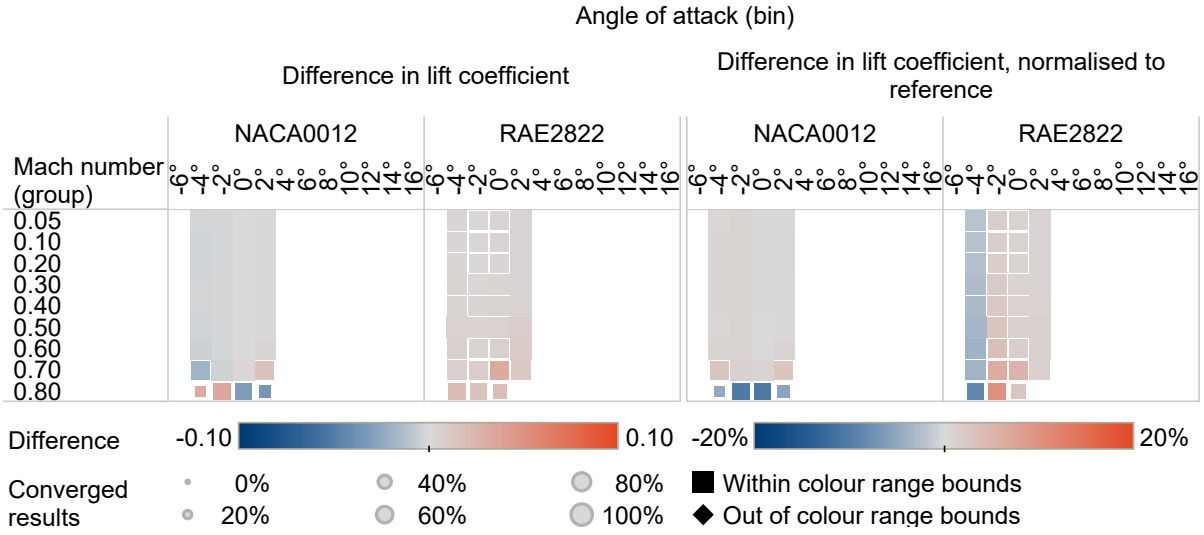
Mass conservation

Similar to the results showing the influence of the incompressible flow assumption, the effect of the irrotational flow assumption is altered when the partially-conservative scheme (VGK) is replaced by a non-conservative (VGK-NC). Figure 6.28 shows the results for both cases. Although most of the figure remains unaffected, the groups of Mach numbers in which the influence of the irrotational flow assumption was established are all different. For $\overline{M_\infty} = 0.70$, the difference is smaller when the rotational result is

compared to the non-conservative scheme, but for the highest Mach number, the situation is reversed. An explanation for this behaviour could not be unambiguously established. It is hypothesised, however, that the non-conservative scheme loses its accuracy at a slightly lower local Mach number than the partially-conservative code.



(a) Partially-conservative (VGK) (repeated from Figure 6.25)



(b) Non-conservative (VGK-NC)

Figure 6.28: Difference between partially-conservative and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

6.3.4. Comparison

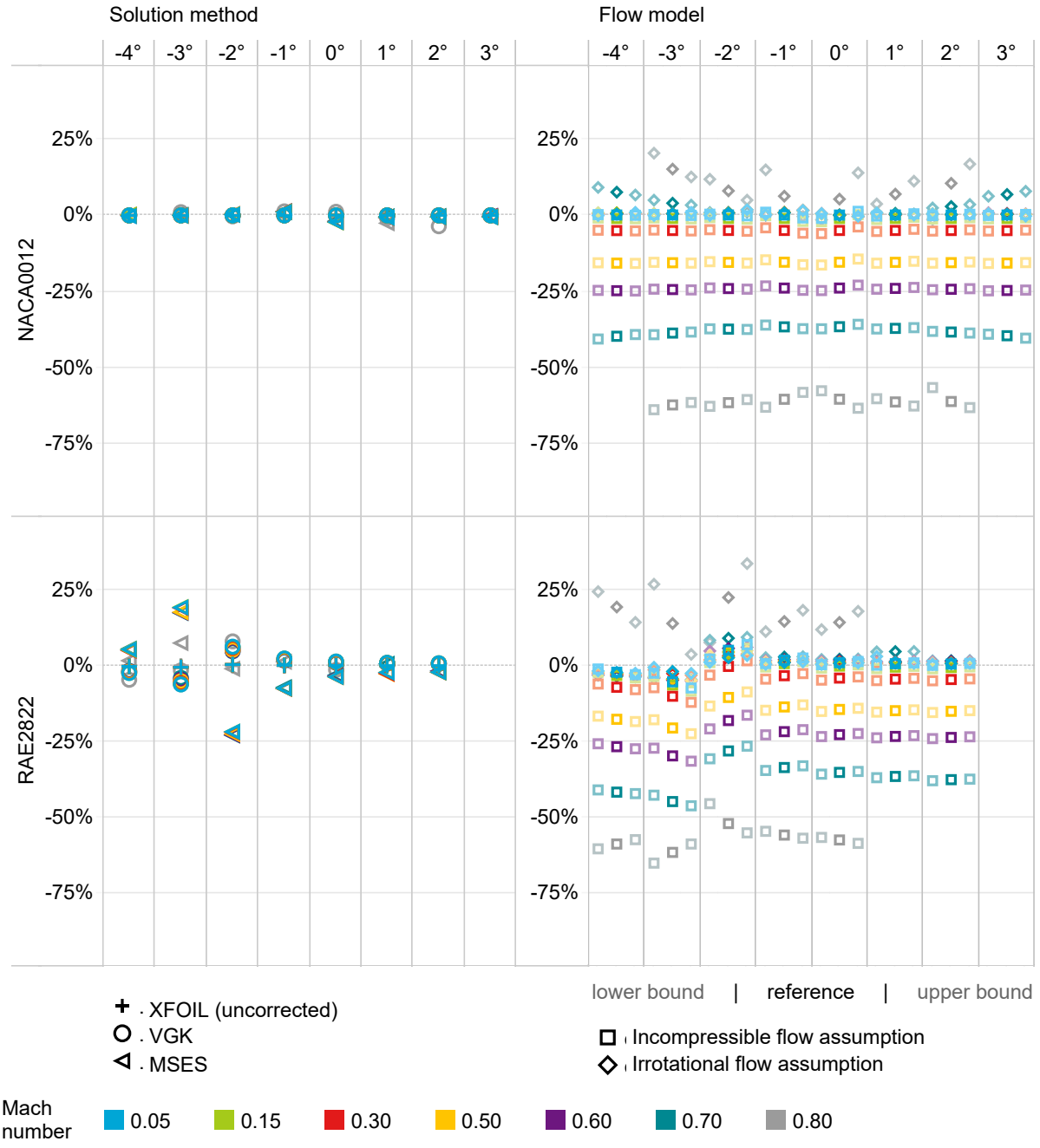
Whereas the previous two sections have analysed the influence of solution method and flow model in isolation, these effects are assessed in combination here. As such, the figures shown in the current chapter summarise the results presented in earlier sections.

Rather than heat maps, scatter plots are used. They show the difference in lift and pitching moment coefficient, normalised to the reference value, for the NACA0012 (top row) and RAE2822 (bottom row) airfoils. The left column shows the influence of the solution method, determined based on the comparison of the reference value with the results of analyses from a particular geometry representation. The columns represent binned angles of attack (limited to $-4° \leq \overline{\alpha} \leq 3°$), the markers indicate the different

solvers and the colours correspond to various (non-binned) Mach numbers. The right column shows the influence of flow model, determined from the pairwise comparison of solvers results. Again, angles of attack are found in the columns, markers indicate the different flow models and colours correspond to the Mach number. Last, the three markers shown in each $\overline{\alpha}$-column correspond to the lower (left-most marker) and upper (rightmost marker) bounds to the reference value, and the reference value itself (middle marker).

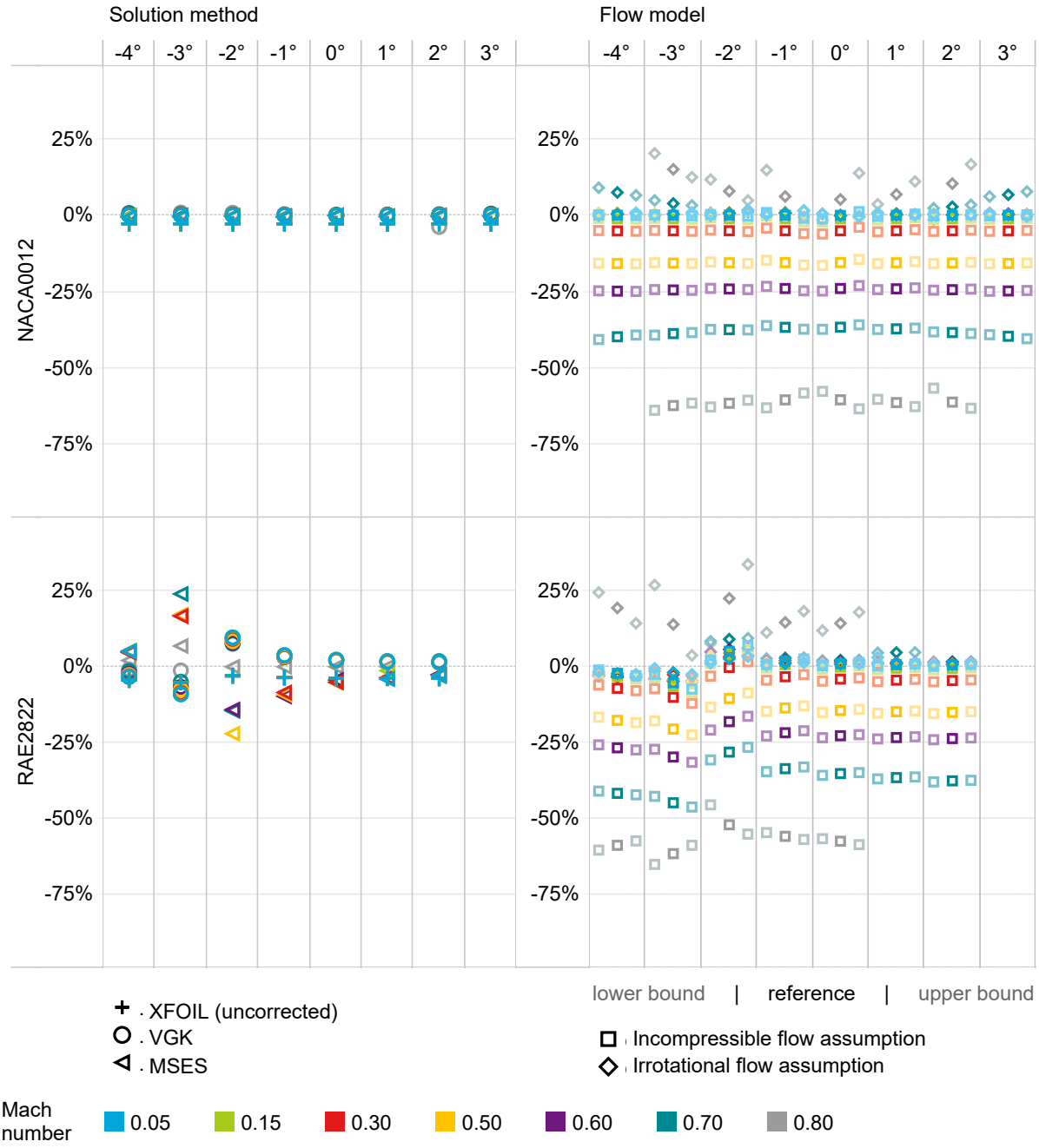
Figure 6.29a and Figure 6.29b show the influence of solution method and flow model on the lift coefficient for airfoils represented using a linear or cosine spacing. Figure 6.30a and Figure 6.30b present the same figure, zoomed in to a smaller range of y-axis values. The right half of the figure is identical in both pairs of figures (as the flow model results are based on reference values independent of the solution method), whereas the left hand is not. This can for example be clearly seen for the NACA0012 results: Figure 6.30b shows a clear solution method influence at $M_\infty = 0.70$ (approximately -2.5%), while Figure 6.30a does not. The top half of the figures also clearly confirm the previously made observation that the influence of the solution method is much lower once Mach numbers increase beyond $M_\infty \approx 0.30$. This is somewhat less so for the RAE2822 shown in the lower half of the graphs, but as the effects can be seen most substantial in cases of low-lift angles of attack, these discrepancies are likely caused by the normalisation procedure. Whereas the flow model impact increases with Mach number and (slightly) with angle of attack, the solution method impact changes little. This is even the case for the linear representation, although the deviation in terms of solution method is higher for that representation than for the cosine distribution. The figures also confirm earlier conclusions that when compared to the influence of the assumptions, the spread between lower and upper bounds is relatively small.

Figure 6.31 and Figure 6.32 show the same figures, but now representing the normalised difference in pitching moment coefficient. For that parameter too, the conclusion that the influence of solution method is lower than the effect of the flow model (given M_∞ > 0.30) holds true, especially at even higher Mach numbers.



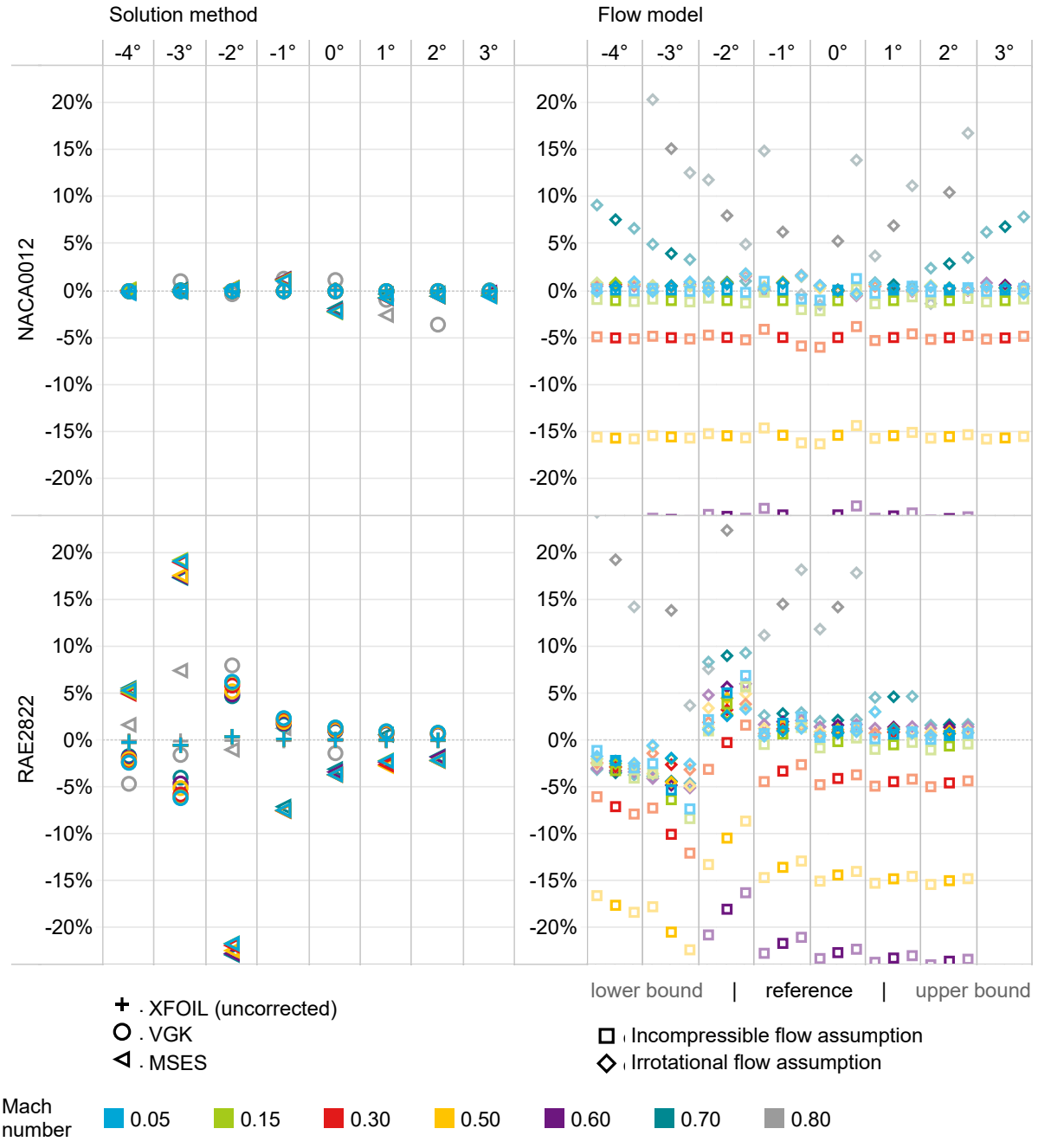
(a) Cosine distribution of coordinate points

Figure 6.29: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representations using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers



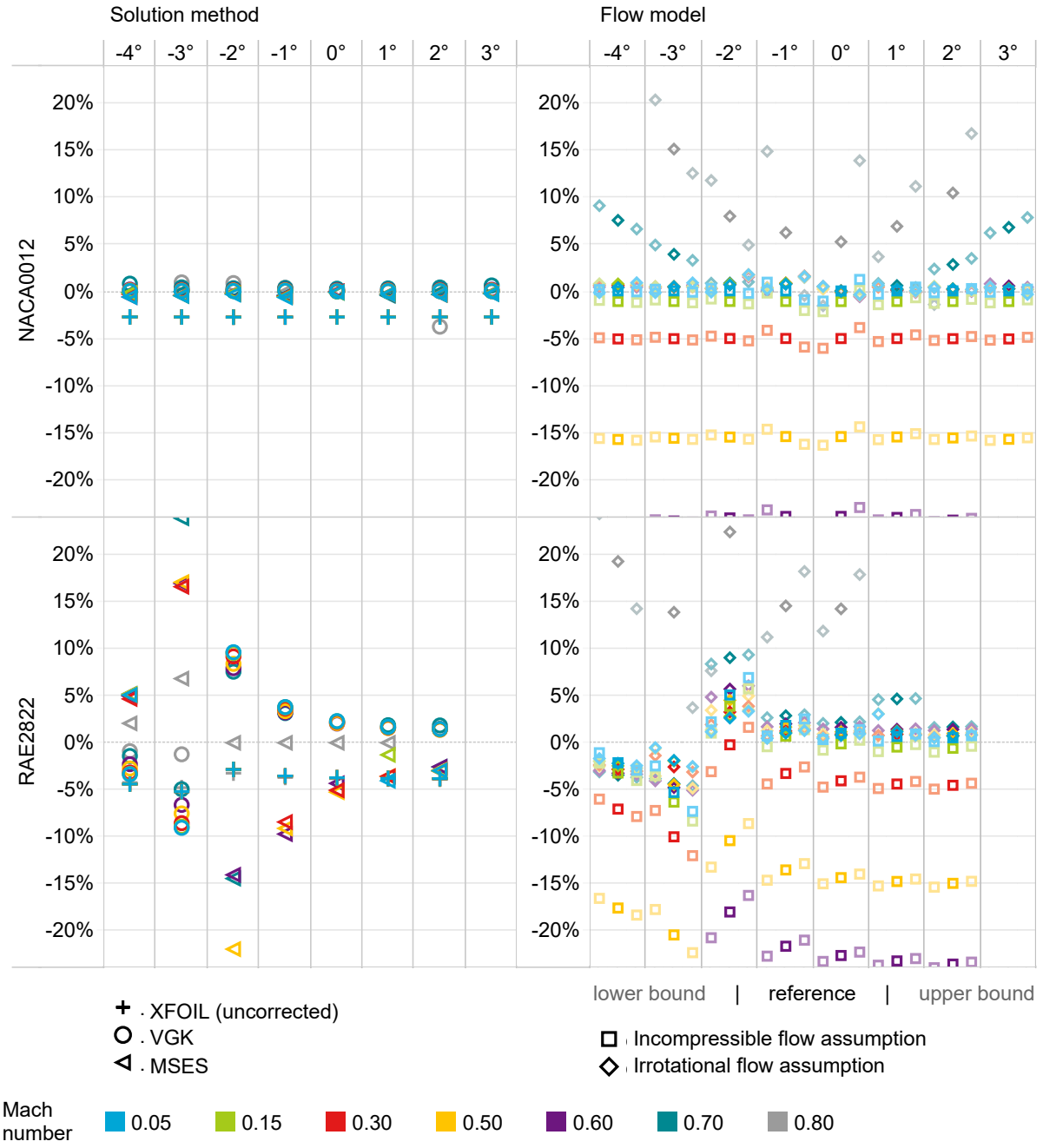
(b) Linear distribution of coordinate points

Figure 6.29: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representations using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers (continued)



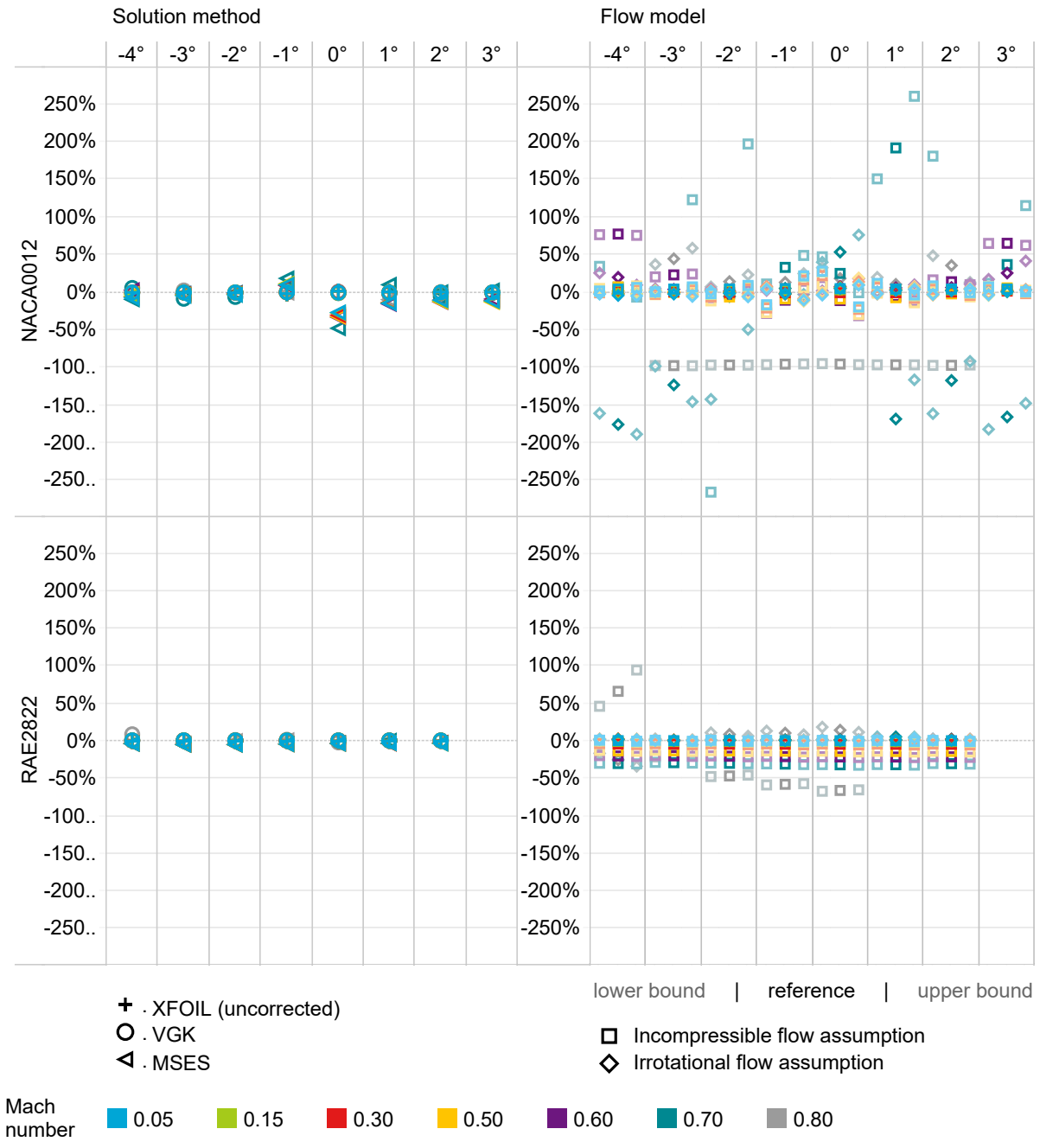
(a) Cosine distribution of coordinate points

Figure 6.30: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representation using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers, zoomed to $\Delta c_l = [-25\%, 25\%]$



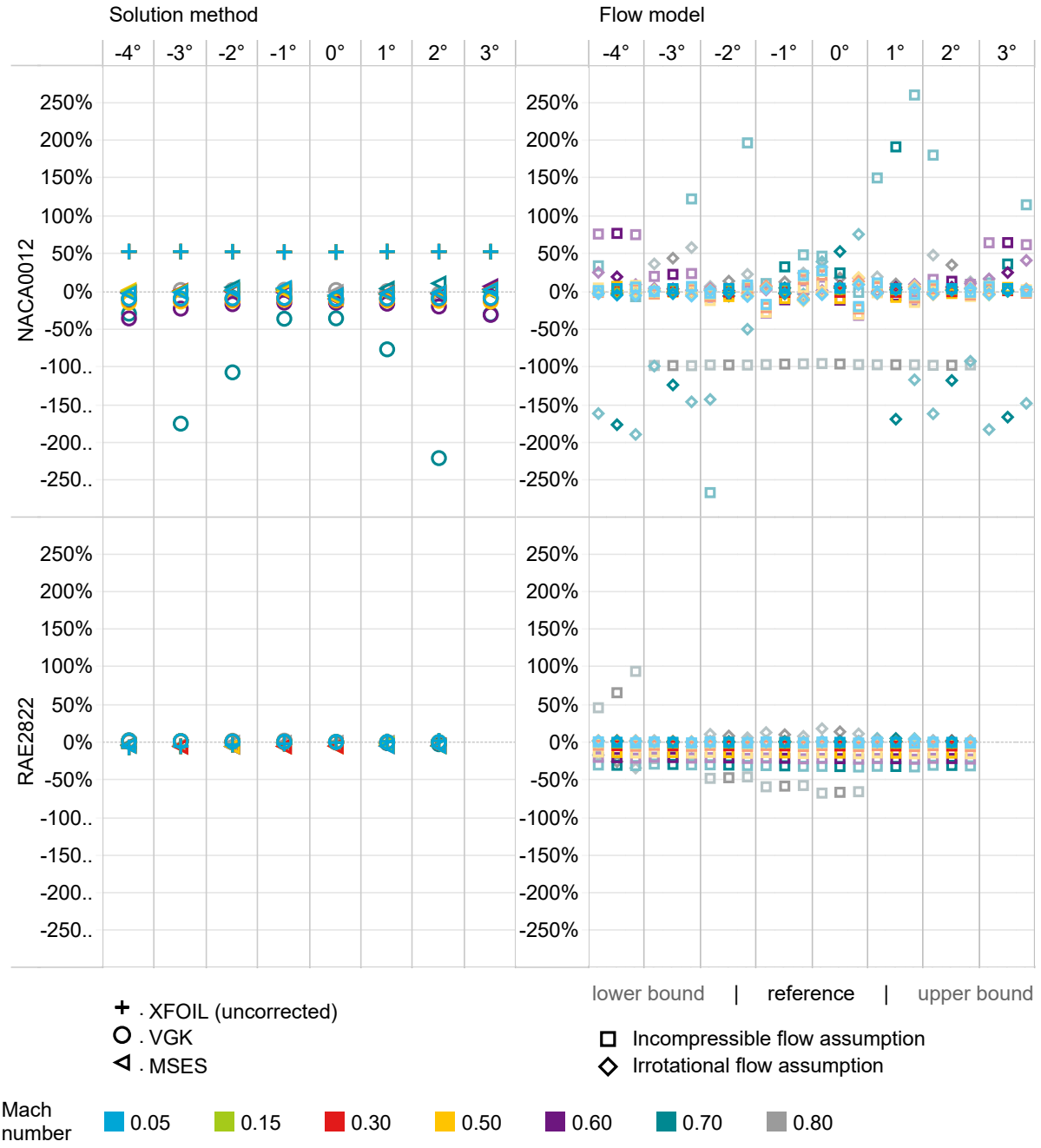
(b) Zoomed in to $\Delta c_l = [-25\%, 25\%]$

Figure 6.30: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representation using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers, zoomed to $\Delta c_l = [-25\%, 25\%]$ (continued)



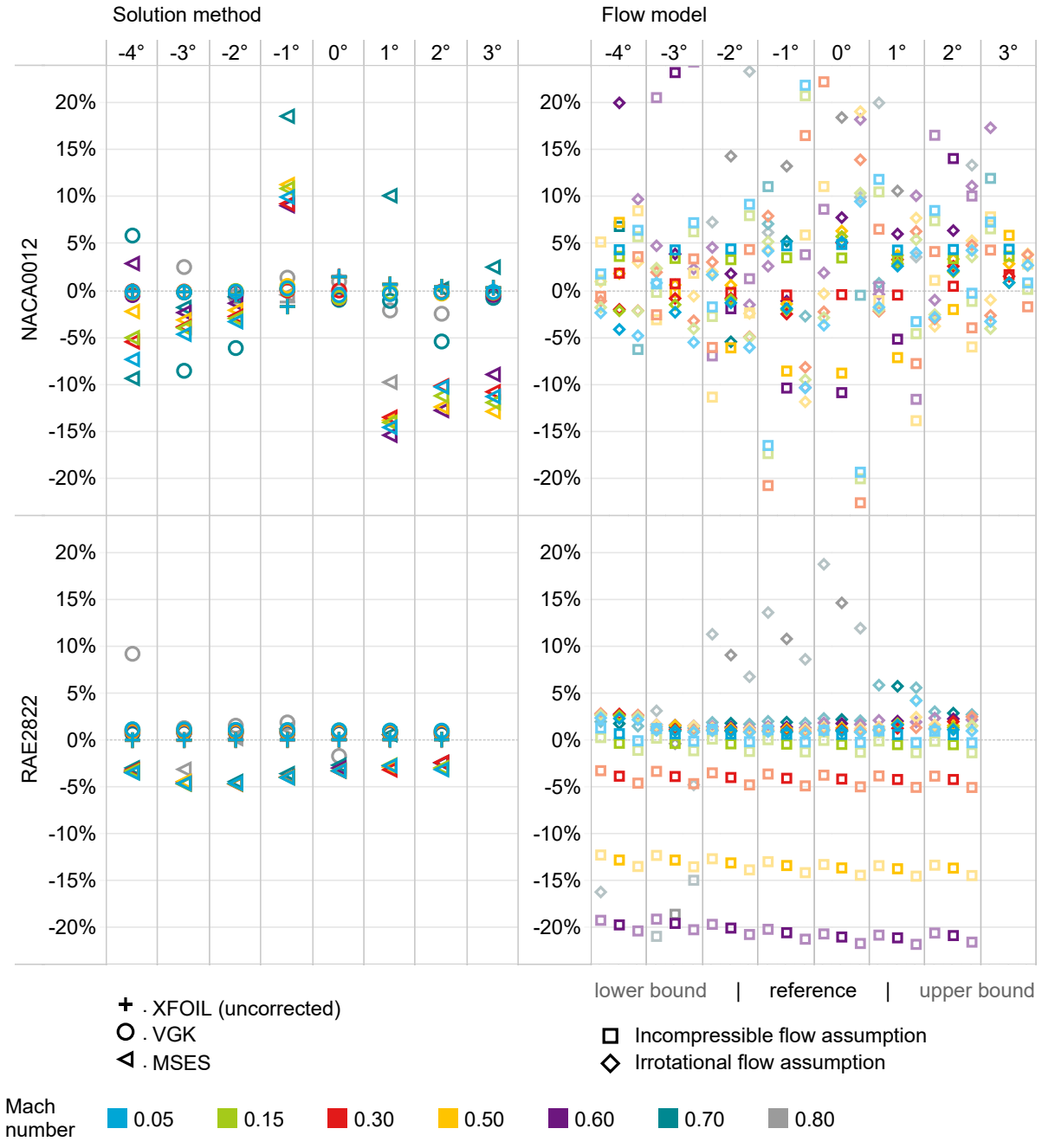
(a) Cosine distribution of coordinate points

Figure 6.31: Difference in pitching moment coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representations using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers



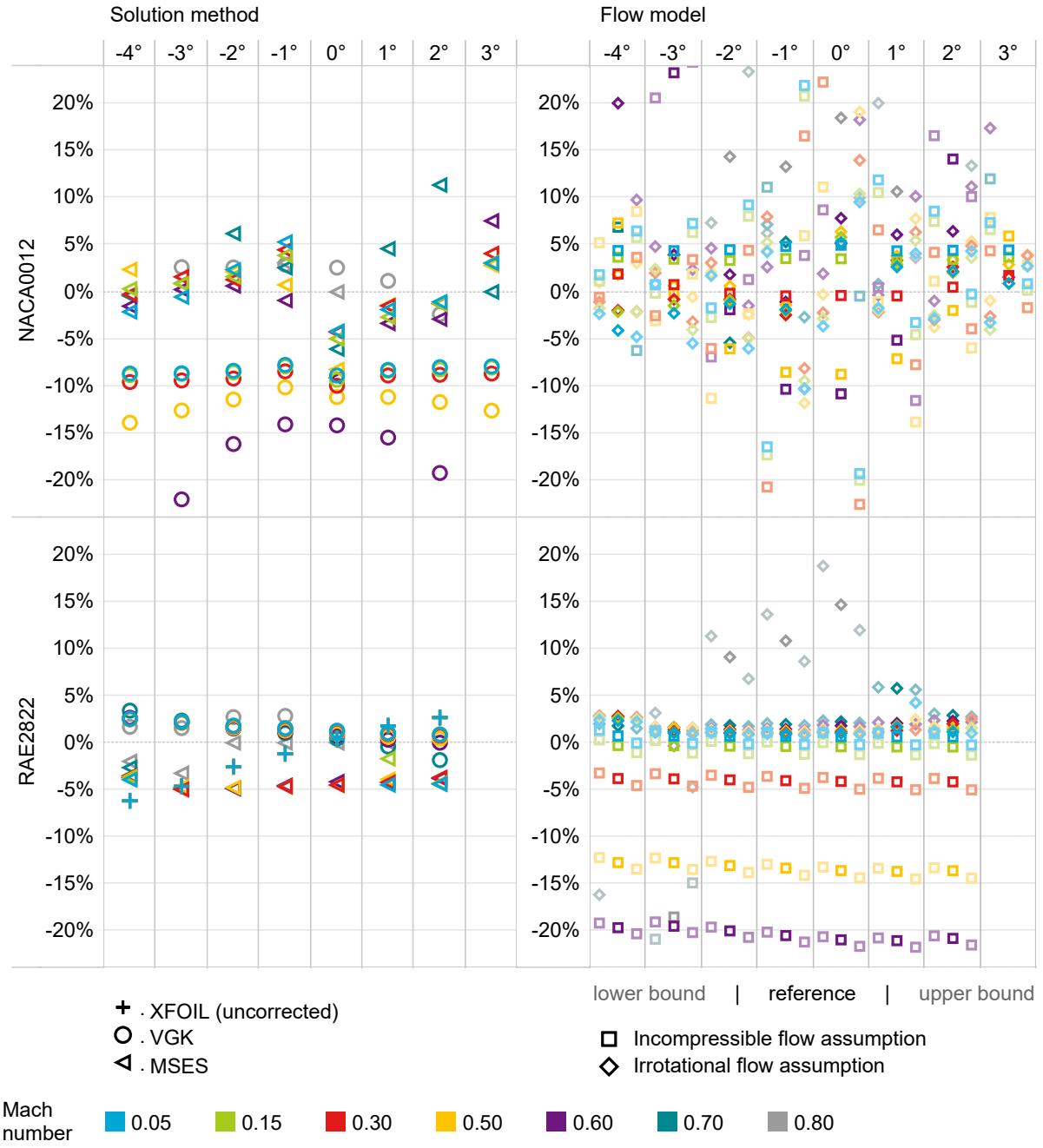
(b) Linear distribution of coordinate points

Figure 6.31: Difference in pitching moment coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representations using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers (continued)



(a) Cosine distribution of coordinate points

Figure 6.32: Difference in pitching moment coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representation using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers, zoomed to $\Delta c_l = [-25\%, 25\%]$



(b) Zoomed in to $\Delta c_l = [-25\%, 25\%]$

Figure 6.32: Difference in pitching moment coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by solution method (reference value compared to cosine and linear representation using 130 coordinate points) and flow model for various (binned) angles of attack and Mach numbers, zoomed to $\Delta c_l = [-25\%, 25\%]$ (continued)

7

Uncertainty propagation

Chapter 6 quantified the influence of solution method and flow model for two different airfoils, a variety of representations (using a diverse amount of coordinate points, distributed in a linear or cosine-fashion), and combinations of Mach number and angle of attack. The current chapter builds upon that analysis and investigates how the uncertainties introduced before affect the higher-level conceptual design process, answering research question I-e: *How do aerodynamic model uncertainties propagate through the Aircraft Design Initiator, thereby (possibly) influencing the output uncertainty?*.

As the impact of the solution method was much lower than that of the flow model, only the latter is assessed. Similarly, only the effect of the irrotational flow assumption as established by comparison of the partially-conservative irrotational flow model (VGK) and the rotational Euler code (MSES) was propagated. Here, too, the difference (following the partially-conservative or non-conservative formulation) was considered too small.

The remainder of this chapter is structured similar to Chapter 6. Section 7.1 outlines the approach and is followed by a more detailed description of the methodology in Section 7.2. The results are subsequently presented in Section 7.3.

7.1. Approach

The current analysis is conducted in two steps and again takes the form of a systematic assessment of the consequences of adjusted input. The effects of the two-dimensional results on three-dimensional wing characteristics are computed first, with the help of AVL, the vortex lattice method described in Section 5.4. Similar to the analyses presented in Chapter 6, these results are then compared with each other. Next, the impact on aircraft-level parameters is assessed using the Aircraft Design Initiator, introduced in Section 5.5. Within each section, solution method and flow model effects are assessed.

Given the fact that moving from airfoils to wings to aircraft greatly enlarges the number of parameters that can be considered, the current analysis is – especially when compared to Chapter 6 – more qualitative in nature.

7.2. Methodology

This section presents in more detail the methodology used to obtain the results presented in Section 7.3. Section 7.2.1 discusses the generation of three-dimensional wing results using AVL; Section 7.2.2 treats the aircraft-level assessment using the Aircraft Design Initiator.

7.2.1. Wing-level analysis

The two-dimensional airfoil data obtained before is coupled to AVL using the built-in lift slope scaling factor, introduced in Section 5.4.1. This scaling factor is multiplied with the default lift slope of 2π (based on thin airfoil theory) and can, for example, be used to account for thickness (Drela and Youngren, 2010, 2017b). The lift slope at an angle of attack α_i is computed from the two-dimensional data using Equation (7.1).

$$\alpha_i = \left(\frac{c_l}{\alpha}\right)_i = \frac{c_{l,i+j^+} - c_{l,i-j^-}}{\alpha_{l,i+j^+} - \alpha_{l,i-j^-}} \tag{7.1}$$

j indicates the size of the domain over which the lift slope is determined and is set to 3. At the limits of the α-range, j^+ and j^- are set to 6 and 0 (or vice versa). If no results are available at $\alpha_{i\pm j}$ (because a solver failed to converge), a seeker algorithm sets $j = j \pm k$ (with $k \in [0, 3]$) in an attempt to find another converged result which can be used as reference point for the lift slope computation.

Various wing geometries are analysed, all shown in Table 7.1 and Figure 7.1. Three straight and two swept wings of different aspect ratios are included, in addition to a 'real-life' example in the form of a wing similar to the one found on the Airbus A320-200. The A320 was selected as it is also the aircraft analysed in the ADI.

Table 7.1: Wing geometries analysed in AVL

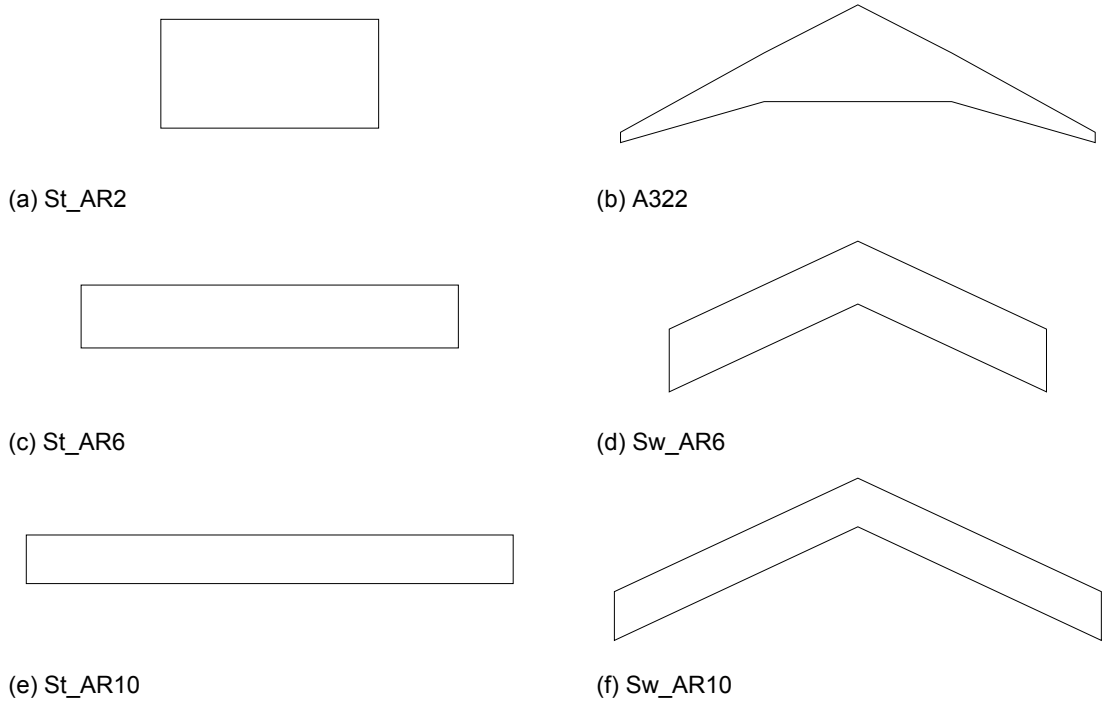
ID	b [m]	S [m^2]	$\mathcal{AR}$ [-]	$\bar{c}$ [m]	$\Lambda_{0.25c}$ [°]	λ [-]	**Remarks**
St_AR2	16.3	133	2	8.16	0	0	
St_AR6	28.3	133	6	4.71	0	0	
St_AR10	36.5	133	10	3.65	0	0	
Sw_AR6	28.3	133	6	4.71	25	0	
Sw_AR10	36.5	133	10	3.65	25	0	
A322	35.6	133	9.5	4.37	33	0.245	Including kink

Due to the fact that wing sweep changes the airfoil section in flow direction as well, the unswept 2D lift slope is scaled with a factor $\cos\Lambda$, based on Equations (7.2) and (7.3) (Obert, 2009, p. 141), and as also done by Mariens (2012) and Mariens et al. (2014) in a comparable study. The subscripts u and s refer to the unswept and swept quantities.

$$c_{l,s} = c_{l,u} \cdot \cos^2\Lambda \tag{7.2}$$

$$\alpha_s = \alpha_u \cdot \cos\Lambda \tag{7.3}$$

In terms of solver settings, the Mach number input to AVL is set to 0 in order to disable its built-in Prandtl-Glauert compressibility correction. Not taking this measure would add an additional compressibility correction on data already stemming from a compressible solver (in case of VGK or MSES), or data that is intentionally incompressible (XFOIL-U). Furthermore, the vortex lattice parameters are kept constant over all cases and are set to identical values as used by the aerodynamic analyses in the Aircraft Design Initiator(which also uses AVL). This means that all geometries are represented using 12 chordwise and 20 spanwise panels, distributed in a cosine fashion. Airfoils are represented by the same set of coordinates used for the coupled two-dimensional analysis. In case of propagation assessment of two- or



(a) St_AR2 (b) A322

(c) St_AR6 (d) Sw_AR6

(e) St_AR10 (f) Sw_AR10

Figure 7.1: Planforms of the wings analysed in AVL

three-dimensional reference values (or their upper and lower bounds), airfoils are represented in AVL using 250 cosine-spaced coordinate points.

As the accuracy of AVL decreases at larger angles of attack – as is the case for any vortex lattice method, given the underlying assumptions of that flow model – the analyses are limited to $|\alpha| \leq 4°$ (Drela and Youngren, 2017b).

Execution and data-analysis were conducted using an extension of the MATLAB-toolkit introduced in Section 6.2.1 and further detailed in Appendix C. In addition to the incompressible and irrotational flow assumptions and correction factors related to the former, the thin airfoil assumption made by AVL was evaluated. This was done to separate the effect of airfoil thickness (not modelled by AVL but present in all two-dimensional data sets) from the other assumptions. These results were obtained by comparing unadjusted ($c_{l,\alpha} = 2\pi$) AVL-results to the set of incompressible two-dimensional results (XFOIL-U).

7.2.2. Aircraft-level analysis

Uncertainty propagation in the Initiator was evaluated qualitatively by adjusting the $c_{l,\alpha}$ scaling input parameter to AVL for the main wing in the analysis of the *DesignCruise*-phase. As indicated in Section 5.5.3, this influences the drag and stability characteristics and associated sizing routines. Comparisons between various sets of AVL-results were used to determine the lift slope scaling parameter necessary to essentially remove or include a particular effect in the Initiator according to Table 7.3.

Subsequently, the results of the cases shown in Table 7.3 were compared in multiple ways to assess the influence of isolated effects on aircraft-level parameters:

- 1 versus 3: influence of thickness
- 2 versus 3 / 3 versus 5: influence of Prandtl-Glauert compressibility correction
- 2 versus 4 / 4 versus 5: influence of Karman-Tsien compressibility correction
- 2 versus 5: influence of incompressible flow assumption
- 5 versus 6: influence of irrotational flow assumption

Table 7.3: Source of lift slope scaling factors for Aircraft Design Initiator

Case	Description	Scaling factor source	Remarks
1	Incompressible flow + Prandtl-Glauert	None	Included by default
2	Incompressible flow + thickness	AVL versus AVL + XFOIL-U	
3	Incompressible flow + Prandtl-Glauert + thickness	AVL versus AVL + XFOIL-PG	Both results include Prandtl-Glauert, XFOIL includes thickness
4	Incompressible flow + Karman-Tsien + thickness	AVL versus AVL + XFOIL-KT	
5	Compressible flow + thickness	AVL versus AVL + VGK	
6	Rotational flow + thickness	AVL versus AVL + MSES	

The analysis was conducted using an aircraft highly similar to the Airbus A320-200, as it is the most accurately represented model available for the Aircraft Design Initiator. A 3D-view of the aircraft as generated by the Aircraft Design Initiator is shown in Figure 7.2.

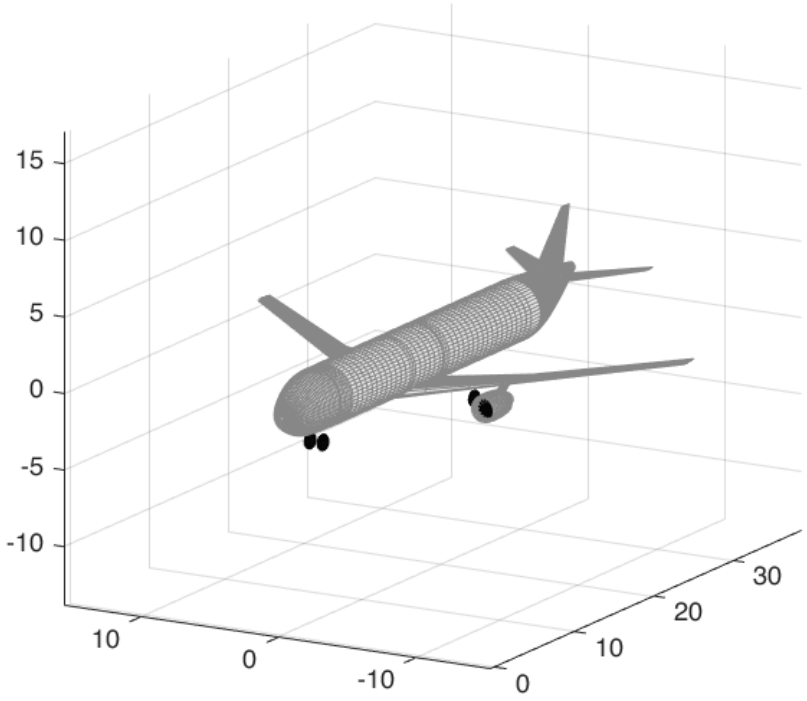


Figure 7.2: Airbus A320-200 geometry as generated by the Aircraft Design Initiator when using a NACA0012 airfoil

7.3. Results

This section shows the results of the uncertainty propagation study: it indicates what the effects of the two-dimensional incompressible and irrotational flow assumption are on a three-dimensional wing (Section 7.3.1) and provides a first estimation of the influence of these assumptions on aircraft level (Section 7.3.2). Results are shown in the form of a true difference as well as a normalised difference. In the

latter case, the true difference is divided by the value for the relevant quantity of interest as computed by the highest-fidelity model considered in the comparison.

7.3.1. Wing-level analysis

The results of the wing-level analysis are presented in this section. Again, the differences observed are shown in heat maps, very similar to the figures shown in the previous chapter: the columns show the true or normalised (with respect to the reference or higher-order result) difference for the two airfoils, rows indicate wing geometry and Mach number, marker size represents the amount of converged results and the colour shows the magnitude and direction of the difference. Diamond-shaped markers indicate the respective difference is outside the range of the colour bar. An important difference with earlier figures is the α-domain. Whereas that previously spanned from $\alpha = -16°$ to $\alpha = 6°$, the current results are only shown for $\alpha = \pm 4°$. Cases in which the $c_{l,\alpha}$ scaling factor exceeded the limits set by AVL ($[0, 2]$, yielding $0 \leq c_{l,\alpha} \leq 4\pi$), resulting in the VLM-code overriding user input and setting the scaling factor to 1, are excluded from the results.

The following pages show and analyse the influence of the incompressible and irrotational flow assumptions. First, however, the impact of the thin airfoil assumption is shown. Following from the fact that AVL does not compute pressure distributions and that no viscous two-dimensional analyses were conducted, the results are limited to the lift and pitching moment coefficients.

Thin airfoil assumption

Figure 7.3 shows the influence of the thin airfoil assumption on the lift coefficient of the NACA0012 and RAE2822, for various (binned) Mach numbers and angles of attack. The vertical axis furthermore shows different wing geometries.

Visual inspection of the results readily indicates the effect is small. This is consistent with the airfoil geometries (having a maximum thickness of 12% and 12.1%) and thin airfoil theory, of which a thickness to chord ratio of 12% is often used as upper bound for applicability. The true (non-normalised) difference is limited to $\Delta C_L = \pm 0.05$. Although the colours are faint, the results of the NACA0012 can indeed be seen to be symmetric in α, most notably in the results corresponding to the straight wings with $\mathit{AR} = 6$ and $\mathit{AR} = 10$, the swept wing with $\mathit{AR} = 10$ and the A322. Also, the sign of the difference (positive at $\overline{\alpha} \leq 0°$; negative at $\overline{\alpha} \geq 0°$) is consistent with theory, indicating that thickness increases the lift slope.

In case of the RAE2822, the (true) differences are negative over all angles of attack analysed. Also, substantial increases are seen in normalised differences for the two lowest $\overline{\alpha}$. Further investigation shows an unexplained offset in the RAE2822 lift curve, which increases with lift slope scaling factor. As Figure 7.4 shows, it seems the lift polars are not rotated around the zero-lift angle of attack, but around a lower value of α. Figure 6.15 (not showing these results) confirms this offset is caused by AVL.

Basing the further assessment of the difference mostly on the NACA0012-results – which do not show the problem shwon in Figure 7.4 – it can be seen that the three-dimensional wing geometry is of little influence. Comparing the results for the first three wings (St_AR2, St_AR6 and St_AR10) shows the true influence increases with aspect ratio, whereas the normalised effect can hardly be seen. This is coherent with theory: a lower aspect ratio decreases the lift slope, and thereby also decreases the (absolute) effect of (relative) correction factors. Comparing wings St_AR6 and St_AR10 with Sw_AR6 and Sw_AR10, respectively, indicates sweep counteracts the changes in lift coefficient – a logical consequence of the simple sweep theory, scaling the lift slope by $\cos\Lambda$. This means that for these swept wings, the effect of thin airfoil theory on the NACA0012 C_L is indiscernible and for the RAE2822 is limited to $\Delta C_L = -0.02$. Based on the A322-wing, it is hypothesised that taper has a similar effect as aspect ratio. Although the A322-wing has an aspect ratio comparable to the most slender of the simple wings ($\mathit{AR} = 9.5$ versus $\mathit{AR} = 10$, respectively) and the largest sweep angle of the set, it shows ΔC_L-values comparable to the ones seen for the straight wing with $\mathit{AR} = 6$.

For most wings, the true differences in pitching moment coefficients are negligible, at values smaller

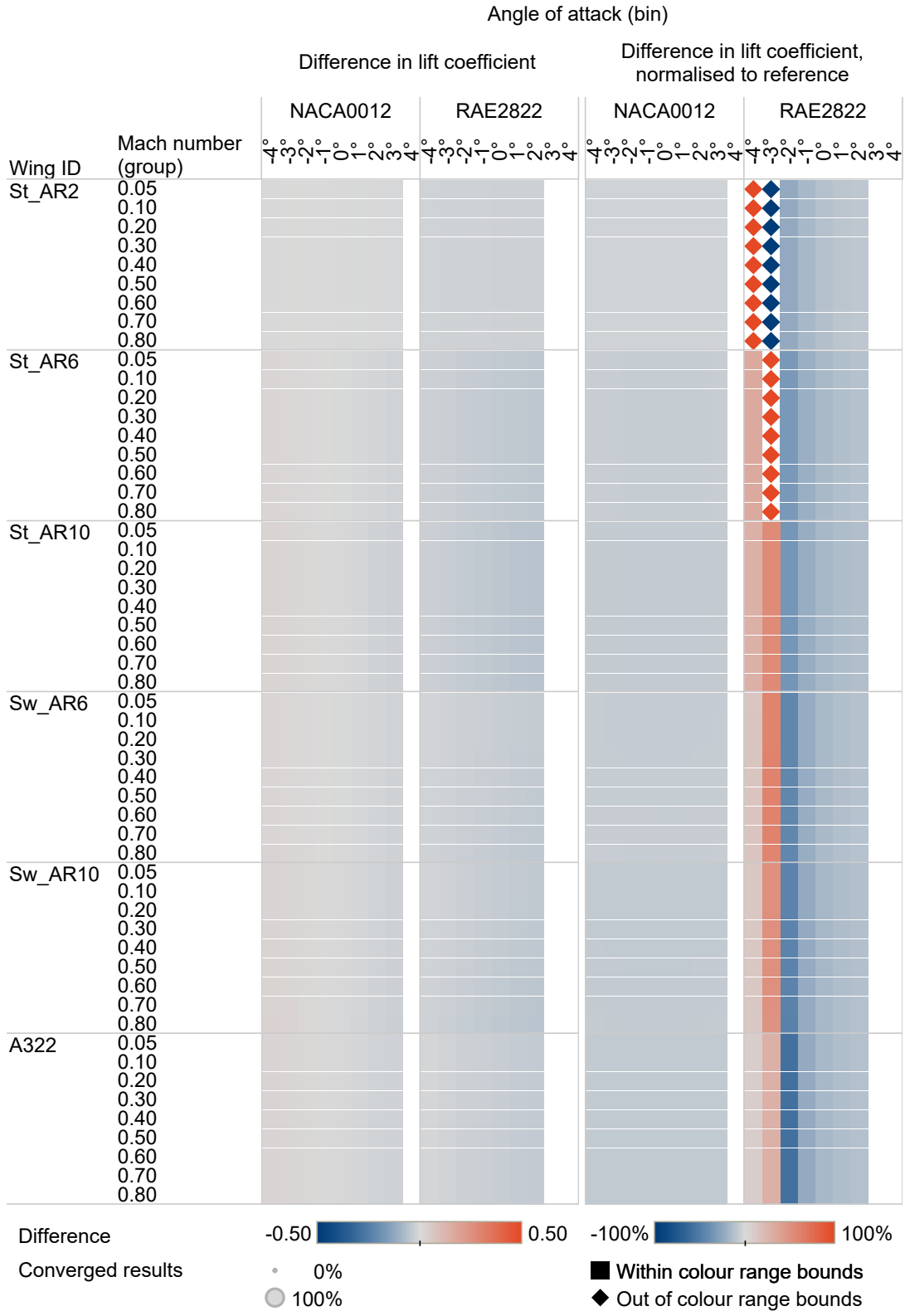


Figure 7.3: Difference in lift coefficient (true and normalised w.r.t. reference) between thin airfoil theory (AVL) and incompressible flow (AVL + XFOIL-U) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

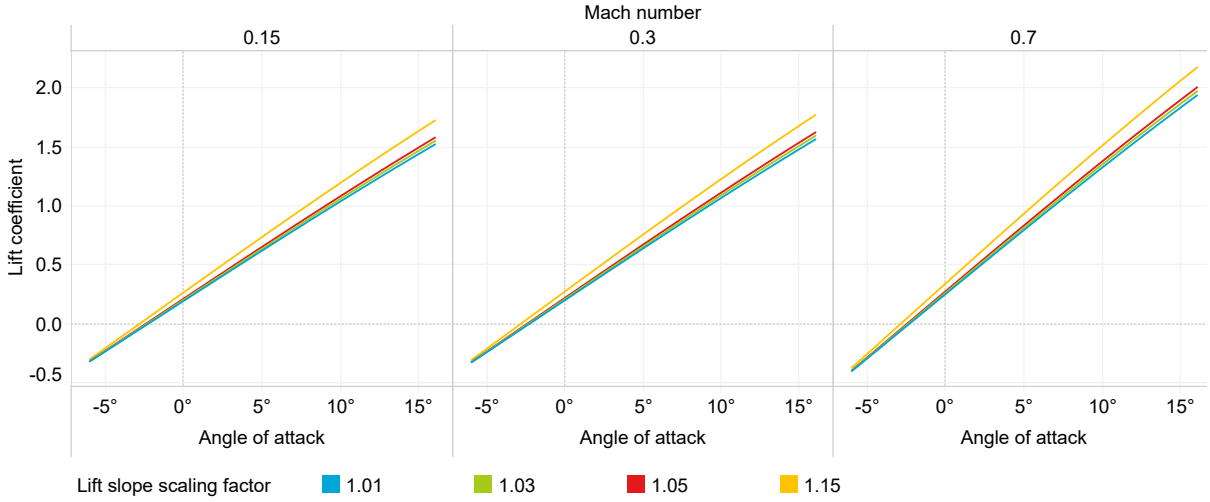


Figure 7.4: Lift polar of the RAE2822 airfoil on a straight wing with aspect ratio 10 for various lift curve slope scaling factors and Mach numbers as computed by AVL, showing the change in zero-lift angle of attack with lift curve slope scaling factor

than $\Delta C_m < 0.01$, although the normalised differences are more substantial. An exception is formed by the most slender swept wing, which shows differences up to $\Delta C_m = -0.2$ (NACA0012) and $\Delta C_m = 0.06$ (RAE2822). In terms of normalised results, assuming a 2π lift slope for a RAE2822-wing yields a discrepancy of approximately -10% for straight wings, growing to about -10% to -20% for swept configurations (neglecting $\overline{\alpha} \approx \alpha_{L=0}$). The situation is more or less reversed when the airfoil is changed to the symmetrical one: results then show a $+10\%$ difference for the three wings with a non-zero sweep angle, whereas the results corresponding to the straight results range from -40% to -80%. These latter values are explained by the low C_m-value and as such should be regarded as a mathematically anomaly rather than a physical effect.

Incompressible flow assumption

Figure 7.5 shows how the uncertainties related to the two-dimensional incompressible flow assumption propagate to the three-dimensional lift coefficient. As the 2D lift slope exceeded 4π at $\overline{M_\infty} = 0.8$, these results are missing from the figure.

The difference between the NACA0012 and RAE2822 geometries is striking – a consequence of the vertical offset in lift polar. The 3D-results of the symmetrical profile are consistent with the 2D-data (see Figure 6.16). Following the observations about the influence of assuming thin airfoil theory, the effects of the incompressible flow assumption increase (in magnitude) with increasing aspect ratio. The influence of sweep is reversed from the previously indicated trend: the influence of assuming constant density on lift coefficient is slightly larger for wing Sw_AR6 than for St_AR6, as well as for Sw_AR10 than for Sw_AR10. The results corresponding to the RAE2822 show this best – although normalisation removes the discrepancies. In the normalised case, neglecting compressibility yields a maximum underestimation of C_L for the NACA0012 between approximately 10% (St_AR2) and 35% (A322).

The (wing) pitching moment is affected in a very similar way. For the three straight wings, the dependence on aspect ratio grows stronger: the (true) influence at $\overline{M_\infty} = 0.70$ and $\overline{\alpha} = -4°$ changes from 0.03 (St_AR2) to 0.07 (St_AR6) to 0.10 (St_AR10) if the wing has a symmetrical cross-section. Of the two untapered swept wings, the most slender one shows the largest difference – reversed in sign from the lower aspect ratio case.

In Figure 7.6, the (Prandtl-Glauert and Karman-Tsien) compressibility corrections can be seen to relatively accurately compensate for the effect of the incompressible flow assumption on three-dimensional lift coefficient. The simplest of the two manages to reduce the differences seen for NACA0012-equipped wings to a maximum of ± 0.06 ($\approx -15\%$) at the highest Mach numbers considered. The Karman-Tsien even reduces these values further, up to (maximum) deviations of only 0.01, corresponding to a nor-

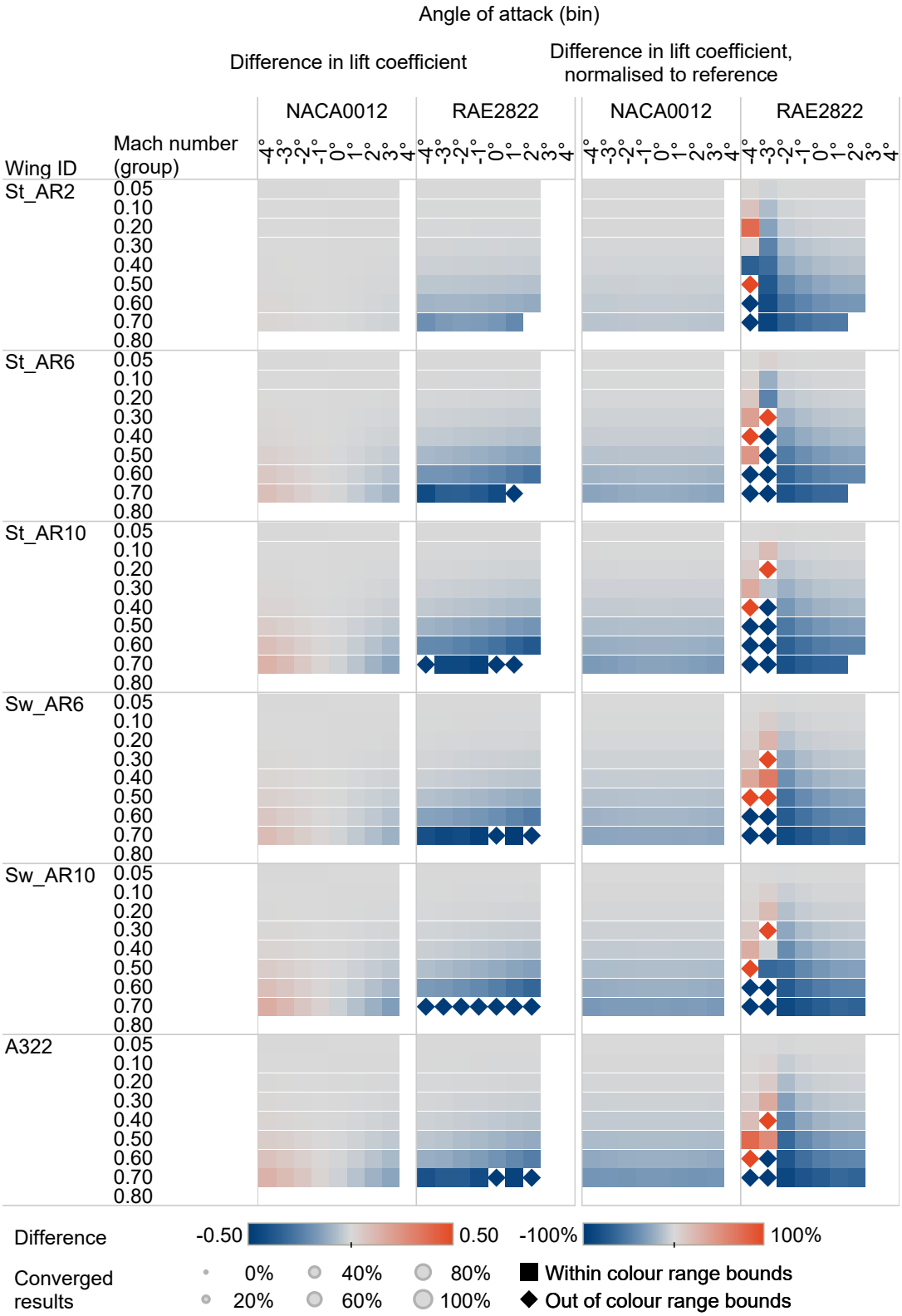


Figure 7.5: Difference between incompressible (XFOIL-U + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

malised difference of just -3%. These results were obtained from the A322-wing. Less complicated geometries show lower differences. When camber is introduced with the RAE2822, the compressibility corrections are somewhat less accurate. The combination of XFOIL-PG and AVL shows C_L-differences growing up to -40% for both the Sw_AR10 as well as the A322-wing. For all geometries, maximum normalised differences (for $\overline{\alpha} > -3°$) are approximately 40%. Applying the Karman-Tsien correction reduces the maximum true and normalised difference by 50% compared to the Prandtl-Glauert equation. The lift curve offset in the right column of the figure is another record of the lift curve offset discussed before.

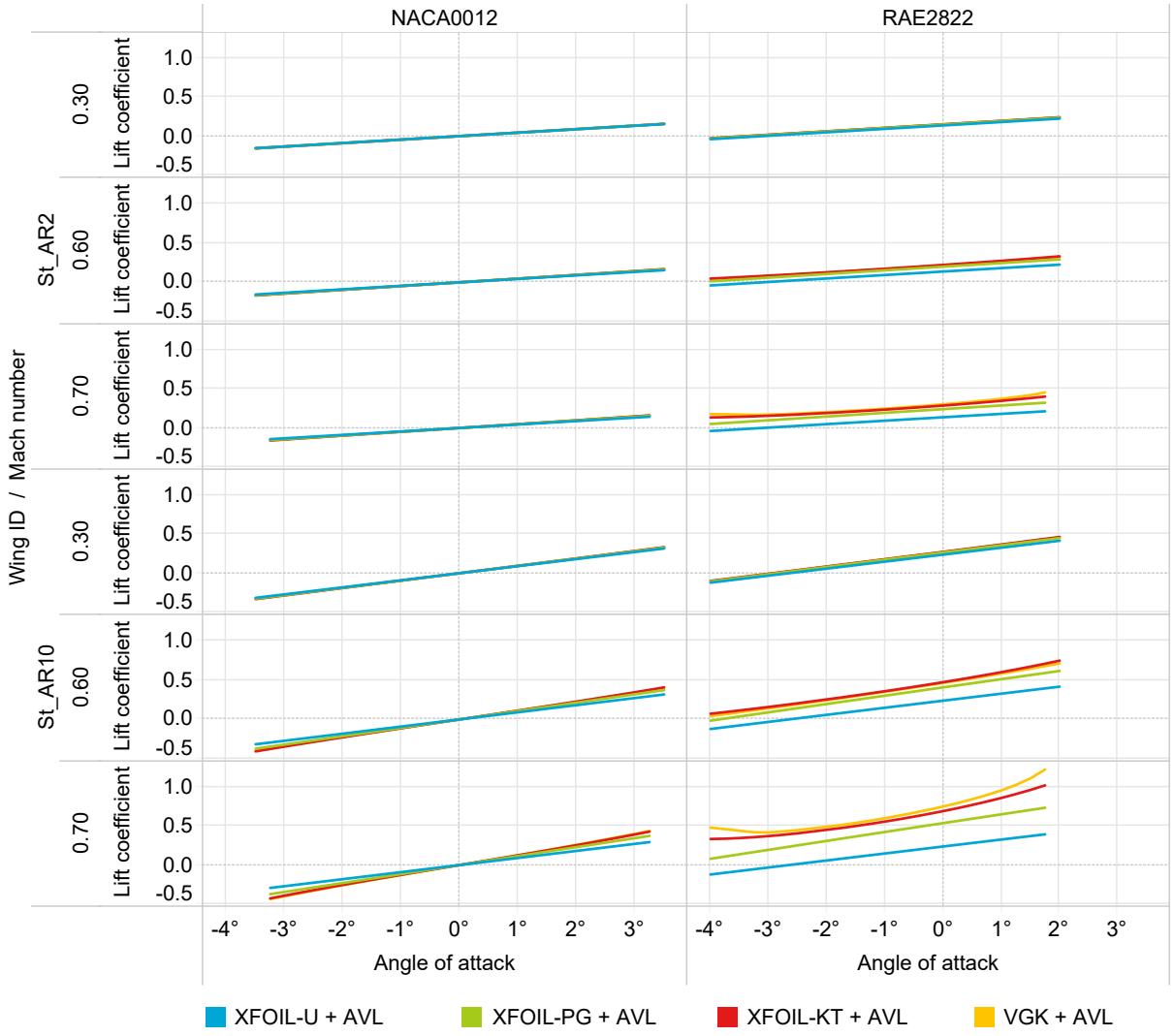


Figure 7.6: Lift coefficients as computed by AVL, coupled to two-dimensional results from (incompressible) XFOIL-U, (Prandtl-Glauert corrected) XFOIL-PG, (Karman-Tsien corrected) XFOIL-KT and (compressible) VGK for different wing and airfoils geometries, Mach numbers and angles of attack

Although the discrepancy between incompressible and compressible results in terms of C_m is also reduced with the application of either of the two compressibility corrections, larger differences remain. For Mach numbers up to $\overline{M_\infty} \approx 0.6$, lower angles of attack and simpler geometries, these are however limited to $\pm 5\%$.

Irrotational flow assumption

The influence of the irrotational flow assumption on the three-dimensional lift coefficient is shown in Figure 7.7. Consistent with the results of the assessment of the effect in two dimensions, the impact of the assumption is best observed at the highest Mach number. Given results presented in the previous

chapter, the impact at $\overline{M_\infty} = 0.8$ – excluded in Figure 7.7 due to exceeding the limits set on the lift slope scaling factor – is likely to be higher. The results closely correspond to those observed in the sections: the effects are amplified by aspect ratio and (slightly) by sweep. The results indicate the influence is somewhat larger for the supercritical airfoil than for the symmetrical profile (maximum $|\Delta C_L|$ are 0.11 and 0.06, respectively, for the the unswept wings considered), although at least part of this difference will be caused by the C_L-offset. Maximum normalised differences for the NACA0012 are at most 18% (Sw_-AR10, $\overline{\alpha} = -4°$) to 19% (A322, $\overline{\alpha} = -4°$). Below $\overline{M_\infty} = 0.6$, the irrotational and rotational flow model yield lift coefficient predictions for these wings coupled to the symmetrical profile that are less than 2% apart.

The relation with angle of attack, slightly visible in Figure 7.7, is more evident when the influence on the pitching moment coefficient is observed. For the straight wing with $\mathit{AR} = 10$, coupled to the symmetrical profile, the normalised difference in C_m at $\overline{M_\infty} = 0.70$ and $\overline{\alpha} = -4°$ is as high as 88%, whereas it is only 13% at $\overline{\alpha} = -2°$. At lower Mach numbers, and especially in a small range around the zero lift angle of attack, the influence of the irrotational flow assumption of the pitching moment coefficient is limited to 5%: a substantially higher value than found for C_L, but nonetheless small-scale.

Comparison

The graphs shown in Figure 7.8a and Figure 7.8b summarise the results presented in this section. They are similar to the figures shown at the end of the previous chapter, but now only concern the influence of flow model (rather than flow model and solution method), display the results of the two airfoils in different columns (rather than rows) and include multiple planforms (on the y-axis). Also. the thin airfoil assumption has been added to the comparison.

The magnitudes displayed are clearly smaller than those for the purely two-dimensional results, in which axis limits ranged from -100% to $+50\%$. This is largely due to the exclusion of the results for $\overline{M_\infty} = 0.80$: the influence of the incompressible flow assumption on the lift coefficient of a NACA0012 airfoil or a NACA0012-equipped wing with $\mathit{AR} = 10$ are very much alike, at approximately -35%.

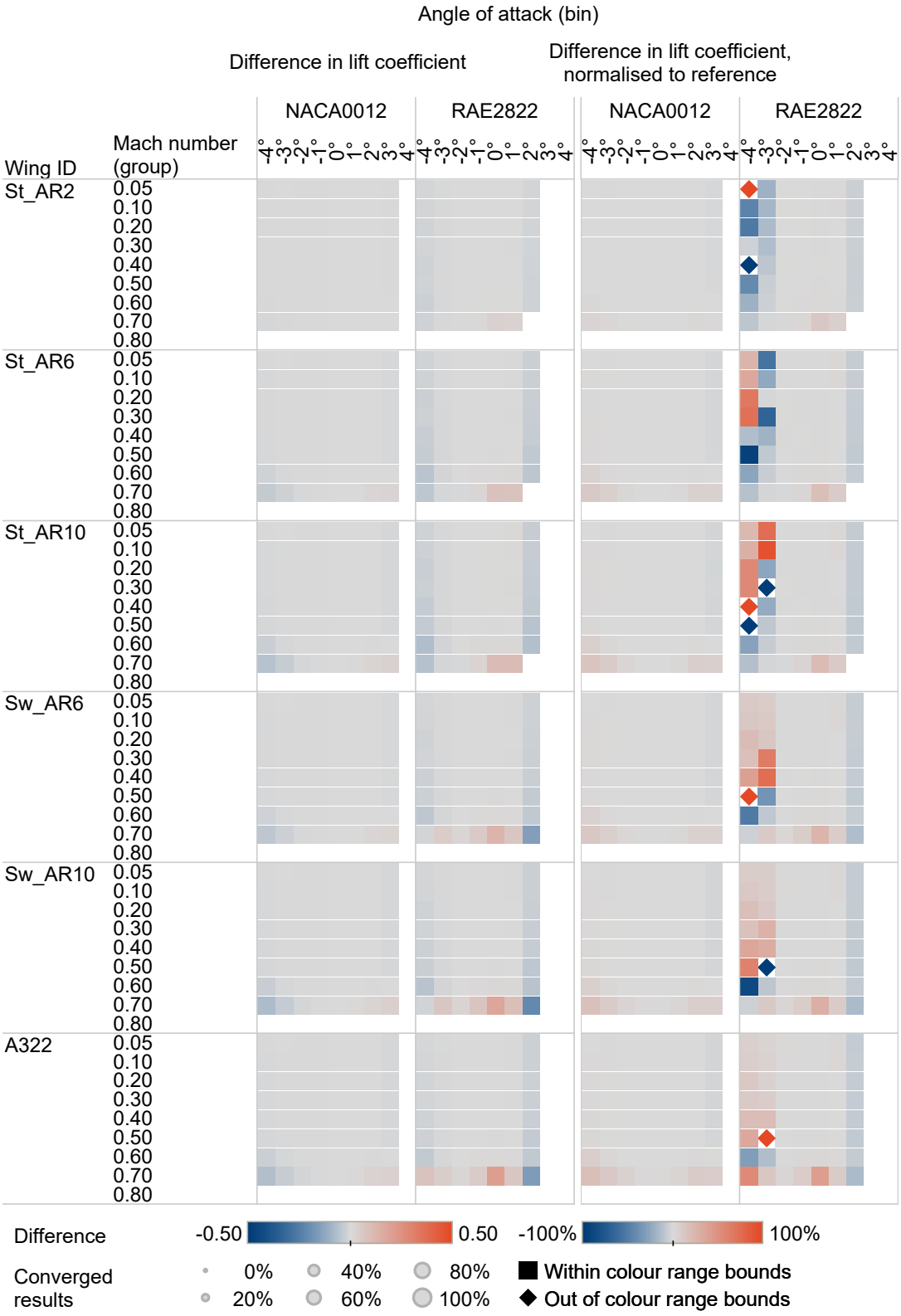


Figure 7.7: Difference between irrotational (VGK + AVL) and rotational (MSES + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack



(a) Straight wings

Figure 7.8: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by flow model for various wings, angles of attack and Mach numbers



(b) Swept wings

Figure 7.8: Difference in lift coefficient (normalised w.r.t. reference) of NACA0012 and RAE2822 geometries, caused by flow model for various wings, angles of attack and Mach numbers (continued)

7.3.2. Aircraft-level analysis

The results just presented provide an indication of how uncertainties of two-dimensional flow assumption propagate to a three-dimensional scenario. Figure 7.9 shows the results of the six cases defined in Table 7.3 for the A322-wing and $\overline{M_\infty} \geq 0.5$, used to determine the applicable lift slope correction factors for use in the ADI. Note that, different from other heat maps shown in this chapter, the results are normalised with respect to the result, i.e., 'clean' AVL. The column headings shown in Figure 7.9a and legends in Figure 7.9e are applicable to all visualisations.

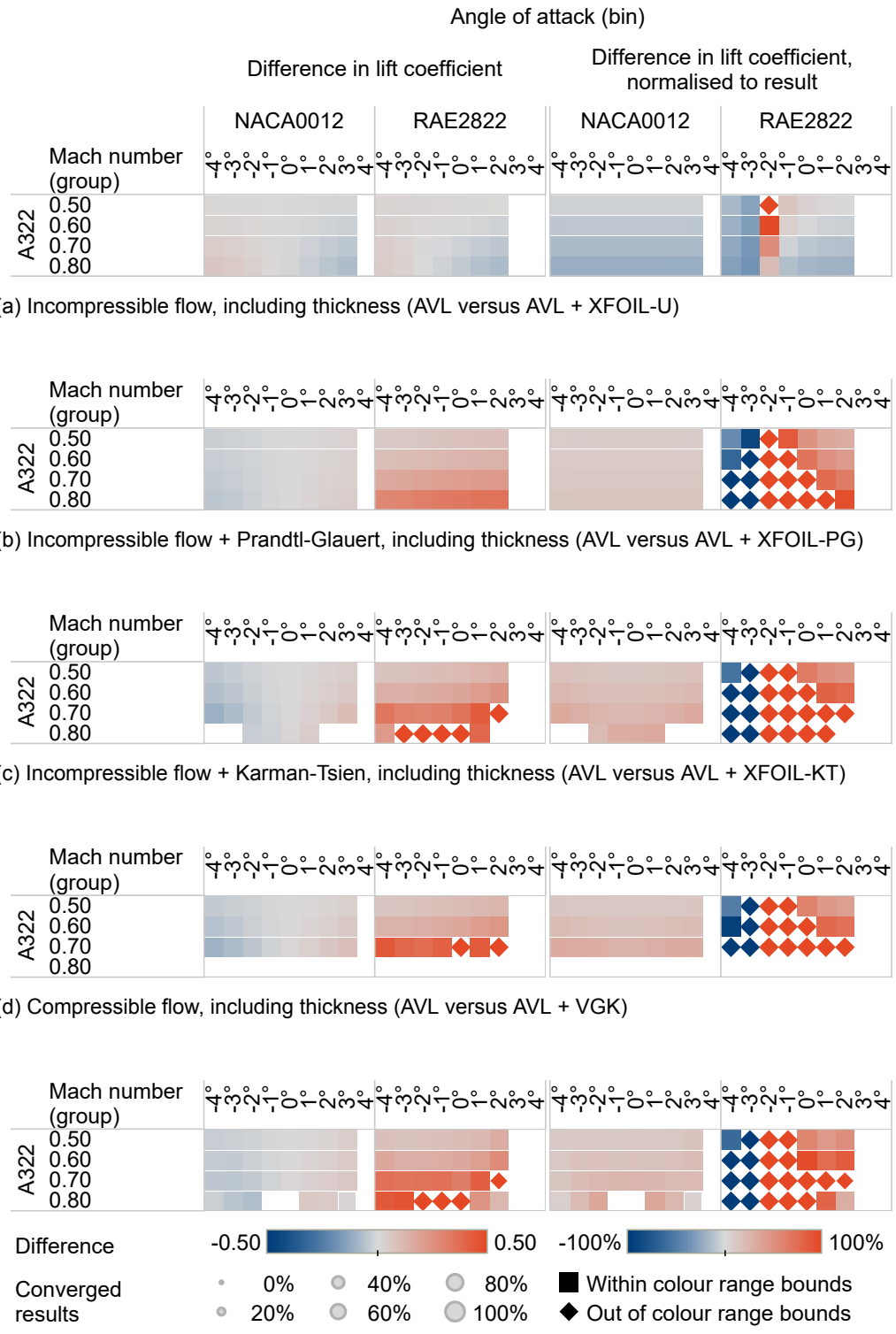
As the (normalised) differences observed for the supercritical profile are considerably larger than those for the symmetrical airfoil (up to ten-fold, in the normalised case), only the latter are used in the further analysis. As such, Table 7.5 shows the ranges of relevant $c_{l,\alpha}$ scaling factors for each of the cases. The values closest to 1 generally correspond to the lowest Mach number group, whereas the values largest in magnitude were obtained from $\overline{M_\infty} = 0.80$ or 0.70.

Table 7.5: Ranges of lift slope scaling factors for the Aircraft Design Initiator

Case	Description	Figure	Minimum	Maximum	Remarks
1	Incompressible flow + Prandtl-Glauert	–	1.00	1.00	
2	Incompressible flow + thickness	7.9a	0.78	0.97	
3	Incompressible flow + Prandtl-Glauert + thickness	7.9b	1.10	1.15	
4	Incompressible flow + Karman-Tsien + thickness	7.9c	1.14	1.35	
5	Compressible flow + thickness	7.9d	1.12	1.34	Maximum from $\overline{M_\infty} = 0.80$
6	Rotational flow + thickness	7.9e	1.06	1.36	

Based on these ranges of the $c_{l,\alpha}$-scaling factor, the results shown in Table 7.7 and Table 7.8 – normalised to the reference data – were obtained. Of all output generated by the Initiator, only a subset is included. These are the main aircraft-level performance parameters (first group), relevant system masses (second group), aerodynamic coefficients (third group) and wing and stabiliser dimensions (fourth group). The parameters shown were selected based on their susceptibility to the influence of the lift slope gradient, or the lack thereof – opposing expectations.

Whereas Table 7.7 shows the results obtained from the aircraft using NACA0012 airfoils, the data in Table 7.8 was found by analysing an aircraft with RAE2822 airfoils, extrapolating the NACA0012-based scaling factors for use with the supercritical airfoil. Given that the previously presented two-dimensional results (Figure 6.16 and Figure 6.25) indicated little difference between the two, as well as the qualitative nature of the current research part, this extension was permitted.



(a) Incompressible flow, including thickness (AVL versus AVL + XFOIL-U)

(b) Incompressible flow + Prandtl-Glauert, including thickness (AVL versus AVL + XFOIL-PG)

(c) Incompressible flow + Karman-Tsien, including thickness (AVL versus AVL + XFOIL-KT)

(d) Compressible flow, including thickness (AVL versus AVL + VGK)

(e) Rotational flow, including thickness (AVL versus AVL + MSES)

Figure 7.9: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Table 7.7: Variation in aircraft-level design and performance parameters on A320 aircraft with NACA0012 airfoils for different $c_{l,\alpha}$-scaling factors, corresponding to the influence of flow model differences

Parameter	Reference	Unit	0.75	0.85	0.90	0.95	0.97	1.03	1.05	1.10	1.15	1.25	1.35	1.50
Maximum take-off mass	61 350	kg	0.03%	−0.08%	0.65%	1.08%	0.26%	0.65%	0.62%	0.65%	0.26%	−0.10%	0.37%	0.37%
Operational empty mass	31 058	kg	0.04%	−0.21%	1.10%	1.81%	0.38%	1.11%	1.07%	1.11%	0.44%	−0.20%	0.58%	0.67%
Total fuel mass	9750	kg	0.10%	0.21%	0.72%	1.13%	0.51%	0.62%	0.62%	0.62%	0.31%	0.10%	0.51%	0.31%
Main wing mass	564	kg	0.00%	−0.53%	0.00%	0.35%	−0.53%	0.18%	0.00%	0.18%	−0.35%	−0.35%	−0.35%	−0.18%
Horizontal stabiliser mass	5619	kg	0.39%	−1.23%	4.79%	8.19%	1.74%	4.89%	5.36%	5.82%	2.08%	−0.62%	2.92%	2.95%
Vertical stabiliser mass	242	kg	−0.41%	−0.41%	0.00%	0.41%	−0.41%	0.00%	−0.41%	0.00%	0.00%	0.00%	0.00%	−0.41%
Neutral point, x-axis	19.7	m	3.05%	2.03%	1.02%	0.51%	0.51%	−0.51%	−0.51%	−1.02%	−1.52%	−2.54%	−3.55%	−4.57%
$C_{L,\text{cruise}}$	0.67	–	0.00%	1.49%	0.00%	0.00%	1.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
$C_{D,\text{cruise}}$	411	cts	1.70%	0.97%	0.24%	−0.24%	0.00%	−0.24%	−0.24%	−0.24%	0.00%	0.00%	0.73%	1.70%
L/D_{cruise}	16.4	–	−1.83%	−0.61%	0.00%	0.00%	0.00%	0.61%	0.61%	0.61%	0.00%	0.00%	−0.61%	−1.83%
$C_{D_0,\text{clean}}$	235	cts	−0.85%	−0.43%	−0.85%	−0.85%	−0.43%	−0.43%	−0.43%	0.00%	0.43%	0.85%	0.85%	0.85%
e_{clean}	0.784	–	−3.83%	−2.04%	−1.15%	−0.38%	−0.13%	0.64%	0.38%	0.51%	0.51%	0.89%	−0.13%	−1.53%
$e_{\text{take-off}}$	0.834	–	−3.60%	−1.92%	−1.08%	−0.36%	−0.12%	0.60%	0.36%	0.48%	0.48%	0.84%	−0.12%	−1.44%
e_{landing}	0.884	–	−3.39%	−1.81%	−1.02%	−0.34%	−0.11%	0.57%	0.34%	0.45%	0.45%	0.79%	−0.11%	−1.36%
$C_{L,\alpha}$	5.96	rad^{-1}	−17.11%	−10.07%	−6.71%	−3.36%	−2.01%	1.85%	3.02%	6.21%	9.23%	15.10%	20.47%	28.36%
$C_{m,\alpha}$	−2.89	rad^{-1}	8.30%	5.54%	2.77%	0.69%	0.35%	−2.42%	−3.81%	−5.88%	−7.61%	−12.11%	−19.03%	−29.76%
Wing area	30.9	m^2	0.00%	0.00%	0.32%	0.65%	0.32%	0.32%	0.32%	0.32%	0.32%	0.00%	0.32%	0.32%
Wing span	92.12	m	0.03%	−0.13%	0.69%	1.14%	0.24%	0.71%	0.67%	0.71%	0.28%	−0.13%	0.37%	0.42%
Horizontal stabiliser area	10.1	m^2	0.00%	0.00%	0.00%	0.99%	0.00%	0.00%	0.99%	0.99%	0.00%	0.00%	0.00%	0.00%
Horizontal stabiliser span	20.53	m	0.24%	−0.05%	0.29%	0.49%	0.05%	0.34%	0.39%	0.44%	0.05%	−0.05%	0.10%	0.19%
Vertical stabiliser area	4.41	m^2	−0.23%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	−1.13%
Vertical stabiliser span	11.6	m	−0.34%	−0.09%	0.26%	0.43%	0.00%	0.26%	0.09%	0.09%	0.09%	0.00%	0.09%	1.81%
Vertical stabiliser tip chord	0.947	m	−0.21%	−0.11%	0.11%	0.21%	−0.11%	0.11%	0.00%	0.00%	0.00%	0.00%	0.00%	16.16%
Vertical stabiliser taper ratio	0.219	m	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	15.98%

Table 7.8: Variation in aircraft-level design and performance parameters on A320 aircraft with RAE2822 airfoils for different $c_{l,\alpha}$-scaling factors, corresponding to the influence of flow model differences

Parameter	Reference	Unit	0.75	0.85	0.90	0.95	0.97	1.03	1.05	1.10	1.15	1.25	1.35	1.50
Maximum take-off mass	62 500	kg	−0.34%	0.14%	0.43%	0.13%	0.26%	0.18%	0.29%	0.24%	0.98%	0.24%	0.34%	0.30%
Operational empty mass	32 022	kg	−0.56%	0.24%	0.68%	0.25%	0.53%	0.31%	0.48%	0.45%	1.63%	0.47%	0.57%	0.52%
Total fuel mass	9940	kg	−0.30%	0.10%	0.50%	0.00%	−0.10%	0.10%	0.30%	0.10%	0.91%	0.00%	0.30%	0.20%
Main wing mass	672	kg	0.15%	0.00%	0.15%	0.00%	0.45%	0.30%	0.00%	0.15%	0.30%	0.30%	−0.15%	0.30%
Horizontal stabiliser mass	6025	kg	−1.58%	1.79%	3.14%	1.13%	2.24%	1.10%	1.83%	1.64%	6.41%	1.43%	2.17%	2.39%
Vertical stabiliser mass	241	kg	0.00%	0.41%	0.41%	2.07%	0.83%	0.83%	0.00%	0.41%	0.41%	2.49%	0.00%	0.00%
Neutral point, x-axis	19.7	m	3.55%	2.03%	1.02%	0.51%	0.51%	−0.51%	−0.51%	−1.52%	−2.03%	−3.05%	−4.06%	−5.08%
$C_{L,\text{cruise}}$	0.67	–	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
$C_{D,\text{cruise}}$	411	cts	1.95%	0.97%	0.49%	0.24%	−0.24%	−0.49%	−0.49%	−0.97%	−1.22%	−1.70%	−2.43%	−2.92%
L/D_{cruise}	16.4	–	−1.83%	−0.61%	0.00%	0.00%	0.61%	0.61%	0.61%	1.22%	1.22%	1.83%	2.44%	3.05%
$C_{D_0,\text{clean}}$	237	cts	−1.27%	−0.84%	−0.84%	−0.42%	−0.42%	0.00%	0.00%	0.42%	0.00%	0.84%	0.84%	1.27%
e_{clean}	0.789	–	−4.69%	−2.41%	−1.39%	−0.63%	0.13%	0.76%	0.89%	1.77%	2.15%	3.68%	4.69%	4.94%
$e_{\text{take-off}}$	0.839	–	−4.41%	−2.26%	−1.31%	−0.60%	0.12%	0.72%	0.83%	1.67%	2.03%	3.46%	4.41%	4.65%
e_{landing}	0.889	–	−4.16%	−2.14%	−1.24%	−0.56%	0.11%	0.67%	0.79%	1.57%	1.91%	3.26%	4.16%	4.39%
$C_{L,\alpha}$	6.05	rad^{-1}	−16.86%	−9.92%	−6.45%	−3.14%	−1.82%	1.98%	3.14%	6.28%	9.09%	15.04%	20.50%	28.43%
$C_{m,\alpha}$	−3.01	rad^{-1}	12.29%	6.98%	4.98%	2.33%	1.99%	−1.00%	−2.33%	−4.98%	−8.97%	−13.29%	−19.93%	−30.23%
Wing area	31.2	m^2	0.00%	0.00%	0.32%	0.00%	0.32%	0.00%	0.32%	0.00%	0.64%	0.00%	0.32%	0.32%
Wing span	93.88	m	−0.35%	0.15%	0.44%	0.15%	0.33%	0.20%	0.30%	0.29%	1.04%	0.29%	0.36%	0.33%
Horizontal stabiliser area	10.9	m^2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Horizontal stabiliser span	23.82	m	−0.17%	0.08%	0.08%	0.00%	0.13%	0.00%	0.13%	0.17%	0.42%	0.04%	0.04%	0.08%
Vertical stabiliser area	4.39	m^2	−0.68%	0.00%	0.46%	0.46%	0.23%	0.00%	−0.68%	0.23%	0.23%	0.23%	0.00%	−0.68%
Vertical stabiliser span	11.6	m	1.64%	0.26%	−0.09%	−0.09%	0.34%	0.17%	1.72%	−0.26%	0.34%	0.34%	0.17%	1.64%
Vertical stabiliser tip chord	0.979	m	12.36%	0.20%	−3.37%	−3.47%	0.20%	0.10%	12.36%	−3.37%	0.20%	0.20%	0.10%	12.36%
Vertical stabiliser taper ratio	0.227	m	12.33%	0.00%	−3.52%	−3.52%	0.44%	0.00%	12.78%	−3.52%	0.00%	0.00%	0.00%	12.33%

Inspecting the results show that for most parameters, the lift curve slope has little impact. The largest changes are seen in $C_{L,\alpha}$ and $C_{m,\alpha}$. This is unsurprising, as one of the parameters was directly adjusted, whereas the other is closely related – as shown in both 2D and 3D wing results presented previously. The difference between input and output lift curve slope is a consequence of other Initiator-modules, besides AVL. The changes in horizontal stabiliser mass are as expected and relate to the altered pitching moment, as caused by the change in lift slope. The largest changes are observed for moderate scaling factors – for both the NACA0012- and RAE2822-variants of the aircraft concept. The shift in neutral point is also a likely result of the changed stability characteristics and subsequent differences with respect to the horizontal tail. The substantial changes in vertical stabiliser tip chord length and taper ratio, observed for (among others) the 1.50 correction factor, are physically unexplained and might be attributed to programming inconsistencies in the Aircraft Design Initiator.

Comparing between the two cases, the differences in the effect on Oswald factors (e) is remarkable. This parameter seems to be more sensitive to the wing $C_{L,\alpha}$ in case of the RAE2822 as compared to the NACA0012. Also, by contrasting the columns with reference values in Table 7.7 and Table 7.8, the influence of camber is made apparent. This changes the maximum take-off mass, operational empty mass and total fuel mass by approximately 2% to 3%. Those changes are larger than the ones observed as a consequence of the adjusted lift slope.

Tracking how particular parameters change over the columns of the results-tables, some discontinuities can be noted. These are most likely a result of the iterative nature of the Aircraft Design Initiator. As all top level design parameters (such as wing span, chord length and tail positioning) are continuous variables, there is no physical reason for any step changes. Quite opposite, a number of parameters can be seen to be highly correlated, such as wing area and span, or cruise drag coefficient and lift-to-drag ratio. The former pair is coupled through the (fixed) aspect ratio; the correlation between L/D_{cruise} and $C_{D,\text{cruise}}$ is a consequence of the fact that C_L is determined from the (relatively constant) total aircraft weight. This also constrains the Oswald factor, a function of $C_{D,0}$, $C_D \approx f(C_L)$ and the fixed AR.

Thin airfoil assumption

The comparison of cases 1 and 3, as described in Table 7.3 and corresponding to lift slope scaling factors between 1.10 and 1.15 provides insight into the influence of the thin airfoil assumption. This assumption is made in the reference result, but not in the scaled data. The largest differences are observed in the horizontal tail size – which, given the fact that no changes beyond a few kilograms are seen in other component masses, also drives the change in operational empty mass. In case of the NACA0012, the Oswald factor is increased slightly (between $+0.45\%$ and $+0.51\%$, depending on flight phase), as well as the span and area of the main wing. That these two parameters change in accordance with each other is explained by the fixed aspect ratio ($\mathit{AR} = b^2/S$). The results of the RAE2822 show, in comparison, a clearer change in cruise drag coefficient (-0.97% to -1.22%) and lift-to-drag ratio. Also, the span efficiency factor increases even further than was seen in the symmetrical airfoil case. The influence on wing planform is similar.

Incompressible flow assumption

The influence of the incompressible flow assumption can be qualitatively assessed by comparing cases 2 and 5, with scaling factors between 0.78 and 0.97, and 1.12 and 1.34, respectively. Combining the fact that the latter value was obtained from AVL-results at $\overline{M_\infty}$ and the trend of the influence of this assumption with increasing M_∞, the results obtained at a scaling factor of 1.50 are also deemed applicable. This range essentially yields a comparison between the first and last data sets presented in Table 7.7 and Table 7.8.

Besides the self-evident differences in lift and pitching moment coefficient derivatives, the impacts (rounded to 0.5%) on horizontal stabiliser mass ($\approx 3.5\%$ to $\approx 4\%$), neutral point ($\approx 7.5\%$ to $\approx 8.5\%$), cruise drag coefficient and lift-to-drag ratio ($\approx 5\%$, only for the RAE2822), cruise zero-lift drag ($\approx 1.5\%$ to $\approx 2.5\%$) and Oswald factor ($\approx 6\%$ to $\approx 10\%$). The influence on geometry and overall aircraft weights is minor.

Irrotational flow assumption

The difference between the results from cases 5 (scaling factor between 1.12 and 1.34, possibly stretched to ≈ 1.50) and 6 (scaling factor between 1.06 and 1.36) gives an indication of the effect of the irrotational flow assumption. Expected as such following the smaller differences in lift slope (caused by the notably smaller effect on two-dimensional airfoil characteristics), the influence on the different parameters of interest are smaller than those associated to the incompressible flow assumption. The horizontal stabiliser mass differs between 0.5% (RAE2822) and 2.5% (NACA0012), although the fact that it is heavier if $C_{L,\alpha}$ is scaled with 1.05 than by 1.50 in case of the symmetrical airfoil raises concerns regarding the validity of these results. The location of the neutral point, drag coefficient, lift-to-drag ratio, Oswald factor and selected aerodynamic derivatives change as anticipated and consistent with earlier results.

Comparison

Assessing the influence of various flow model assumptions as discussed in this section, or more generically comparing the results shown in Table 7.7 and Table 7.8, indicates the influence of three fundamental aerodynamic flow model assumptions as translated using the lift curve slope on aircraft-level parameters computed by the Aircraft Design Initiator is limited. Consistent with expectations, the changes in lift and pitching moment characteristics affect induced drag and horizontal stability, the latter of which driving adjustments to the horizontal tail. The impact on the truly high-level quantities of interest, such as maximum take-off mass and fuel mass, deviate at most 1%. Given the uncertainty margins of the Initiator – generally accepted as a few percent – it is however not possible to definitively determine the influence of the aforementioned assumptions on high-level aircraft performance parameters.

8

Closing

This chapter forms the end of Part I. Section 8.1 answers research question I, as well as the connected sub-questions. Section 8.2 details a number of limitations to the research, mostly detailing with methodological shortcomings influencing the validity and reliability of this work. Suggestions for further research and implementation into practice are shown in Chapter 16.

8.1. Conclusions

This part initially posited that models providing a *more* or a *simplified* representation of the underlying physics (fidelity level L2 and L1) are suitable for aerodynamic analyses in a conceptual design process. A distinction was made between two-dimensional and three-dimensional flow, because of the inherent complications introduced by adding an extra dimension. For two-dimensional problems models up to the thin-layer Navier-Stokes equations were argued to be applicable; in case of three-dimensional problems, it was posited that conceptual designers should not use models beyond the full potential equation. Given the interrelation between flow model and solution method, no specific limits were established for the latter.

Given the fact that conceptual design is focused on high-level parameters, it was concluded that lift, drag and pitching moment are the most relevant quantities of interest for aerodynamic conceptual design, in addition to derivatives. These can either take the form of direct (mathematical) derivatives, or of derive quantities, such as lift-to-drag ratio and maxima and minima. Aerodynamic analysis tools that compute these quantities equally well are equally suited for use in the conceptual design phase.

Within the realm of models relevant to the conceptual design phase, the various flow models variate in making (or not making) two fundamental simplifications: disregarding vorticity and neglecting compressibility. Solvers doing the first and assuming irrotational flow are limited by output accuracy to low-transonic freestream Mach numbers, $0.7 \leq M_\infty \leq 0.8$, depending on profile thickness and angle of attack. Assuming incompressible flow limits solvers to the subsonic domain, as shock waves cannot be predicted. This assumption is generally considered acceptable up to freestream Mach numbers of $M_\infty \approx 0.3$.

Three two-dimensional solvers – an incompressible panel method solving the Laplace equation (XFOIL), a finite difference method using the (compressible) full potential equation (VGK) and a finite volume method using the (rotational) Euler equation (MSES) – were compared in their ability to predict inviscid lift and pitching moment coefficients for a symmetrical (NACA0012) and supercritical (RAE2822) airfoil over a range of Mach numbers ($0.05 \leq M_\infty \leq 0.80$). Given an accurate enough geometry representation and grid (in terms of number and distribution of coordinates), the impact of solution method was found to be much smaller than the impact of flow model, and mostly independent of Mach number and angle of attack when normalised to a reference value (obtained from a grid refinement study). Differences in flow model were found to be mostly independent of angle of attack, much more influential for Mach numbers larger

than 0.30, growing to more than 50% at $M_\infty = 0.80$, when normalising differences to the highest-fidelity model in the comparison. Assuming incompressible flow was found to result in an under-representation of the quantities of interest much more significant than the over-estimation that resulted from assuming irrotational flow. In the former case, the largest differences were observed for the chordwise location of the minimum pressure point, with the lowest impact on pitching moment coefficient. In the latter case, the magnitude of the minimum pressure coefficient was least sensitive. The impact of the geometry on the magnitude of the uncertainty was limited, although shifts with angles of attack were observed. The Prandtl-Glauert and Karman-Tsien compressibility corrections were confirmed to reduce the impact of assuming incompressible flow, although the latter showed over-compensation in situations at high Mach numbers and angles of attack. The impact of the geometry on the magnitude of the uncertainties was limited, although differences in zero-lift angle of attack did manifest themselves.

Propagating these two-dimensional results to a three-dimensional vortex lattice method using scaling of the lift slope indicated results consistent with the 2D analyses. The impact was found to be increased with increasing aspect ratio and application of sweep and results fuel the hypothesis that the effects are smaller for tapered than for untapered wings. Again, the incompressible flow assumption showed a bigger influence than the irrotational flow assumption. A qualitative further extension of these results to an automated aircraft design and synthesis tool showed a very limited impact of the incompressible and irrotational flow assumptions on aircraft characteristics and key performance indicators. Given the fact these impact measurements were found to be smaller than the uncertainty associated to the tool, the effect of the aforementioned assumptions could however not be unambiguously established.

Guided by the sub-questions answered in the preceding paragraphs, model uncertainty was quantified, assessed and propagated bottom-up. The influence of two fundamental flow assumptions was systematically investigated for different geometries and flow cases. By varying parameters one-by-one and using scaling and correction factors, the impact on two-dimensional quantities of interest was translated into higher-level effects. Although the current approach and (to a lesser extent) specifically developed toolkit are not suitable for quantifying and propagating uncertainties up to tenths of a percent, the results – and their agreement with theory – indicate the method is fitting for providing a first assessment.

8.2. Limitations

Notwithstanding the conclusions presented before, various limitations have to be acknowledged.

A first limitation is a direct consequence of the research type. The vast amount of data and high multi-dimensionality of the problem (also noted by Roelofs and Vos (2018b)) necessitated data aggregation in order to reduce the results to a manageable set. This might, however, have removed particular isolated results from view. As most results could be physically explained, the impact of this limitation is most likely small. Nevertheless, the ‘known unknown’ is recognised.

Another limitation concerns the solvers that have been used. Although it was assumed that possible other differences between the solvers are negligible compared to the influences investigated here, there might be specific situations where that assumption is invalidated. Using the small difference between the two variants of the full potential solver considered (the partially-conservative and non-conservative schemes in VGK) as an illustration, it is argued that this limitation does not invalidate the conclusions drawn before. Regarding MSES, it is noted that as the flow separation problem observed (further documented in Appendix E) could not be explained, it is impossible to definitively confirm the underlying cause did not influence the results in other ways – although this is highly unlikely. A minor shortcoming is the fact that not all reference values (obtained in Section 6.3.1) could be established with great certainty.

More significant simplifications had to be made in the uncertainty propagation part of this research. As indicated before, this renders those results mostly qualitative. Concrete limitations follow from the use of the lift slope (and its associated scaling parameter in the analytical tools used) to bundle the effect of the incompressible and irrotational flow assumptions. The generalisability of the conclusions with respect to the influence of high-level aircraft parameters is limited due to the fact that this was only assessed using the Aircraft Design Initiator. This is further discussed in Chapter 16.

End of Part I: Technical perspective

II

Socio-psychological perspective

Having treated the technical perspective of the information input to the decision making process in Part I, the current part investigates that process itself. Hence, it approaches the goal of improving decision quality from a socio-psychological perspective, aiming to realise the second research objective. This is repeated below.

> Make a contribution towards improving group decision making about technology assessment and selection in the context of aircraft conceptual design, by proposing a model and subsequent support tool which contributes to solving a (combination of) relevant challenge(s) in aircraft conceptual design and technology assessment.

Connected to this objective is the second research question, also quoted below:

> How can a (combination of) relevant socio-psychological factors negatively impacting group decision quality be combined in a conceptual model and subsequent tool that helps to understand and mitigate that impact?

Contrary to Part I, which selected one such factor (information in and about uncertain situations) beforehand based on literature, the present part starts with a more detailed analysis of decision making in project MANTA and the project itself, yielding a clear problem definition. This is the topic of Chapter 9, which thereby answers research questions II-a and II-b. Chapter 10 combines these observations with the insights on decision quality gained in Chapter 3 to build a theoretical framework, centred around one of the specific factors identified before, in order to increase understanding of the problem(s) identified before. As such, this chapter provides an answer to research question II-c. The knowledge gained from the theoretical framework is subsequently used to develop a model which aims to contribute to higher quality decisions within project MANTA in Chapter 11, answering research question II-d. Research question II-e is answered in Chapter 12, which presents a possibility for using the model as a tool. Finally, Chapter 13 closes the part by drawing conclusions and discussing limitations.

9

Project description and problem definition

Although the introduction to this report briefly mentioned project MANTA, that description does not come close to a detailed description of the project – nor does it investigate which (socio-psychological) factors of decision making negatively impact decision quality. The current chapter aims to fill both these voids by answering research questions II-a (*What does group decision making in project MANTA look like?*) and II-b (*What socio-psychological factors negatively impact group decision making in project MANTA?*).

Section 9.1 starts with the former, mostly from an outside perspective, and limited to the formal process: what are the project goals, what are the main activities, what is investigated, and how is the project organised and funded. The following three sections are based on a much more internal perspective and together evaluate decision making and collaboration within project MANTA. First, Section 9.2 shows the methodology and results of an extended review of project documentation, undertaken to gather initial impressions. Thoughts and ideas collected this way were subsequently tested in interviews with project participants, which are discussed in Section 9.3. Last, Section 9.4 treats insights gained as an observer to a face-to-face meeting between the consortium partners, adding yet another perspective to the collected data. The problem statement that is distilled from all this, is presented in Section 9.5.

9.1. Project description

Project MANTA is a response to the Clean Sky 2 3rd call for core partners, regarding next generation movables for high speed aircraft, focusing on “smart mobile control surfaces” for “novel control” methods in order to realise a fuel burn reduction of 3 to 5% (van Goozen and Bastiaansen, 2017, pp. 4-5). Additionally, the findings are expected to contribute to further development of innovative aircraft architectures, advanced laminar flow and optimised high lift configurations (Fokker Aerostructures BV et al., 2014, p. 11). In simpler terms, project MANTA is concerned with developing new, improved or integrated wing movables on the wing, such as flaps and ailerons. (A description of aircraft and wing nomenclature, including a graphical depiction of these elements, can be found in Appendix A.) Having started in December 2016 and ending in June 2023, the six-million Euro undertaking aims to mature a selection of novel movable technology concepts form Technology Readiness Level (TRL) 1-3 (up to an experimental proof of concept) to TRL 4-5 (validated concepts) (van Goozen and Bastiaansen, 2017)[1].

The subsequent sub-sections treat the project goals and project phasing, discuss concepts and target applications, present which organisations are involved in the project and provides insight into the funding of project MANTA.

[1] More detailed definitions and explanations of the various TRLs are included in Appendix G (European Space Agency, 2008).

9.1.1. Project goal

The description of action, a document that can be seen as project description, describes the project goal as follows (Fokker Aerostructures BV et al., 2014, p. 9):

> The overall objective of the MANTA project is to make a contribution to the technology maturation TRL 1-3 to TRL 4-5 for novel aircraft movable concepts that will contribute to the Airframe-ITD TS 4 challenging objective of 3 to 5% aircraft fuel burn fuel [sic] reduction.

The project consortium identifies three perspectives from which the objective can be viewed. First is the societal perspective, in which project MANTA contributes to "society in general" (Fokker Aerostructures BV et al., 2014, p. 10). Second, there is an industrial perspective, which aims to make "a valuable contribution to realize the ambition of the industrial partners" (Fokker Aerostructures BV et al., 2014, p. 10). Third is the research perspective, which includes objectives "in terms of new ideas, new knowledge, new capabilities and new tools".

This overall project objective is consistent with the objective of TS-A-4 (the fourth technology stream in the group *High Performance and Energy Efficiency*, further treated in Section 9.1.4), which is "to reduce the global aircraft weight, either by mutualisation of functions (lift & control) in a single mobile part, reducing then the number of control surfaces, or by load alleviation with active load control. Such will lead to the reduction of consumed fuel and CO_2 footprint" (Fokker Aerostructures BV et al., 2014, p. 11).

9.1.2. Project outline

The project work is split up in four work packages (WPs) (Fokker Aerostructures BV et al., 2014), consisting of the following tasks:

WP1 **Idea generation**, ~ 6 months
Review of limitations to and opportunities of current state-of-the-art technologies (Maseland, 2017), assessment of their technological impact (Delft University of Technology, 2018) and subsequent initial selection of most promising concepts (Heuer, 2018), from approximately 30 concepts to 9.

WP2 **Performance impact assessment**, ~ 18 months
System-level aero-performance assessment and further development (structural integration, kinematics and actuation) of selected concepts to TRL 2-3, as well as aircraft-level (a large commercial aircraft and high-speed business jet) impact assessment and comparison to the baseline model, using the Aircraft Design Initiator (Roelofs and Vos, 2018a).

WP3 **Down-selection for further development**, ~ 6 months
Further down-selection to one or two concepts for further development, including a plan to do so.

WP4 **(Detailed) development to TRL 4-5**, ~ 3.5 years
Building and testing of a demonstrator for the selected technologies to attain TRL 4-5.

Separate from the technical work is a work package (WP0) dealing with project management, administration and communication.

9.1.3. Concepts and target applications

Figure 9.1 illustrates the innovations proposed in project MANTA. Up to the final down-selection (in WP3), the project focuses on four parts of the wing for which innovations will be developed: the so-called target applications (TAs). Some TAs might include multiple innovations that exclude or build atop each other. These are listed below.

- **Adaptive outer wing and winglet**, focused on load control and improved performance at off-design conditions.

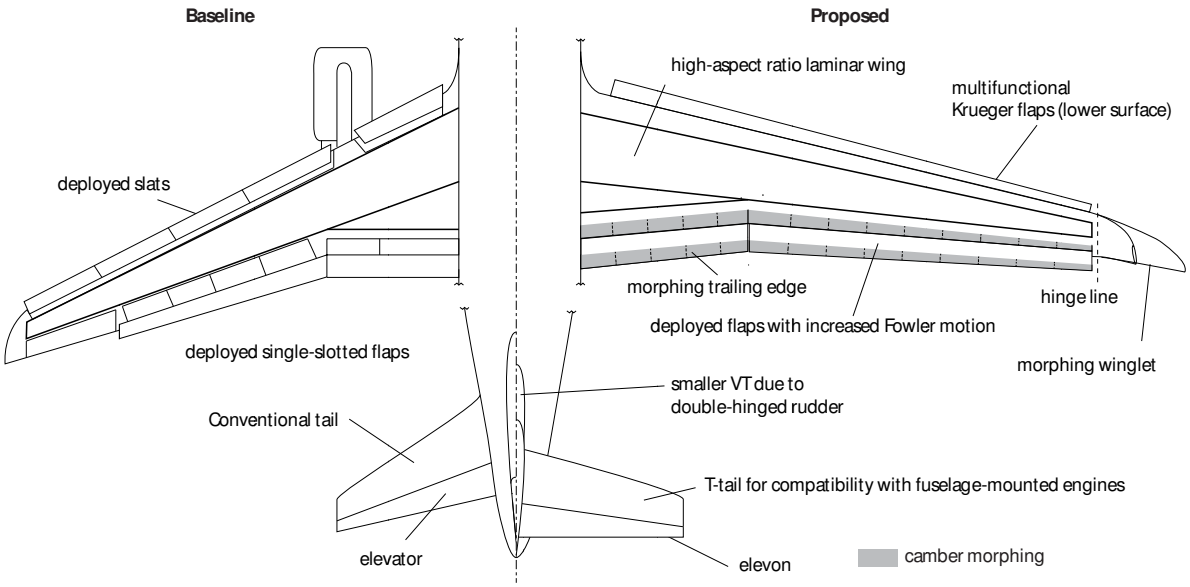


Figure 9.1: Primary and secondary wing movables, showing the state-of-the-art (left) versus the proposed (right) situation (Fokker Aerostructures BV et al., 2014, p. 13)

- **Multifunctional trailing edge flaps**, focused on combining functions of trailing edge movables and reducing subsystem complexity.
- **Adaptive air inlets**, focused on reducing drag, weight and complexity of the secondary air intake, as well as reducing the maintenance cost by stretching the maintenance interval.
- **Morphing spoiler**, focused on improving high-lift performance over conventional spoilers.

Originally, the morphing spoiler was not part of the project. It replaced a target application for the development of an affordable leading edge slat in early 2018 (Heuer, 2018; Maseland, 2017).

9.1.4. Organisation

Although the actual research and development work is done by 'just' five consortium partners, many more parties are involved in the larger organisational ecosystem. This section aims to shed some light onto that by discussing the various organisations concerned with project MANTA. The section is structured inside-out: starting with the consortium, then moving on to the so-called topic leaders and finally discussing the Clean Sky Joint Undertaking – the organisation providing the direction and funding for all Clean Sky and Clean Sky 2 projects.

Consortium

The MANTA consortium consists of two[2] industrial partners, two research institutes and a university:

- **Fokker Aerostructures** (FAE) / **Fokker Technologies Holding** (FTH)
  Fokker Aerostructures (an operational company of Fokker Technologies Holding) designs, develops and produces lightweight wing and wing movable structures for (among others) large commercial aircraft (e.g. Airbus A350 and A380 programs) and business jets (for e.g. Gulfstream, Dassault Aviation and Cessna). In addition, it is involved in various defense programs, such as the Lockheed Martin F-35 Joint Strike Fighter. Besides FAE, Fokker Technologies Holding consists of units designing, developing and producing electrical wiring systems (Fokker Elmo) and landing gear (Fokker Landing Gear), as well as a service company (Fokker Services). Both FAE and FTH are headquartered in The Netherlands. Fokker is involved in all target applications.

[2] In this text, Fokker Aerostructures and Fokker Technologies Holding are counted as one partner, unless specified otherwise.

- **ASCO**
  ASCO is a company active in the design, manufacturing and certification of high-lift mechanisms for aerospace applications. The company has been involved in a large number of recent commercial aircraft programs (a.o. Airbus A350 and A380, Boeing 787 and Embraer E2-series) and manufactures high-lift supports for various business jets. ASCO is located in Belgium. After the cancellation of the affordable leading edge slat, activities for ASCO in WP2 were reduced and the company shifted more of its attention to the development of multifunctional trailing edge flap concept, in parallel to the work done by Fokker.
- **Netherlands Aerospace Centre** (NLR)
  The Netherlands Aerospace Centre is the primary applied aerospace research institute in the Netherlands, in role comparable to TNO and MARIN. The not-for-profit organisation tries to build the bridge between universities and industry and assist in further developing new technologies to make that step. In order to do so, NLR operates various simulators, wind tunnels (together with DLR) and a research aircraft (together with TUD). NLR has its headquarters in The Netherlands and is mainly contributing to project MANTA with (aerodynamic) analysis and simulation work.
- **German Aerospace Center** (DLR)
  The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt) is the German equivalent of NLR. Involved in project MANTA are the DLR institutes of Flight Systems (flight vehicles and subsystems), Aerodynamics and Flow Technology (aerodynamics research), Composite Structures and Adaptive Systems (lightweight composite design and manufacturing methods), and Aeroelasticity (aeroelasticity research). DLR operates various facilities across Germany, e.g. in Braunschweig and Berlin. DLR is most actively involved in the development of adaptive concepts, most notably in the outer wing and winglet region.
- **Delft University of Technology** (TUD)
  The Faculty of Aerospace Engineering of Delft University Technology is one of the largest faculties in Europe that is entirely devoted to aerospace engineering. It has expertise in e.g. materials and structures as well as in novel design approaches and operates various wind tunnels and a research aircraft. As the name suggests, Delft University of Technology is located in Delft, The Netherlands. Besides fulfilling a role in technology assessment, TUD is leading the development of the selected adaptive air inlet concept.

Within the consortium, various organisational levels can be distinguished. The highest project body in project MANTA is the **Steering Committee** (SC), which is formed by a representative of each partner and chaired by the project coordinator. It determines “overall strategy, management and control policy, [and is] managing [the] dissemination and exploitation plan” (Fokker Aerostructures BV et al., 2014, p. 63). The **Project Management Committee** (PMC), also chaired by the project coordinator, sits below the SC and is the executive body in charge of day-to-day management. It receives external input from the **Advisory Board** (AB), which is tasked to provide advice to the consortium and “facilitate the decisions made by the SC” (Fokker Aerostructures BV et al., 2014, p. 64). The operational level is formed by the work package leaders (WPLs) – consortium partners responsible for a particular work package. Furthermore, the **Points of Contact** (POCs) play an important role, as they are the main representative of their organisation. FAE acts as project coordinator of project MANTA. The people involved in project MANTA are generally highly educated (holding MSc- or PhD-degrees) and work as engineer or project manager with an engineering focus or background.

The steering committee meets twice a year, face-to-face. Representatives of the consortium partners meet in point-of-contact meetings that are held every two weeks by means of a web conference. Additionally, one or two face-to-face meetings are held each year.

Topic leaders

Besides the MANTA consortium, three topic leaders (TLs) play a role and steer the decisions of the project. This role is based on their “integrator knowhow, market knowledge and strategy” (Fokker Aerostructures BV et al., 2014, p. 24). The participation of these companies furthermore aims to strengthen the European competitiveness in their respective aerospace markets.

- **Airbus**

Airbus is Europe's primary commercial aircraft manufacturer, designing, developing and producing aircraft seating from 100 to over 500 passengers. To keep its competitive edge, "Airbus will need beyond-state-of-the-art technology that further improves performance and reduces fuel burn and noise", to which project MANTA "aims to deliver an important share" (Fokker Aerostructures BV et al., 2014, p. 25). In this, the OEM is focused on the high-volume 150 - 200 seater market (Airbus A320, Boeing 737). Airbus has major facilities in France, Spain and Hamburg, in addition to other departments in Europe. Its Bremen-division, responsible for the development of high-lift devices, is most involved in project MANTA. In this project, Airbus' main interests are with the adaptive outer wing and winglet, the adaptive air inlet and the morphing spoiler.

- **Dassault Aviation** (DAV)
  Dassault Aviation is widely known for its military aircraft programs, but in project MANTA is mostly involved because of its role as Europe's major business jet manufacturer. That part of the company has seen declining deliveries in 2014 and 2015. Other business jet manufacturers (notably Gulfstream Aerospace and Bombardier) have especially competitive product offerings in the long-range market, in which Dassault is currently not as well-represented. As for Airbus, project MANTA aims "to deliver an important part" for Dassault's need for "further performance improving and fuel burn reducing technologies on their next generation aircraft" in order to "stay competitive with the North American [business jet] manufacturers and maintain Europe's position in the business jet market in the future" (Fokker Aerostructures BV et al., 2014, p. 26). Dassault Aviation is located in France. In project MANTA, Dassault is primarly focused on the multifunctional trailing edge flaps, although the company is also interested in the morphing winglet.
- **SAAB Group** (SAAB)
  SAAB Group is an aerospace and defence company that is best known for the design and production of jet fighters. Additionally, the company is responsible for producing structural parts for other aircraft manufacturers. The Description of Action of the project (Fokker Aerostructures BV et al., 2014) does not specify a clearly defined (industrial) goal for SAAB, besides MANTA contributing to strengthening the aerospace industry in Europe and growing the number of jobs in that field. SAAB is based in Sweden. There is no target application specifically relevant to SAAB and the company is notably less involved in project MANTA than the other two TLs.

As for the consortium partners, the topic leader representatives are highly educated and have an (aerospace) engineering background. On average, they however hold more senior positions, managing rather than executing projects. Topic leaders meet with the points of contact of the consortium partners every other week using a web conference, besides sometimes joining the aforementioned face-to-face meetings.

Clean Sky Joint Undertaking

Zooming out even further brings the Clean Sky Joint Undertaking (CSJU) in sight. This organisation is a public-private partnership (PPP) between the European Commission (EC) and the European aeronautics industry, receiving its public funding from the larger Horizon 2020 framework. The CSJU manages the Clean Sky (2008 – 2017) and Clean Sky 2 (2014 – 2024) research programmes, which address different technological challenges in various areas of interest. The Clean Sky 2 programme involves three *Innovative Aircraft Demonstrator Platforms* (IADPs) – large passenger aircraft, regional aircraft and fast rotorcraft – which look at the complete vehicle level. Then, there are *Integrated Technology Demonstrators* (ITDs), in which research and development projects on airframe, engine and systems levels are carried out. Last, there are two *Transverse Activities* (eco-design[3] and small air transport) and a *Technology Evaluator*, with the latter aiming to assess the impact of Clean Sky 2 on CO_2, NO_x and noise emissions (Clean Sky 2 Joint Undertaking, 2019; Clean Sky Joint Undertaking).

As the CSJU organisation only manages the research, it needs other organisations to outline and conduct it. To this extent, it involves leaders and various types of partners. The **leaders** form the private-component of the public-private partnership and are generally large aerospace companies and their affiliates. They "jointly commit to researching and completing projects within the Clean Sky programme, and thereafter are able to further advance the technologies developed" (Clean Sky, b). The leaders also

[3] According to one of the people involved in project MANTA, eco-design has been moved to the airframe-ITD in 2019. This has however not (yet) been updated on the Clean Sky 2 website (https://www.cleansky.eu/eco-design).

play a role in writing the calls to which core partners – such as the ones part of the MANTA-consortium – respond with their research proposals. These **core partners** are one level down from the leaders. Despite this difference, they too are permanent members of the CSJU. Core partners contribute to multiple projects, often in multiple IADPs or ITDs. **Partners** are the least-integrated organisations that are involved in the projects conducted in Clean Sky. They are no member of the CSJU and often contribute to a single project, for a limited amount of time, in the form of contract work (Clean Sky, b,c). As of April 2018, Clean Sky 2 had some 35 leaders and approximately 150 core partners, both excluding affiliated organisations (Clean Sky 2 Joint Undertaking, 2019).

Overview

Having laid out the larger Clean Sky organisation and composition, project MANTA can be positioned within it. In terms of the research content, project MANTA falls in the Airframe-ITD, more specifically in the first activity line, titled *High Performance & Energy Efficiency* (Clean Sky 2 Joint Undertaking, 2019). Dassault, Airbus and SAAB are the leaders[4] of this ITD (Clean Sky, a).

This activity line is further sub-divided into various technology streams, dealing with challenges such as developing improved high lift configurations, advanced fuselages or novel forms of control. Project MANTA directly contributes to that last technology stream, but also has beneficial impact in three others: *innovative aircraft architecture*, *advanced laminarity* and *optimized high lift configurations* (Fokker Aerostructures BV et al., 2014, p. 11). Other projects in this technology stream are GAINS (*Green Airframe Icing Novel Systems*) and NACOR (*New innovative Aircraft COnfigurations and Related issues*) (Clean Sky 2 Joint Undertaking, 2019; GAINS, 2015; ONERA, 2017).

Figure 9.2 graphically shows project MANTA within the European Union research framework.

All consortium partners are core partners to the CSJU. Besides their involvement in project MANTA and thereby the Airframe-ITD, most partners contribute to other projects within Clean Sky 2. Fokker (FAE as well as FTH), DLR, NLR and Delft University of Technology are core partners in the large passenger aircraft IADP. DLR and NLR furthermore participate in the Engine-ITD, with the latter also involved in the regional aircraft IADP (as is Delft University of Technology) and the Systems-ITD (Clean Sky 2 Joint Undertaking, 2018). At the time of writing this report, no other partners were involved in project MANTA, although this is foreseen in the future (Fokker Aerostructures BV et al., 2014).

Complexity

The previous discussion has already shown the Clean Sky 2 research program – and in it: project MANTA – to be concerned with *complicated* content: morphing structures, smart materials and substantial amounts of integration between various components and (sub)systems. Besides the complicated content, the collaboration itself is *complex*, mostly because of the inter-relations between various stakeholders and their individual agendas. This is visualised in Figure 9.3.

As the situation it represents, the figure is quite complex. Organisations are shown in boxes; interactions and inter-relations are represented using lines. Stakeholders involved in the project are shown in boxes with a black outline. The text colours represent the countries these actors operate in: **cyan** for The Netherlands, **green** for Germany, **red** for Belgium, **yellow** for France and **dark purple** for Sweden. Organisations that are no part of project MANTA itself, but are relevant to include are shown in grey.

The colour of the background of the box indicates whether an organisation is a commercial and for-profit entity (white), completely non-profit (dark grey) or somewhere in between (light grey), as is the case for research institutes involved in both commercial as well as publicly-funded projects. Even without considering the particular connections between the stakeholders, this difference is highly relevant, as it results in fundamentally different organisational goals. Public institutions, such as Delft University of Technology, have knowledge generation and sharing as a main goal, for example, whereas commercial

[4] The remainder of this text adheres to the designation *topic leader*, even though they are sometimes referred to as *topic managers* and are obviously equivalent to what the official CSJU-documentation indicates as *leaders*.

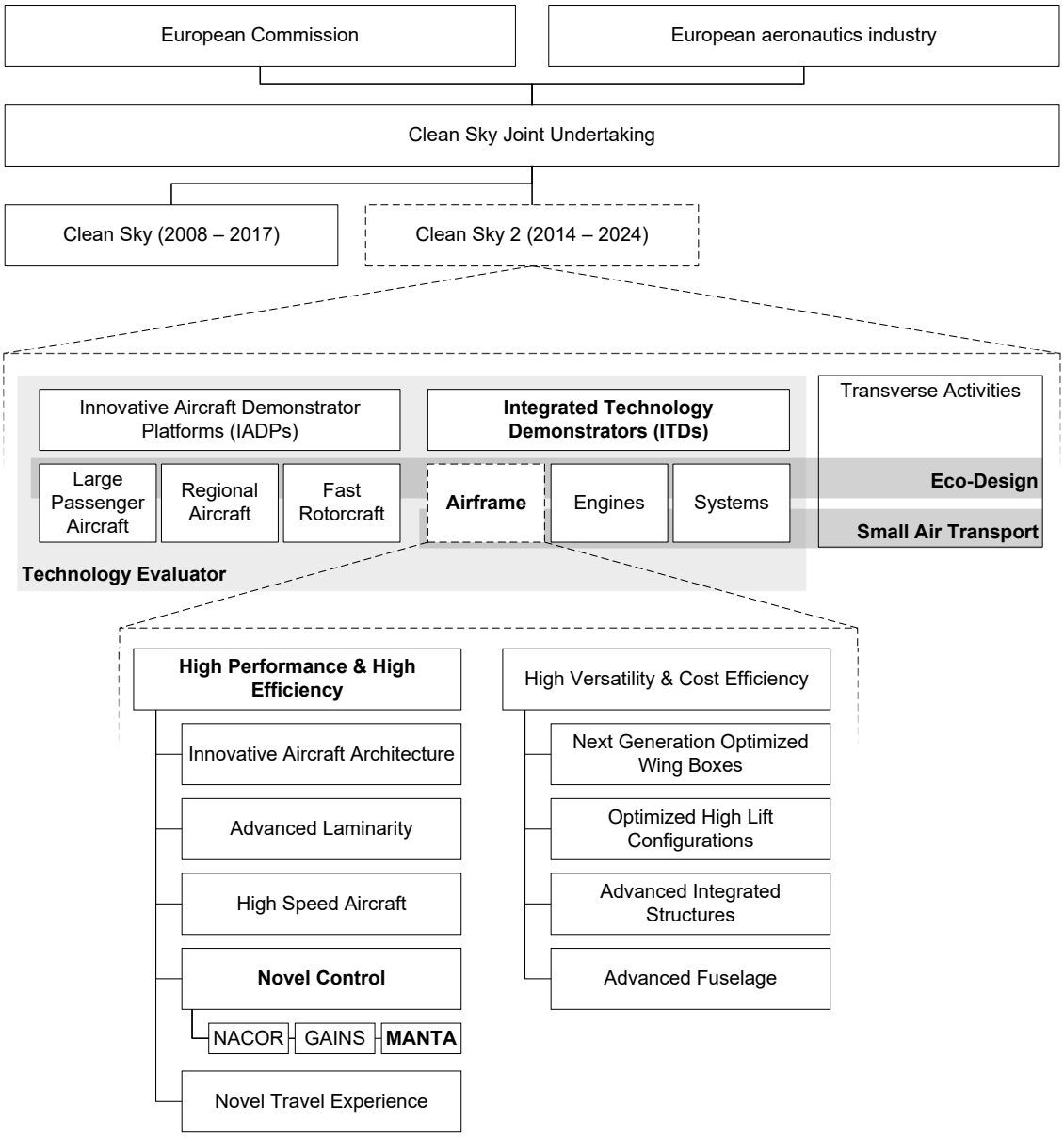


Figure 9.2: Clean Sky programme overview, showing the position of project MANTA, based on (Clean Sky 2 Joint Undertaking, 2019; Clean Sky Joint Undertaking; Clean Sky, a)

parties will want to protect their intellectual property in order to obtain a business advantage over their competitors.

The style and colour of the connecting lines indicate the type of relationship. Dashed black lines indicate that the connected parties have previously collaborated in one or more related non-profit research projects[5], such as AFLoNext (on active flow, loads and noise control on wings; ASCO, Fokker, DLR and NLR), DeSiReh (high-lift devices for a natural laminar flow wing; ASCO, DLR and NLR) and SADE (smart high-lift devices; DLR and TUD) (Fokker Aerostructures BV et al., 2014).

[5]The previous collaborations shown are limited to projects concerning similar challenges as the ones addressed in project MANTA. If one would widen this scope, Figure 9.3 would essentially turn into a spider web as – over the years – practically all parties have worked together one way or the other.

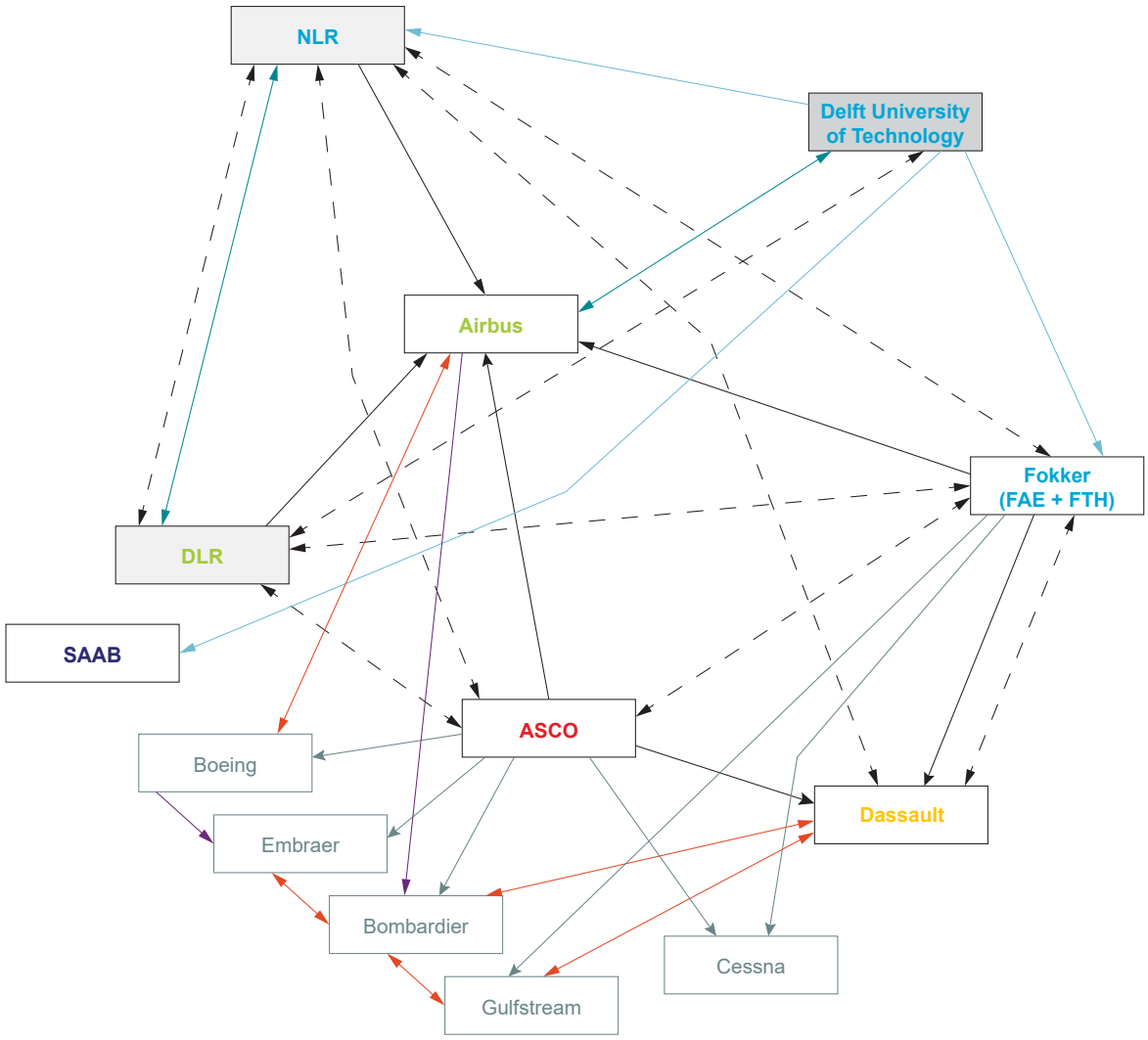


Figure 9.3: Inter-relations between stakeholders and external parties in project MANTA, based on Fokker Aerostructures BV et al. (2014)

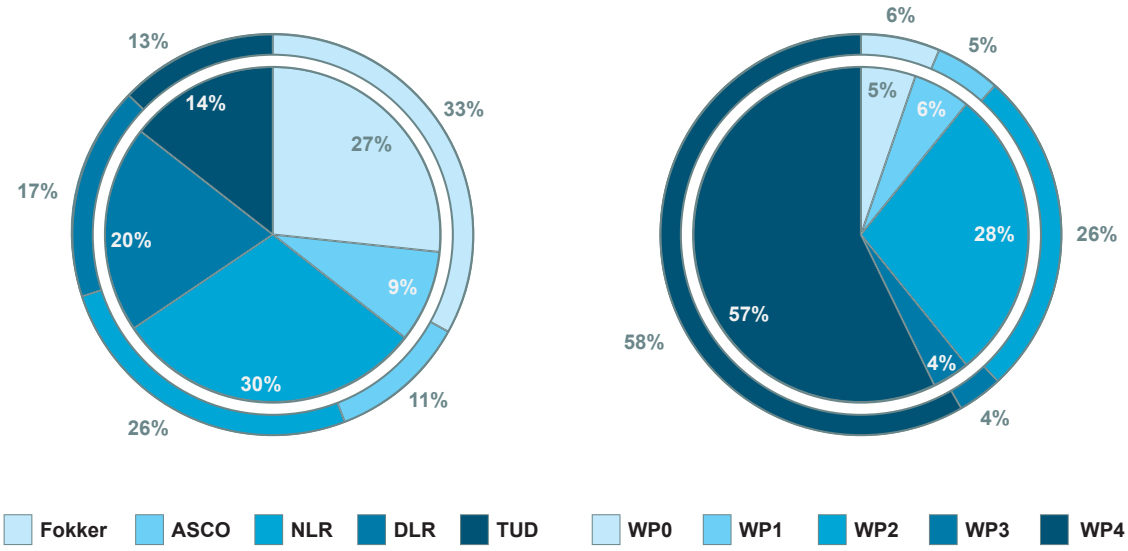
Solid lines, then, indicate other – mostly for-profit – relations. The **black** and **grey** lines denote a supplier-relationship, to either organisations inside or outside project MANTA. The **light blue** lines (from TUD to Fokker, NLR and SAAB) indicate people flow (i.e., alumni or exchanges within the MANTA-consortium). The **blue-green** lines, then, indicate shared ownership of facilities (German-Dutch Wind Tunnels, by DLR and NLR) and a university-partner program (TUD and Airbus).

Orange and **purple** lines are mostly connected to the (external) organisations in the grey boxes. These lines indicate partial ownership (Airbus – Bombardier and Boeing – Embraer) and competition, respectively. Combining that information with the supplier-relationships shows a main driver of complexity: indeed, both industrial partners in the consortium are not only supplier to the topic leaders involved, but also to their subsidiaries and competitors. These competitors included in the diagram are limited to organisations ‘upstream’ in the supply chain. However, many more could be added when taking ‘downstream’ relations – such as other suppliers to Airbus, which could be competitors of any of the commercial organisations shown – into account.

9.1.5. Funding and budget

The total budget of Clean Sky 2 – comprising €4.0 billion – consists of both public (€1.8 billion) and private (€2.2 billion, among others coming from the topic leaders) funds (Clean Sky, b; Clean Sky Joint Undertaking). Project MANTA receives a total grant sum of €6.000.000, which includes a budget (fixed at 25% of the total direct costs) for indirect costs. The industrial partners in the consortium (Fokker and ASCO) add a little over €900.000 to this 6 million budget. This follows from the fact that only non-profit entities have a 100% funding rate, whereas funding towards commercial organisations is limited at 70% (Fokker Aerostructures BV et al., 2014). Any additional indirect costs (i.e., overhead) beyond the 25% is to be paid by the consortium partners themselves. This is an additional 2 million Euros, approximately (Fokker Aerostructures BV et al., 2014).

Figure 9.4 shows the budget broken down over the various work packages and consortium partners. The outer circle and percentages represent the total budget and the inner circle and percentages represent the Clean Sky JU contribution, whereas the ratio between the outer and inner circle is a measure for the total cost of each. The difference between the outer and inner graphs is most substantial in Figure 9.4a than in Figure 9.4b due to the aforementioned funding rate, which has a direct effect on partners, but not so much on work packages. Figure 9.4b immediately shows the bulk of the work of project MANTA is executed in WP4, the (detailed) development to TRL 4-5.



(a) Broken down over the consortium partners (b) Broken down over the work packages

Figure 9.4: Project MANTA budget, based on (Fokker Aerostructures BV et al., 2014, p. 77)

The budget breakdown shown in Figure 9.4 only concerns the consortium partners and as such does not include the remuneration received by the topic leaders for their coordination and support.

9.2. Initial impressions

Following a factual understanding of the scope and workings of the project – which has been presented in the previous section – various types of project documents were reviewed in order to gather initial impressions of decision making and collaboration. The next section presents the methodology of the analysis, followed by a section discussing the results.

9.2.1. Methodology

The choice to do a document analysis was made for two reasons in particular. First of all, it is unobtrusive and thereby can be conducted without placing a burden on people involved in the project (such as is the case for questionnaires, interviews and, to a lesser extent, observations) (Bryman, 2012). Second, it is non-reactive and therefore provides a relatively 'unspoiled' account of events – even if these took place some time back, in which details are easily lost in personal recollection (Bryman, 2012).

In the analysis, attention is paid to both the content of the documents, as well as to meta-information, such as meeting attendance records and the availability of minutes. This can provide valuable information in and of itself (another reason for opting to analyse these documents), for example indicating the effort and commitment put into the project.

The list below shows which documents have been included. Documents made available after November 2018 are excluded from the analysis due to time restrictions for this research phase.

- Description of action [DoA] (Fokker Aerostructures BV et al., 2014), the project plan
- Minutes of meetings and supplementary material:
  - Steering committee [SC] (2 meetings, June 29th, 2017 – November 27th, 2017)
  - Topic leader [TL] (16 meetings, January 20th, 2017 – September 26th, 2018)
  - Point of contact [POC] (17 meetings, January 24th, 2017 – June 18th, 2018)
  - Technical meetings [TM] (7 meetings, July 7th, 2017 – September 22nd, 2017)
- Project deliverables:
  - Survey of movable concepts [D1] (Maseland, 2017), review of concepts
  - Technology impact matrix [D2] (Delft University of Technology, 2018), qualitative assessment of concepts
  - Synthesis of solutions [D3] (Heuer, 2018), first down-selection (from 29 to 9 concepts)
  - Multi-fidelity multidisciplinary analyses, design and optimization tools [D4] (Roelofs and Vos, 2018a), quantitative assessment of remaining concepts

All documents are authentic and meaningful (in some cases aided by factual clarification provided by helpful project members). Assessing representativeness and credibility is somewhat more difficult, but no reasons to doubt these could be found (Scott, 1990; Bryman, 2012). This especially holds for the minutes of meetings, which were created solely for internal use. Whereas the project plan and deliverables – more external documents – might be more susceptible to being coloured with a particular, more positive, perspective, there are no indications for this in case of the internal documents.

The documents were reviewed chronologically, marking any content possibly addressing difficulties or problems and thereby inductively or abductively identifying relevant topics for further investigation (Elo and Kyngäs, 2008; Saldaña, 2011). Although not a strict methodology, the approach taken bears similarities with qualitative content analysis (Bryman, 2012; Mayring, 2014), conventional content analysis (Hsieh and Shannon, 2005), thematic analysis (Drisko and Maschi, 2016; Boyatzis, 1998) (lacking, however, strict coding), qualitative description (Sandelowski, 2000), interpretive description (Thorne et al., 1997) and holistic coding (Dey, 1993, p. 110), aiming to "grasp basic themes or issues in the data by absorbing them as a whole rather than by analysing them line by line". Fitting with the research scope, most attention was paid to topics estimated to influence collaboration and decision making. Reasons to include particular topics were (among others) recurrence, length or conflicting information or disagreement. Nevertheless, some subjectivity in this selection is acknowledged. Because the method is used to gather initial impressions, which are tested in later research stages (triangulation), this downside is accepted. Due to the variety of documents, the fact that the results of the document analysis are only part of the research material and time limitations for this research phase, it was decided not to code or quantitatively analyse the documents. Instead, quotations are used to illustrate and support the observations. The abbreviations between square brackets from the previously presented document list are used to identify specific sources. In case of meeting minutes and supplementary material, a date (YYYYMMDD) is added to the abbreviation.

9.2.2. Results

This section presents the results obtained from the document analysis. Observations with respect to project goals and sub-goals (and the potential for conflict between these) are discussed first. Treated next is the (type of) information used to base decisions on. Extra observations, not specifically fitting with either theme, are discussed afterwards. Last, the results of the analysis of meta-information is presented.

Project goals and objectives

As discussed in Section 9.1.1, project MANTA aims to "make a contribution to the technology maturation TRL 1-3 to TRL 4-5 for novel aircraft movable concepts what will contribute to the Airframe-ITD TS 4 challenging objective of 3 to 5% aircraft fuel burn fuel [sic] reduction" (Fokker Aerostructures BV et al., 2014, p. 9) [DoA]. In a presentation for a topic leader meeting, the goal is further detailed by specifying it is to be obtained "by becoming more effective and multifunctional, and by [realising a] further decrease of weight and drag" [TS20170120]. Later deliverables deviate from this objective to a greater or lesser extent. Possibly related to the fact that it has an industry rather than a research partner as main author, Heuer (2018, p. 8) [D3], besides acknowledging the main objective, places more emphasis on industrial goals: the desire to "implement the two concepts (or at least one of them) on a future aircraft or platform" and the preference "that the chosen concepts matches [sic] the product strategy of the industrial partners". Roelofs and Vos (2018a, p. 10) [D4] stick to the overall objective more closely, but state the fuel consumption reduction goal is 5%, omitting the 3 – 5% range.

Although these differences and inconsistencies are relatively minor, they show a notable degree of haziness regarding the project objective(s). A larger (potential) conflict is found when comparing the overall objective with specific (sub-)goals, especially the "industrial perspective: objectives in terms of making a valuable contribution to realize the ambition of the industrial partners and the Topic Leaders" (Fokker Aerostructures BV et al., 2014, p. 10) [DoA]. Even though the DoA is a research plan, it provides fairly detailed accounts of the business challenges faced by the topic leaders (shown previously in Section 9.1.4). The difference between project and industrial goals can also be observed in minutes of meetings, as the excerpts below show (emphasis added):

- "All partners agree that Airbus has not clearly indicated *what Airbus wants* and that the meeting was not helpful in getting direction [...]" [POC20170124]. "MANTA project lacks input from TL" [POC20170628]. "We need more directions from the Topic Leaders" [SC20170629]
- "[...] the eccentric rod actuation *is a no-go for Airbus*, already investigated this: too complex (amongst which too tight tolerancing), too much effort (costs) *for too low profit*." [TL20170220]
- "Dassault is *interested in* the flap but it *is not giving any directions yet*" [SC20170629]
- "*Priority of Topic Leader Airbus is in the following order*: 1. Outer wing & Winglet; 2. Leading Edge Slat; 3. TE. [...] *The interest of DAV* is first to Target Applications 'multi-functional Flap + TE' and 'Outer Wing and Winglet'.", "[...] *explains again that Airbus is interested* only in the morphing spoiler for this TA [multi-functional flap and trailinge edge]." [TL20170705]
- "As a plan B, Airbus *is also interested in the [f]lap*. Especially about the development of a patent that they filed on active shock bump." [SC20171127]
- "ASCO immediately responded that *it is not interesting for them* to do it in the MANTA project but that they will set-up their own project outside MANTA" [SC20171127]

The deliverables show similar remarks, e.g. Heuer (2018, pp. 8-10) [D3] stating that "[t]he selection of concepts should [...] preferably be in line with the capabilities the MANTA partners would like to develop" and that "*Topic Leader Airbus has given highest priority* to the development of this target application". Similarly, a kick-off presentation details "a down-selection of target application has been conducted [...] in close cooperation with leading partners and full alignment with their strategic orientations", to continue with listing possible motivations and rationales for airframers to be interested in particular target applications [TL20170120]. In the DoA, industrial interests are also discussed ("[...] partners will exploit the project results according to these given conditions with the aim to individually and collectively provide the

air framers with solutions that will meet their needs for the airframe of the forthcoming aircraft" (Fokker Aerostructures BV et al., 2014, p. 30)), but position these *succeeding* the project, rather than *steering* it.

Decision bases

Section 9.1.2 already described the work packages defined in project MANTA and showed the multiple rounds of concept review, assessment and down-selection. The first assessment round (end of WP1) is based on a (qualitative) technology performance matrix, which includes "aerodynamic-, aero-acoustic-, structural-, volume-, power-, energy- and weight- & cost analysis" (Fokker Aerostructures BV et al., 2014, p. 42) [DoA]. The second assessment round (WP2) is based on aircraft-level performance estimations, generated using the Aircraft Design Initiator. In (potential) conflict with these academic assessment approaches are parts of the same document that state "[t]he industrial partners [...] will establish a ranking of concepts for evaluation at aircraft level" (Fokker Aerostructures BV et al., 2014, p. 42) [DoA]. Although this does not specify on what elements this ranking will be based, the context (this statement succeeds the previous excerpt) seems to imply it will use aforementioned 'technical' characteristics. Criteria for the second down-selection are largely consistent with this list, but are extended to include factors "such as [...] cost, maintenance, noise, safety, IP, partners own strategic preferences, etc", with Fokker Aerostructures BV et al. (2014, p. 51) [DoA] explicitly stating the "[s]election will take into account the Airframe ITD global objective and priorities for both next generation BJ and LPA [and] the core partners' own priorities". This is confirmed by Heuer (2018, p. 9) [D3], stating "it is preferred that the chosen concepts matches [sic] the product strategy of the industrial partners". Summarised, the DoA seems to indicate a shift from academic to more business-oriented decision bases as the work progresses. Nevertheless, that same document stipulates that "day-to-day decisions will be made [...] strictly respecting the project objectives, financial plan, dissemination or exploitation strategies" (Fokker Aerostructures BV et al., 2014, p. 64).

Reviewing the minutes of meetings shows business interests play a more substantial role from the start. Especially notable is the (unexpected, judging from complementary meeting material) decision by the topic leaders to "remove the Affordable Slat as Target Application from the project" [TL20180125] because "[b]oth companies do not show any interest in the further development of this Target Application". As a replacement, "Topic Leader Airbus introduced the idea of a morphing spoiler to enhance performance of the high lift system" (Heuer, 2018, pp. 12-13) [D3]. In this same meeting, Dassault "asks to research the possibilities for a morphing spoiler also for the BJ", which is agreed to as long as the budget permits [TL20180125]. Of the target application *outer wing and winglet*, the *outer wing* was removed as "[t]he reference platforms provided by the Topic Leaders do not include a foldable outer wing so there is no basis for further assessment of this option" [TL20180125].

These observations are consistent with a review of the technology impact matrix (Delft University of Technology, 2018) [D2], used for the first down-selection. This document was created by the consortium and indicates how all concepts were (qualitatively) scored (using a five-colour scale[6]) based on the impact of the solution on a number of performance indicators, yielding a subsequent selection. Concepts were scored on the performance indicators shown below and blank cells were used to indicate non-applicability of a particular score to a particular concept.

- Component mass
- System mass (i.e., mass impact on aircraft level)
- Direct operating cost (DOC)
- Manufacturing / recurring cost (RC)
- Non-recurring cost (NRC)
- Lift-to-drag ratio L/D (i.e. aerodynamic efficiency)
- Noise
- Maximum lift coefficient $C_{L,max}$
- Power (required)

[6] The colours – in their presumed order from good to poor – used are bright green, light green, yellow, orange and dark red. It is unknown whether the colours correspond to interval/ratio (rank-ordered, equidistant) variables or to ordinal (rank-ordered, not equidistant) variables (Bryman, 2012, p. 336). Based on the lack of features indicating otherwise, the former is assumed.

Table 9.1 shows the technology impact matrix as found in Delft University of Technology (2018), extended with numerical scores (based on the colour coding), weighting factors (estimated by the present author, based on the project objectives) and total scores in both unweighted (Uw'd) and weighted (W'd) form. Comparing these scores with the check mark indicating a particular concept was selected by the consortium to proceed to further analysis shows a number of discrepancies. The selected concepts for the target application *outer wing and winglet* (4.02, 4.03 and 4.X), for example, score substantially lower than some other concepts, most notably concept 4.12, applicable to the same TA. Similarly, none of the concepts in the *affordable slat*-TA is selected (as mentioned previously), even though their scores (especially concepts 4.21 and 4.22) are among the highest seen in the table.

Other

Especially in minutes of earlier meetings, there is evidence of a growing frustration under consortium partners with respect to topic leader involvement – specifically regarding reference models that would be made available. After various discussions in point of contact and topic leader meetings over the course of a few months, this was escalated to the steering committee: "MANTA project team indicates that Topic Leaders are reluctant in giving complete reference models which are essential for assessing the concepts on aircraft level. Also the promised content sometimes varies per meeting" [SC20171127].

In that same SC-meeting, questions were raised about the involvement of SAAB and the impact thereof on information sharing. SAAB and Fokker are competitors.

Table 9.1: Technology performance matrix (Delft University of Technology, 2018) [D2], extended with (total) weighted and unweighted analytical scoring

TA	ID	✓	CP	Platform	Part scores and weight factors: Component mass (2)	System mass (4)	DOC (2)	RC (1)	NRC (1)	L/D (5)	Noise (3)	$C_{L,max}$ (3)	Power (3)	Total scores: Uw'd	W'd
Outer wing and winglet	4.01		DLR	LR	-2	1	-1	-2	-2	1			-1	-6	-4
	4.02	✓	Fokker	LR	-2	1	-2	-2		1			-1	-5	-4
	4.03	✓	Fokker	LR	-2	1	-1	-2	-2	2	1		-1	-4	4
	4.11		TUD	LR	0	1	-2	-2	0					-3	-2
	4.12		Fokker	LR	0	1	0	0	-2	2	1	1	-1	2	15
	4.X	✓	Fokker	LR	-2	1	-1	-1	-1					-4	-4
	4.Y		Fokker	LR	-2	1	-1	-1	-1					-4	-4
Multifunctional flap + TE	4.04		DLR	HSBJ	-1		-1	-1	0	1			-1	-3	-3
	4.05		DLR	HSBJ	-1		-1	-2	0	1			0	-3	-1
	4.06		DLR	HSBJ	-2	1		0	0	1			0	0	5
	4.07		NLR	HSBJ	-1		-1	-2	0	2	1		-2	-3	1
	4.08		NLR	HSBJ	-1	1	-1	-2	-1				-2	-6	-9
	4.09	✓	Fokker	HSBJ	-1		-1	-1	-1	1	1	2	0	0	8
	4.10		NLR	HSBJ	-2		-2	-2	0	2	2	2	-2	-2	6
	4.13		TUD	HSBJ	0		0	0	-2	2	1	1	-2	0	8
	4.14	✓	Fokker	HSBJ	-1		-1	-1	0	2		2	-1	0	8
	4.15	✓	DLR	HSBJ	1		-1	-1	0	2	2	2	-1	4	18
	4.16		ASCO	HSBJ	1		0	1	0	1				3	8
	4.17	✓	TUD	HSBJ	-2		0	0	0	2		2	-1	1	9
	4.18	✓	Fokker	HSBJ	2		2	2	2					8	12
	4.19		NLR	HSBJ	-1			-1					-1	-3	-6
	4.20		TUD	HSBJ		1	0	-1	-1			1	-1	-1	2

Continued on next page

Table 9.1: Technology performance matrix (Delft University of Technology, 2018) [D2], extended with weighted and unweighted analytical scoring – continued

TA	ID	✓	CP	Platform	Part scores and weight factors: Component mass (2)	System mass (4)	DOC (2)	RC (1)	NRC (1)	L/D (5)	Noise (3)	$C_{L,max}$ (3)	Power (3)	Total scores: Uw'd	W'd
Affordable slat	4.21		DLR	SA	2		0	-2	0	2	2	0	0	4	18
	4.22		DLR	SA	0	0	0	-2	0	2	2	-1	0	1	11
	4.23		DLR	SA	1		0	1	0		1		0	3	6
	4.24		ASCO	SA	1		1	1	1					4	6
	4.25		ASCO	SA			0	0	0	0	-1		0	-1	-3
AAI	4.26	✓	TUD	SA	2		2	2	-1	2	2		0	9	25
Other	4.27		NLR, Airbus	LR	2			-1	0	2			-2	1	7
	4.28		TUD	TBD (SA)	2			-2	-2	2		2		2	16

Meta-information

Except for face-to-face meetings, minutes often take the form of e-mail annotations. Face-to-face meetings often take up a full day and are alternatively hosted by any of the organisations involved in project MANTA. In these meetings, representatives present their work based on PowerPoint-slides. These are sometimes also used in WebEx-meetings, using screen sharing to display the content to all meeting participants.

From approximately Autumn 2018, the project coordinator decided to stop making minutes. The coordinator felt the benefits did not outweigh the cost of making them, getting approval and distributing possible updates. Since then, meeting attendees are expected to make their own notes and – when relevant – share them within their organisation. It is unknown how meeting information (tasks, especially) is distributed if an organisation cannot manage to attend at all. Furthermore, not taking minutes increases the risk of miscommunication, as there is no process in place where meeting participants all agree on one particular representation of the meeting and the agreements that have been made during. Nevertheless, minutes are sometimes made 'live' during the meeting (again using screen sharing), either by the project coordinator, or by the representative presenting a particular work and gathering feedback.

Meeting attendance is varied, with face-to-face meetings seeing the largest number of participants. Of the total number of 51 identified[7] meetings for SC-, TL- and POC-meetings, attendance records are available in 28 cases (2 SC-, 12 TL- and 14 POC-meetings). In total, 42 people attended at least one meeting. 19 people attended 3 or more; 10 people attended 10 or more. This latter group includes representatives of all consortium partners[8] and the two topic leaders most involved.

Figure 9.5 graphically displays the attendance of meetings in project MANTA. The first three columns indicate the organisation (topic leaders on top, followed by consortium partners), the person and their role: topic leader (TL), consortium partner (CP) or external (EXT), such as a researcher or engineer that normally is not involved in the project. The grid on the right, then, shows actual attendance. The various colours correspond to the type of meeting (**point of contact**, **topic leaders** and **steering committee**), the shapes indicate the meeting format (circles for face-to-face, triangles for teleconferences, squares for WebEx-meetings and diamonds in case the format is unknown) and the size shows whether people attended the meeting, or were only sent the minutes afterwards.

From the wealth of information incorporated in the visualisation, a few things stand out. First of all, it shows that most organisations only have one contact that attends most of the relevant meetings. This holds for the topic leaders (AE for Airbus, GB for Dassault and CJ for SAAB), as well as for the consortium partners (MRA for ASCO, DV for DLR and JM for NLR). Notable exceptions to this rule are Fokker and – especially – TU Delft, of which two to three people attend most of the meetings. Furthermore, the figure shows attendance of face-to-face meetings is generally better than that of teleconferences or WebEx-sessions. The kick-off meeting early 2017 shows this clearest, but it also holds for meetings halfway through 2017 (point of contact and topic leader meetings) and in 2018 (topic leader meetings). In addition, Figure 9.5 shows the non-face-to-face meetings moving from teleconferences (triangle) to WebEx-meetings (square) late 2017. Last, some participants show (temporary) withdrawal from the project following high attendance early on (Fokker's HG, for example), whereas others have joined later on (such as ASCO's MD).

[7] Minutes are not available for all meetings. Using announcements for successive meetings, other meeting dates have been identified.

[8] As indicated before in Section 9.1.4, this sees FTH and FAE as one partner.

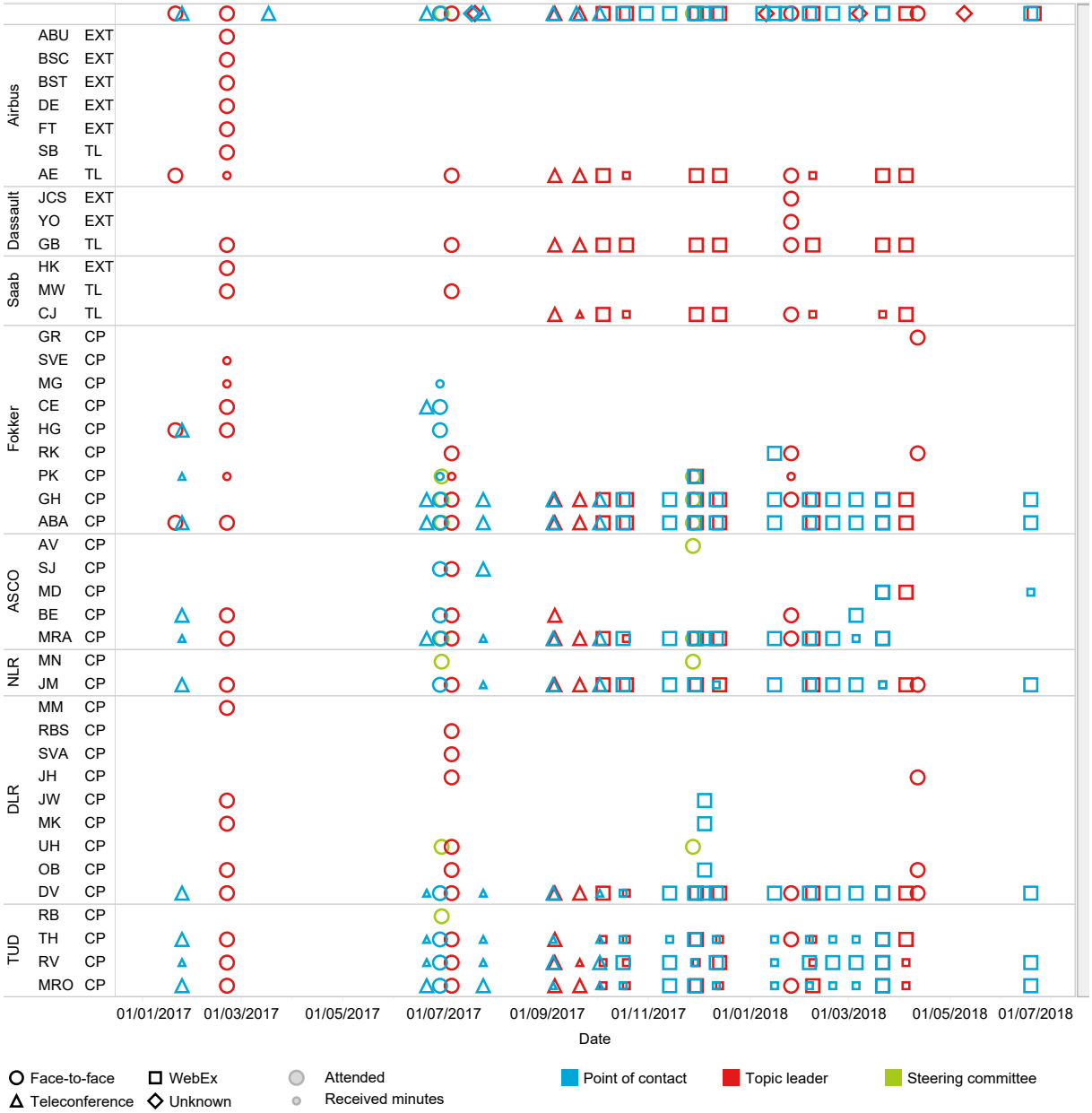


Figure 9.5: Project MANTA meeting attendance, showing organisations (first column), persons (second column) and roles (third column), meeting type (steering committee, topic leader or point of contact; colour), meeting format (face-to-face, teleconference or WebEx; shape) and attendance type (attended or only received minutes; size) from January 1st, 2017 to July 1st, 2018. The first row shows all meetings, including the ones of which attendance records were unavailable. For reasons of legibility, a meeting on September 26th, 2018, without attendance information was removed from the visualisation.

9.3. Participants perspectives

In order to further explore the inner workings of project MANTA from the perspective of project participants, as well as to validate findings from the document and literature review, individual qualitative interviews with participants were conducted. This section first discusses the methodology and subsequently presents the results.

9.3.1. Methodology

Interviews were conducted in a semi-structured fashion, discussing topics rather than specific questions. This leaves more room for the point of view of the interview participant and allows exploring unexpected directions (Bryman, 2012). The topics treated are listed below, including some of the sub-topics, and were selected based on the project context and research focus, the initial impressions gathered earlier (Section 9.2) and factors from literature (Section 3.2).

1. Project goals, including possibly different goals among participants.
2. Uncertainty, both in technological and socio-psychological terms, including discussion thereof, and personal impact.
3. Collaboration and cooperation.
4. Decision making, including e.g. information exchange and conflict.
5. Impact, in a general sense as well as specified to professional and personal levels.

The full interview guide – which takes into account remarks and suggestions from the research supervisors – is included in Appendix H.1. Open questions were used in order to explore opinions and sentiment as openly and unbiased as possible, regardless of the (partial) validation objective of the interviews.

The interviews were conducted in two phases. Interviews with two project participants of Delft University of Technology took place in December 2018 and were done face-to-face. Participants of the other consortium partners – with the exception of one organisation, which declined to participate – were held by telephone in May and June of 2019, after interviewees were solicited in person, following observation of a face-to-face meeting (further discussed in Section 9.4). The decision to do telephone interviews was first and foremost made to save cost and time (as the interviewees were dispersed over various countries). The suggestion that sensitive questions can be better asked by telephone than in person (Bryman, 2012), however, is considered an important benefit of this method.

Although one or more group interviews or focus groups might have provided interesting insights into the interaction of the participants as well as their possibly different views on the collaboration, this research method was not used as it might incline participants to hold back their personal views or answer in a more desirable way (Bryman, 2012).

Interviews were transcribed “verbatim” (IndianScribes, 2018), but[9] including stutters, repetitions and some fillers[10]. Pauses and ambient sounds were not included. This choice was made to strike a balance between detail – preserving parts where interviewees required multiple attempts to find the correct words – and transcription cost. The transcripts were subsequently structurally coded in order to categorise the various themes in the text (Saldaña, 2016). A pre-defined coding tree was used (included in Appendix H.3), but was extended when relevant. Subcodes were used to gather additional detail and in case particular transcript sections were relevant for multiple codes, simultaneous coding was applied

[9] For verbatim transcription, the following definition is used: “In this style, every word on the recording is transcribed as is, including grammatical errors and false starts. However, extra details like stutters and repetitions are removed.” This is different from *true verbatim*, which “is the most detailed account of a recording, including every word, sound and non-verbal communication” (IndianScribes, 2018).

[10] Less common fillers, such as the Dutch phrase “zal maar zeggen” were transcribed, whereas common fillers (such as “uhm” and “ah”) were not. Similarly, utterances used to acknowledge a response and/or show understanding were not transcribed, except in case these were part of the active conversation.

(Saldaña, 2016). Coded texts were then compared and analysed to arrive at the results presented in the next section.

With the exception of one interview, all were held in Dutch. Quotations from the interviews that are used to support the analysis that follows have been translated in English. Dutch texts are included in footnotes.

9.3.2. Results

This section presents the results obtained from the six participant interviews that were held, and simultaneously includes the analysis and interpretation. This choice was made to prevent readers from continuously having to go back and forth between separate results- and analysis-sections. In order to not let transparency suffer, interpretations or hypotheses inferred from the results are printed in **grey**.

The structure of the text follows the code tree as shown in Appendix H.3, largely corresponding to the outline shown in Section 9.3.1. **Blue** headings indicate the topic, **black** headings (in-line) are used to label particular elements of a topic.

Participants

This section discusses the background and role of the interview participants. Except for one, people from all consortium partners have been interviewed. Two people (per organisation) were interviewed in case of two organisations; only one person (per organisation) in case of two other partners.

Background The background of the interview participants varies from PhD-students to seasoned professionals. Most interviewees have experience with research projects (for one, project MANTA is their first). Half the participants have a pronounced research-background (although for two of three, project MANTA is their first project of this scale), whereas others have previously occupied engineering or (engineering) management positions. All hold degrees of higher education and have an educational and/or professional background in the aerospace industry.

Role Four of six people are their organisations' representative (*point of contact*) within the MANTA-team. That means they coordinate the work that their organisations do for project MANTA and as such, they generally occupy somewhat managerial role, having job titles as *engineering lead* or *technical project manager*. Half of the people spoken to have been involved with project MANTA from the start (including the proposal and project definition phases), two others have joined in the execution phase and one of the interviewees on-boarded later (early 2018, during WP2), due to personnel changes at one of the consortium partners.

Goals

This section discusses goals, treating the main project goal as well as derivative goals, individual goals of the various project partners and possible conflicts between these.

Project goals Whereas the project goal is officially described as making a "a contribution to the technology maturation TRL 1-3 to TRL 4-5 for novel aircraft movable concepts that will contribute to the Airframe-ITD TS 4 challenging objective of 3 to 5% aircraft fuel burn reduction", participants responded differently and variably when asked for this. Only two of six participants 'got it right'. Two others did mention fuel but not specifically denote movables, whereas the final two interviewees emphasised the development of morphing technology, but did not mention fuel.

Elaborating on this, one interviewee explicitly stated having the impression that the focus has shifted and noted that only one consortium partner seems to strive to attain the original project objective, whereas others have more and more moved towards fulfilling the ambitions of the topic leaders. Another interviewee described this as "bad practice", because "the moment you define an objective in a project plan,

I feel that you have to try and meet that goal, and that if you start diverting [from that goal], you would need to start a new project"[11].

Sub-goals Besides showing different recollections of the overall project goal, the interviews indicated that sub-goals exist, either at the level of individual organisations or groups thereof. One topic leader, for example, expressed an interest in increased climbing performance or getting an overall assessment of the usefulness of the technologies under investigation, regardless of fuel burn impact. Two people independently hinted at the idea of project MANTA being a benchmark study, set up to test and validate ideas the topic leaders have developed previously.

The consortium partners, then, all to a greater or lesser extent aim to further build their own knowledge, expertise or product portfolio, or push technologies they already have got under development. A number of interviewees furthermore mentioned relationship-oriented goals, such as building or maintaining a professional network or taking the opportunity to see the questions their clients are currently dealing with, providing companies with a knowledge of future market needs. In terms of sharing or protecting research outcomes, the interviews show a difference between the research institutes and the commercial partners involved in the project.

Lastly, some interviewees discussed the grander collaboration and innovation objectives the European Commission aims to attain through public-private-partnerships of which project MANTA is part.

Conflict Given the wide array of interpretations of the project objective, let alone the substantial amount of sub-goals, conflicts between these objectives would not be surprising. Whereas some participants indicate this is not the case in project MANTA, others do see some conflicts. This ranges from people describing "differences in point of view"[12] to others noting the "company interests clearly outweigh the academic, purely knowledge-based interests"[13]. One interviewee stated that these differences are not always explicated, but that some discussions do give the impression of being driven by an individual agenda. Another participant noted being "relieved"[14] that the concepts selected in WP3 matched the interests of the topic leaders.

Uncertainty

This section reviews the participants perspectives and impressions of uncertainty. It starts by discussing what uncertainties people see, subsequently moving on to how these are discussed and managed.

Types During the interviews, participants mentioned various types or sources of uncertainties. The majority sees uncertainties or risks with respect to project management, budget and group composition.

Also, interviewees noted uncertainties inherent to the conceptual design project that project MANTA is: as the outcome of selection processes is initially unknown, there is uncertainty about the type of activities that are to be conducted in a later stage. This is similar to uncertainty about market and industry trends, mentioned by one interviewee, and the uncertainty about the chances of concepts making it through more detailed design phases to a commercially viable product. Related – but still notably different – is the fact that four people mention the project goals are uncertain. This uncertainty has reduced over time, but was especially notable during earlier phases of the project. Associated to this is uncertainty about sub-goals: it is not explicated what it is that drives the consortium partners to participate in the project. As such, it is also unknown what changes in the project might drive participants away.

There are more pronounced technical uncertainties, too. Three people noted that there are uncertainties related to the results generated by analysis tools. Similarly, one participant indicated that it is not known to everybody in what ways goals (or deliverables – such as the fuel burn impact assessment) can be realised.

[11] "op het moment dat jij in een projectplan een doel opstelt dan vind ik dat je binnen dat project dat doel moet trachten te halen en als jij daarvan gaat afwijken dan moet je eigenlijk een nieuw project gaan beginnen"
[12] "een verschil in zienswijze"
[13] "de bedrijfsbelangen die overschreeuwen de, nou ja, 'wetenschappelijke', puur kennis-gerichte belangen"
[14] "mag ik het een opluchting noemen?"

Discussion Participants show a mixed response when asked about the extent to which uncertainties are discussed, with answers ranging from “not explicitly”[15] to “it comes up”[16].

A broader analysis of the interview transcripts fuels the hypothesis that ‘smaller’ uncertainties – such as finding a suitable approach to writing a particular report – are discussed more openly, but that the ‘larger’ and more fundamental uncertainties – about project goals, for example – are not explicated very well. It seems the consortium is more at ease discussing technical or project management related uncertainties, then they do talking about social uncertainties. It might be that people are more reserved when it comes to the latter category because they are not sure how others will respond.

Management From the interviews, it shows that uncertainties within project MANTA are managed by reducing the uncertainties or by essentially insuring against these. The former is, for example, realised by asking topic leaders for additional steering or guidance, writing a call for partners to invite external parties with particular expertise to contribute to parts of the project or performing (additional) tests. The latter strategy includes adding budgetary buffers. Besides this, uncertainties are postponed to be dealt with when they result in problems or issues.

Collaboration

This section treats the collaboration within project MANTA, discussing the general impression participants have of the collaboration, the extent to which people know each other and are aware of their expertise, group or team integration and hierarchy.

Impression When discussing collaboration in general, the interviewees did not mention any problems. There are no conflicts and people respect the work of others’. One interviewee noted that communication is not always centralised, as some organisations are more tightly linked to one another (such as Airbus and DLR, and DLR and NLR), because of previous collaborative experience or for historical reasons. That is not necessarily a bad thing, according to that same interviewee. The collaboration can be further improved with increased and more distributed initiative (which is already happening, over time). Also, work can be done to better meet deadlines.

Acquaintance People indicate they have gotten to know each other better over time, starting from not knowing each other before writing the proposal, to knowing them “fairly well”[17] at the time of the interview. According to various interviewees, the fact that there were little personnel changes has aided in this. Face-to-face meetings are especially helpful for building these relationships. This was mentioned both by people involved from the start, as well as by the person who joined project MANTA at a later stage. That person said “it is very difficult to put a face to a name if you only talk to each other through teleconference”[18].

Unsurprisingly, people mostly answered questions about being acquainted with fellow project participants at the level of points of contact. One interviewee explicitly mentioned not knowing what all engineers (that contribute to project MANTA, but whose contributions are often shared by their organisation’s point of contact) do.

Expertise At the start of the project, most people only had knowledge of the activities and expertise of partner organisations. With time (and with growing acquainted with one another), interviewees gained insights in the individual expertise of other project partners.

Integration Consistent with previous responses, the interviews show a shift in team integration. Various participants indicate they felt the consortium operated as a group in the earlier project phases, but has become more integrated (towards a team) over time. Elaborating on their answer, interviewees linked team integration closely to shared goals and a shared understanding of the problem. One participant indicated feeling closer integration with some partners than others, due to more open collaboration (sharing information, for example) and less focus on an individual agenda.

[15] “Niet zo expliciet, eigenlijk. Nee.”
[16] “het komt bij meetings wel naar boven”
[17] “vrij goed”
[18] “als je enkel *telcon*-contact hebt is ‘t heel moeilijk om op de stem een gezicht te plakken.”

Hierarchy According to the interviewees, project MANTA is somewhat hierarchical – in the sense that one organisation (Fokker) is coordinating the project. One interview participant in particular noted this mostly concerns having certain responsibilities, but would otherwise see the consortium partners as "equals"[19]. Opinions differ on the hierarchical position of topic leaders. Whereas one participant felt one of the topic leaders was not reluctant to exploit its hierarchical position (while nevertheless realising the topic leaders to some extent indeed do have this role) and thereby taking more than giving, another was less critical. That person indicated that the topic leaders "can sometimes be more steering, to put it that way"[20], but at the same time stated this was "acceptable"[21] and "positive when making choices"[22].

Decision making

This section presents the interview results with respect to decision making. Starting from the participants' impression, it discusses dominance, strategy, information exchange, on what information or arguments decisions were based, and (organised and unorganised) conflict.

Impression In a general sense, the interviewees are mostly positive about decision making. One participant feels it is object of discussion. People especially indicate being content about the last selection meeting, which was a constructive process with a clear goal and increased involvement of the various consortium partners.

Dominance Contrary to earlier phases in the project, decisions in the later stages are made by the project consortium. According to various interviewees, no single partner is dominant in pushing for a particular outcome: the consortium is "fairly balanced"[23]. However, it does occur that one partner makes an initial proposal towards a decision, which the other consortium members then follow or refute. Earlier on, topic leaders had a more pronounced role in the decision making, with one participant acknowledging that from their perspective, the topic leaders essentially made the most important decisions. The change in target applications, described in Section 9.1.3, is a clear example.

Strategy The interview results confirm Fokker Aerostructures BV et al. (2014), stating that decisions are generally reached by consensus. At least one exception to this is the aforementioned decisions to change target applications, which one interviewee confirmed was "not very democratic"[24].

If the consortium partners are unable to make a decision, it is left to the steering committee of project MANTA or – ultimately – management structures of the Clean Sky organisation. Up to now, that has not been necessary. On the other hand, consortium partners have had to make some concessions – between each other or to accommodate the ideas of the topic leaders.

Bases Multiple interviewees indicate the selection choices are largely based on engineering judgement of analysis results. As one participant put it, that method is "of course up for debate, [...] but of course has everything to do with [...] how much time you can spend on each concept"[25]. This was confirmed by somebody indicating that it is not always possible to analyse everything in detail due to the complexity of the product.

Contrary to these results, another interviewee indicated that during early stages, "decisions were mainly based on strategic interests, business interests [...] rather than technical interests: what are the capabilities of the consortium partners, what do they want to develop and what do the topic leaders want to see developed?"[26]

[19] "gelijkwaardig"
[20] "dat de topic leaders wel eens sturend zijn, om het zo maar te zeggen"
[21] "acceptabel"
[22] "positief ervaren is in het maken van keuzes"
[23] "redelijk gebalanceerd"
[24] Researcher: "[...] was wat dat aangaat dan ook niet heel democratisch." Interviewee: "Nee, dat denk ik niet, [...]"
[25] "daar kun je natuurlijk wel wat vraagtekens bij stellen, [...] maar dat heeft natuurlijk alles te maken met [...] hoe veel tijd heb je te besteden aan ieder concept"
[26] "de besluitvorming werd vooral genomen op basis van strategische belangen, dus, bedrijfsbelangen, [...] in plaats van technische belangen: [...] wat kunnen de consortiumpartners, wat willen ze graag ontwikkelen en wat willen de topic leaders graag ontwikkeld zien worden?"

Information exchange Information is exchanged prior to decisions in meetings, as well as continuously through a file sharing system.

Conflict During meetings or in separate conversations between these, there is room for consortium partners to raise questions about each others' work. "Critical questions are asked in generally all meetings, about the results: what are the assumptions, what are the reference values, and so on, and so on. That happens."[27] Multiple interviewees note that most scrutinising happens between partners with similar expertise, such as DLR and NLR, or ASCO and Fokker. For a structural engineer, for example, it is difficult to properly assess the work of an aerodynamicist.

Despite the fact that questions are raised, this does not take the form of organised conflict, devil's advocacy, or people explicitly asking for feedback. No single participant indicated feeling that there might be conflict below the surface. Most of them regard conflict as bad, probably interpreting the term too harshly as compared to its use in the decision making literature treated earlier.

Facilities Although various data sharing and collaboration facilities exist, various participants noted there is room for improvement in this area. One interviewee in particular stated that face-to-face meetings have played an important role in getting to know the other consortium partners and that teleconferences or WebEx-meetings are no match for face-to-face contact. Another interviewee agreed that face-to-face meetings contribute to easier communication.

The interviews also show that one participant feels that data exchange can be improved in terms of format (it relies heavily on PowerPoint-presentations) or structure, suggesting it might be interesting to set up a data sharing platform for the entire set of Clean Sky projects. Another person criticises the lack of minutes of meetings and project documentation. Without that, it cannot be objectively established what was agreed upon during an earlier phase, meaning time is lost when that discussion has to be recollected.

Impact / problems

This final section combines participants' response to questions regarding the impact of all other topics, on both a personal, project and (more general) professional level.

Personal On a personal level, impact seems rather limited. Most people feel good about the project, find it interesting and/or are not really affected by the things that do not go so well. On the other hand, one interviewee noted feelings of "indifference"[28] due to poor collaboration, communication, data exchange and shifting objectives. This leads to reduced motivation. Another participant shared a related experience from a previous project, stating that it felt more like product development, even though that was not what the project was set up to be.

Project At project level, participants are slightly more critical. A more outspoken interviewee noted that the changing objectives "limit the attainability and success"[29]. This also holds for the uncertainty about individual sub-goals. In the opinion of this participant, the process of working together is improved by being more open towards each other. Another interviewee, too, is under the impression that the collaboration is hampered by diverging interests of the various consortium partners. Two others mention that they feel the budget has not always been spent most effectively (because of unclear project goals and direction) and that various partners could have shown more initiative. This last item does not seem unrelated to the personal notion of indifference and reduced motivation.

Professional Besides personal and project impact, one participant argued that it is bad practice to set particular objectives, then work towards achieving other goals without explicating this shift.

[27] "Er worden eigenlijk altijd wel kritische vragen gesteld bij die, bij die meetings, naar resultaten: wat zijn de aannames, wat zijn de referentiewaardes, et cetera, et cetera. Dat gebeurt."
[28] "een zekere mate van onverschilligheid die je kweekt"
[29] "de haalbaarheid of het succes van een project belemmert"

9.4. Decision making in action

Following a welcome invite by one of the consortium partners, a face-to-face meeting was attended and observed in order to study the collaboration and decision making process in real life. This method was selected to provide a third data source, in order to improve the validity of the overall data set. It adds to the research methods described previously by providing insight into the *process* (rather than only the outcome, as is the focus of the documents reviewed) and preventing biased recollection of events (which is a associated to doing interviews).

In the observed meeting (which took place on Thursday, May 2nd at the Fokker-offices in Papendrecht, The Netherlands from 08:30 to 17:00 hrs[30]), the consortium partners finalised the down-selection at the end of work package 3. Going from multiple concepts for various target applications, the meeting had as its objective to "[t]rade the concepts and select 2 concepts for further development" [meeting invitation]. Scoring criteria and weighting factors were agreed upon in WebEx-teleconferences preceding this face-to-face meeting (totalling approximately three hours). The observed meeting was attended by one or two representatives of all consortium partner organisations, with the exception of one of the research institutes.

The next sections describe the method uses as well as the insights gathered using the observation. The meeting agenda, as sent to all invitees, is shown in Table 9.2. For reasons of confidentiality, names of the persons chairing a particular topic are left out.

Table 9.2: Agenda for observed meeting *Workshop Trade table and concept selection*

Start	End	Duration	Topic
08:30	08:45	00:15	Introduction
08:45	09:00	00:15	Summary criteria & weighing factors
09:00	09:20	00:20	Discussion baseline
09:20	09:30	00:10	Coffee break
09:30	12:00	02:30	Trade multi-functional flap concepts
12:00	13:00	01:00	Lunch
13:00	15:30	02:30	Trade winglet concepts
15:30	15:40	00:10	Coffee break
15:40	15:55	00:15	Selection of concepts
15:55	16:10	00:15	Closure of meeting

9.4.1. Methodology

In order not to impose on or disrupt the project's progress during the meeting and unsure about the detailed planning of the day, no detailed observation plan was made beforehand. Rather, brief notes were taken as notable things happened. In terms of the field roles discussed by Bryman (2012), the author tried to balance partially participatory and full participatory roles: on one hand being a true external observer, but on the other hand, interacting with the group when asked a question or when detecting significant bias or decision making errors.

[30] Vigilant readers will note this observation took place before the majority of the interviews, discussed in the previous section, were conducted. The current reporting structure was selected as it is deemed more logical with respect to both the level of detail (least in the document analysis, more in the interviews and observations) and perspective (mostly external in case of the document analysis and much more internal in the phases involving direct contact with project parties.

9.4.2. Results

This section presents and discusses the most relevant insights gained from the observation. These are grouped in a number of subjects: references, scoring and criteria; information availability; making versus supporting decisions; and organisational representation, participation and collaboration. In terms of the categories defined in Section 3.2, the first two are mostly technical, whereas the last two groups are mostly socio-psychological aspects.

References, scoring and criteria

Contrasting the meeting objective with the agenda immediately shows a potential discrepancy, as the agenda anticipates concepts from each target application being selected. Related to this is the surprising fact that the overall aircraft assessment outcomes were not used, as these could only distinguish between target applications (with the flap concepts achieving a higher fuel burn reduction than the winglet concepts) and not between individual concepts.

Despite the earlier WebEx-meetings to discuss criteria and scoring, considerable vagueness was observed regarding these topics. Whereas it was first decided to score concepts with respect to a baseline aircraft, the group later started scoring relative to concepts, as the baseline-comparison made it difficult to distinguish between concepts – the ultimate goal of the meeting. A clear decision or announcement regarding this was however not made.

Moving to relative rating was further supported by the fact that different concepts were analysed relative to different baselines, most notably in the business jet concept (multi-functional flap target application). Another problem with the original approach with which the project group was confronted, is that particular concepts originally scored worse that the baseline. Even though this has a straightforward explanation (detailed in the box below), it surprised the meeting participants.

> **Why did a new concept score worse than the baseline?**
> Two causes contributed to the fact that some concepts initially scored worse than the baselines they were compared to: prescribing improvements as design criteria and scoring concepts on part-level, rather than on system- or aircraft-level.
>
> All concepts within a particular target application (such as a winglet or a multi-functional flap) were designed to be alternatives and meeting a number of design requirements. As such, these aspects were removed from the trade-off criteria – as the concepts would all meet these, and they could therefore not be used to distinguish between concepts. However, when comparing to a baseline that does not meet these design requirements, the comparison is skewed. In other words: it causes the concepts to be penalised for additional complexity or a low TRL (and associated development and commercial risk), without rewarding these concepts for the fact that they meet design criteria the baseline does not meet.
>
> The aforementioned problem is worsened by comparing isolated concepts with baseline (sub-)systems. Especially in case of the multi-functional flap, the flap itself will be heavier, more complicated and more expensive than a regular flap. However, its advantages are in the fact that it can fulfil functions of other wing movables – thus making these redundant or unnecessary. If that difference is not taken into account when contrasting the concepts and the baseline, the comparison is again skewed in favour of the baseline concept.

In summary, it seemed the selection objective and methods employed were not in accordance with each other. Whereas the goal was to determine the best of a number of concepts (warranting relative comparisons), baseline-comparisons – fitting with the question of whether any of the new concepts are better than current state of the art – were proposed. Although the group was puzzled to find the baseline outperforming some of the conceptual designs, no consortium partner noted, shared or discussed the analysis shown in the box.

In terms of scoring, then, one party proposed scores of 1, 3 and 5, whereas another moved to rate concepts as worse, neutral or better/good. After discussion, these metrics were accepted as equivalent. In case of uncertain information, conservative scores were awarded. Engineering judgement was used to

classify information as certain or uncertain, without the possibility of using various levels of (un)certainty or risk. Although it is not necessarily bad to score conservatively (it only indicates the consortium to be risk-averse rather than risk-seeking, or, put differently: not wanting to envision something is better than it is), the fact that multiple criteria (performance and risk) are combined into one number decreases transparency, making it more difficult to validate or challenge a particular score. No difference of this tactic was observed between criteria with low or high weighting factors.

Furthermore, an unintended effect of the selected method of combining scores (summing scores averaged over the number of scores in their group, rather than directly summing scores, yielding to an additional weighting factor inversely proportional to the group size) was corrected after observer interference. Lastly, some criteria were adjusted during the meeting.

Information availability

Most scores were determined from combined engineering judgement of the group, not seldom introduced by one of the participants asking “what do we think?” Sometimes, participants referred to analyses or reports created by colleagues not present at the meeting. On multiple occasions, participants admitted to not knowing the underlying details or assumptions.

Making versus supporting decisions

The most interesting observations were made when scores were combined and conclusions were drawn. When, for example, one particular flap concept scored lower than a baseline, one meeting participant stated “now the only question is how to turn things so it’s like we want it”. Something similar occurred when the scoring of winglet concepts lead to the selection of a concept that did not fit the preferences of the partners. Rather, a participant asked “how can we turn it that [the desired concept] is better than the [highest-scoring concept]?” Changing the reference and scoring the concepts again proved effective, after which a meeting attendee concluded somewhat enthusiastically “we now have the winner we want to have” and “we succeeded, we tweaked towards the desired answers”.

Organisational representation, participation and collaboration

Overall, the meeting atmosphere was relaxed, with no particularly dominant or passive attendants or situations of conflict, and room for some laughter every now and then. One meeting participant recorded the agreed-upon scores in a spreadsheet to perform the summation and keep track of progress, whereas another wrote down the rationale for these choices. Both documents were available to the other participants by means of a large screen, allowing other attendees to identify and correct any errors or omissions. Initial suggestions for scores were sometimes provided by the person in charge of the spreadsheet and sometimes by other attendees. Every now and then these were directly accepted by the rest, or formed the start of an effective discussion ending in consensus.

More than before (judging from the document analysis and interviews, specifically the meeting in which one of the target applications was removed from consideration at the discretion of the topic leaders), the consortium partners acted as a team. At the end of the meeting, it was happily concluded that every partner (co-)owned one of the selected concepts. Also, previously more competitive partners now were more cooperative in, for example, making sure the concept proposed by the other did not come out to look bad in the down selection report. Last, the group jointly took up the assignment of determining the most effective approach to share the meetings’ conclusions with the topic leaders, rather than only caring about getting support for the choice that selected their concept. Despite this, one of the representatives of one of the industrial partners left the meeting after their concept made the selection, stating not having the feeling of being able to contribute a lot. Although this was not verified, it is not unlikely that this person only attended to see to it this outcome was reached.

Lastly, the influence of the topic leaders was observed – even though they were not represented at the meeting. Airbus’ was brought up multiple times, speaking about and referring to the company as if it was the main customer of the consortium. Utterances included “what [...] wants us to do”, “the wish-list of [...]” and “[...] is asking a lot”. A meeting participant later clarified Airbus was explicitly mentioned, as

Airbus also represents the interests of Dassault and Saab. This was however not mentioned during the meeting, nor could this role be verified in the DoA (Fokker Aerostructures BV et al., 2014).

9.5. Problem statement

Based on the information presented above, several difficulties and potential problems can be identified. The project is complex in terms of organisation and collaboration, minutes of meetings are not always available, consortium partners could show more initiative, data sharing can be slow, meeting attendance is varied and the way meetings are held (i.e., through teleconference or WebEx, rather than face-to-face) compromises on clarity and effectiveness.

Most notable, however, is the widely shared impression that goals and sub-goals are unclear. Put formally: *goal uncertainty* exists. This uncertainty also seems to spur some opportunism, as mostly industrial and commercial (sub-)goals often seem to outweigh the objectives as seen from the societal and academic perspectives. In turn, this results in the fact that decisions are in some cases based more on individual (personal or organisational) goals, interests and opinions, rather than analytical results. A related and possibly even more fundamental problem observed in project MANTA is the fact that this situation is seldom explicated, hindering transparency. Following the definition presented in Section 3.1.5[31], this directly reduces decision quality. Lacking openness and a clear goal, the ideal observer determining decision quality is not completely aware of the decision goal and therefore cannot make an accurate assessment. Although that seems a largely theoretical problem, it is much more than that in reality: if one cannot determine the quality of something, it is impossible to accurately evaluate and subsequently improve. Specifically in the context of project MANTA, this might result in project resources being spent less effective or efficient than they might have been, slowing the pace of research and innovation.

The remainder of this report is focused on this latter problem, formally defined as follows:

> The quality of screening decisions in project MANTA is negatively impacted by the fact that goal uncertainty exists and is not sufficiently explicated, reduced or otherwise managed.

This choice is made for a variety of reasons, most important of which is the observation that many of the other problems identified before have been resolved, either thanks to the passing of time or because of the adjustment of (individual) expectations. The personal preference of the author also played a role in this decision. This is further elaborated in the following box.

> **Personal preferences influencing the problem definition**
> When I was raised, my parents paid a lot of attention to fairness, justice, transparency, openness and accountability. Equal opportunities were important, as was being rewarded for the work you did rather than the name you beared. Looking back, I don't think they were surprised to find me writing a letter to the board of my elementary school, questioning why other classes had privileges we hadn't and why people were sent for detention for dubious reasons. In the end, they supported me, proofreading my text and standing up for me when called in to explain why they had raised such a condescending brat. At home, there never was a question that I couldn't ask (as long I would accept "no" as an answer, if it turned out that way). Similarly, when having conversations with their friends, my parents rarely sent me away and almost always allowed me to participate in the discussion.
>
> All throughout this research project, I've noticed these values popping up. At first, this took the form of doubts regarding the project goals of project MANTA. "It almost seems as if Airbus gets their research and development department paid for by public funds", I remember thinking. When I learned in interviews other research participants also noted a (potential) conflict between academic and industry goals, I wondered why no-one spoke up. Later on, I became much more aware of the various levels of complexity, that (might) explain why people didn't act. Later still, I realised funding agencies like the European Commission don't only sponsor research for the sake of producing knowledge, but see it as a method to contribute to larger policy goals: mitigating global warming, making sure there is a flourishing economy, reducing unemployment. The

[31] "The extent to which a (group of) decision maker(s) at the decision point can convince an ideal observer that the decision will yield the decision goal, insofar possible."

> more time I spent on this project and the more insights I gained, the more I found myself seeing both sides. "If Airbus getting a discount on their R&D spending is what it takes for knowledge from universities and research centres to bridge the gap to industry and for *theoretical knowledge* to become *practical knowledge* (something for which these institutions lack the resources), it might actually be a very good deal!"
>
> What remains, is the problem that nobody seems to explicitly address this dichotomy – neither in- nor outside the project. Decision are made first, analytical reasoning is conceived after the fact. In the process, transparency is lost: did a score in a trade-off table follow from calculation, or was it entered in order to end up with a ranking that was predetermined all along? Besides the fact that one might argue this is a problem in and of itself, it makes it next to impossible to set any form of normative criteria. Extending the earlier example: given a particularly effective public-private-partnership, how much industrial sponsoring are we – the European Commission, tax-paying citizens – willing to pay for that? And from a research perspective: how much academic independence are we – researchers, institutions – willing to give up in such a partnership, given the fact the budgets that come with it allow us to gather new insights and test new ideas? Although I am not of the opinion that *I* should set these norms in this research project, I am strongly convinced of the opinion that *it should be possible* to set norms. This not only increases transparency, but also makes it easier to take accountability and responsibility for the project – both along the way, as well as when the project comes to an end

Depending on the level at which the problem is observed, various problem owners can be identified:

- Individuals in the project team, as it can negatively impact their attitude towards the project and therefore their working pleasure.
- In turn: the project team, as it will be less enjoyable to work in a team in which people are not motivated.
- Organisations involved in the research project, as they might not obtain the results they are (ultimately, individually) looking for, yet have no way of knowing up front these goals are reasonable or not – as precisely that discussion is not held. Organisations investing more resources might be affected more than parties involved to a lesser extent.
- Sponsor(s) of the (research) project, who might not get the best results for their investment.

Extension beyond project MANTA

Even though the results shown in the current chapter are obtained from a detailed analysis of project MANTA, it is reasoned the problem statement presented is not limited to project MANTA alone. Rather, it is argued that the problem identified in project MANTA is a result of a combination of project characteristics, which are not unique to this project or the aerospace industry. For example, in a biopharmaceutical context, Pronk et al. (2015, p. 240) have too argued the importance of acknowledging, discussing and aligning different objectives, noting that failure to do so "will, at best, cause friction and wasted time [and] at wordt, it may result in a complete failure to meet objectives". Based on the analysis of project MANTA and discussions with various others, five aspects are proposed below:

- **Conceptual or exploratory nature**
  Projects that are largely conceptual or exploratory are likely to include higher levels of uncertainty about the project goal. Both fundamental and more applied research projects often fit this description, but examples can also be found outside academia or R&D.
- **External sponsor**
  Projects with a sponsor[32] external to the team – in other words: the project group is working on an assignment it was given by another party – will be more susceptible to misalignment of internal and external goals, simply because these internal and external environments exist.
- **Limited resources**
  Projects strictly bound by time, as that will likely make it more difficult to spend enough time or attention to correct possible misalignment.

[32] To be interpreted as the Dutch 'opdrachtgever', rather than 'funding agency'.

- **Varying interests**
  Projects that involve a lot of stakeholders but lack a clear hierarchy are more likely to entertain a variety of interests, which give rise to different objectives.
- **New collaborations**
  Projects that comprise new groups of collaborators will see more ‘social uncertainty’, possibly reducing the extent to which people raise attention to uncertainty of or misalignment between project objectives.

Given this claim for (limited) generalisability, the following chapters (and research questions answered in these chapters) are not restricted to project MANTA specifically. The remainder of the report is, however, limited to group decision making in projects which are characterised by the aspects shown above.

10

Theoretical framework

Whereas Chapter 9 described the project and defined a problem negatively impacting decision making, the current chapter sets a first step towards designing a solution. In order to do so effectively, a theoretical framework is set up – with the aim to gain theoretical understanding of the problem and the underlying complexities of decision making. In other words, it attempts to consolidate, integrate and synthesise the research objectives (Section 1.2), the problem statement (Section 9.5) and the influences on decision quality (Section 3.2) presented earlier. This chapter presents that theoretical framework and thereby answers research question II-c, *What theories or frameworks can be used to improve understanding of the most relevant of these factor(s) impacting group decision making?*. In turn, the framework provides an overview of the fundamental principles that need to be included in the model, to be developed in Chapter 11.

The basis for the theoretical framework is found in the comparison of the specific problems faced in project MANTA to the influences on decision quality. McLeod (2013), Hirokawa and Scheerhorn (1986), Schultz et al. (1995) and Sassenberg et al. (2014) identify the importance of setting clear group goals and Salazar (2009), Larson Jr. et al. (1998a), McLeod (2013) and Oetzel (2017) stress the need for *vigilant interaction*[1]. Many of these publications are based in *vigilant interaction theory*, which is one pillar on which the framework is built. A second pillar is formed by *effective intercultural workgroup communication theory*, which is closely related to vigilant interaction theory and was identified in a related publication. Most importantly, effective intercultural workgroup communication theory was included as it explicates both the task (reducing fuel burn) and relationship (strengthening a business network) dimensions of the project goals of project MANTA.

The remainder of this chapter discusses these two theories in greater (historic) detail, in order to provide a foundation for the theoretical framework. This is done in Section 10.1. Section 10.2 presents a critical reflection on the theories and their limitations. Somewhat opposite, Section 10.3 reiterates the underlying core concepts and enforces the elements of the theories that hold the promise of providing further insight into the problem and possible solutions. Their applicability to project MANTA is treated in Section 10.4.

10.1. Foundations

This section presents the two theories which take a central place in the theoretical framework, starting with vigilant interaction theory in Section 10.1.1 and ending with effective intercultural workgroup communication theory in Section 10.1.2. Besides an introduction to the theories, this section discusses their origins and closely related work.

[1] Vigilance – the state of being vigilant – is synonymous to *alertness*, *caution* and *diligence* and antonymous to *indifference* and *carelessness*. In Dutch, it can be translated as *oplettendheid* or *waakzaamheid*.

10.1.1. Vigilant interaction theory

As the name suggests, vigilant interaction theory, which originated in the 1980s, links the quality of interactions within a group to the quality of the output (Hirokawa and Rost, 1992). Hirokawa and Rost (1992, p. 269) see interaction as a "social instrument" which is instrumental in the process groups go through in order to arrive at a decision. It "maintains that group interaction affects decision-making performance by directly shaping the quality of vigilance (or critical thinking) that leads to a final group choice" (Hirokawa and Rost, 1992, p. 269) and, as such, "is able to specify the factors that contribute to high- or low-quality group decisions" (Hirokawa and Rost, 1992, p. 270). With this notion, it connects to the equation "actual productivity = potential productivity – losses due to faulty processes", put forward by Steiner (1972, p. 9) (Gouran and Hirokawa, 1983; Orlitzky and Hirokawa, 2001).

Analysing the theory from a historical perspective, it is clearly grounded in systems thinking (Oetzel, 1995) or cybernetics (Littlejohn and Foss, 2011) – seeing the decision-making process as a system that takes input (such as information and group composition) and turns it into output (a decision). Vigilant interaction theory is most often attributed to Hirokawa, although the idea of *vigilant problem solving* was first put forward by Janis (1989, p. 20) and other scholars have contributed to the theory. Gouran and Hirokawa (1983, p. 174), for example, stress that critical reflection or vigilance is required to apply criteria to alternatives. Furthermore, they note that sound judgement is not an automatic result of such an assessment – which requires "skills, knowledge, and a highly developed sense of objectivity". Hirokawa and Scheerhorn (1986, p. 66), although not using the term *vigilance* explicitly, outline the main stages of the vigilant interaction process: assessment of the situation, identification of alternatives and objectives, and assessment of the positive and negative consequences of any alternative. Since its (mostly descriptive) inception, vigilant interaction theory has developed in a more prescriptive dimension and is nowadays also used "to teach groups how to make better decisions" (Littlejohn et al., 2017, p. 296). They should, as quoted from Littlejohn et al. (2017, p. 296):

1. clarify their interests;
2. find adequate resources for making a decision;
3. recognize obstacles;
4. consciously manage the process or procedure;
5. create ground rules;
6. intervene effectively to eliminate constraints; and
7. review and reconsider the decision as needed.

More recently, McLeod (2013) has extended the theory in three areas: in information exchange (especially in hidden profile situations, discussed in Section 3.1.3), in virtual teams and in groups that work over prolonged periods of time. In the first area, she concluded that exchange of unique information, attention to information introduced by others, systematic attempts of combining task information and cues to remind the group of the information distribution improves decision quality. With regard to the second extension, (spatial) group distribution was not found to influence the effect of vigilant interaction on decision quality – thus successfully extending the theory to include virtual teams (Littlejohn et al., 2017). Only very little support was found that temporal vigilance influences the quality of decisions a group makes, although vigilance is reduced in teams in which team members are more than one timezone apart.

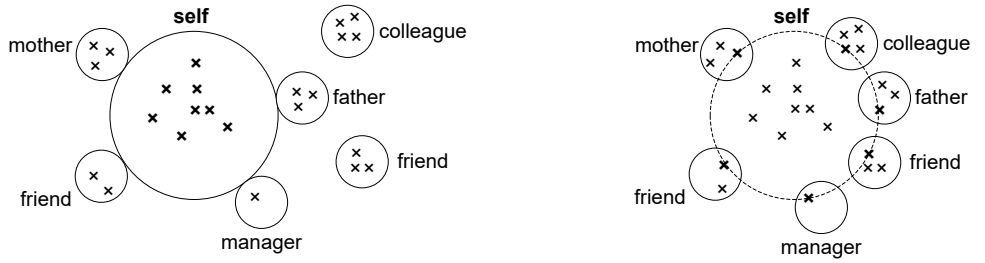
The theory closely connects to earlier work presented in this current text. The connection between the quality of decisions and the quality of the decision-making process was already proposed in Figure 3.2. Furthermore, as vigilant interaction theory especially emphasises the importance of interaction when analysing the problem, setting goals and objectives and evaluating the alternatives (Hirokawa and Rost, 1992), it is consistent with the problem solving process as shown in Figure 3.1. This is unsurprising, given their shared basis in the work by Dewey (1910) (Littlejohn et al., 2017). In a wider context, Hirokawa and Rost (1992) and Oetzel (1995) as well as Orlitzky and Hirokawa (2001) present or refer to publications providing empirical support for the theory. This is confirmed by variety of other sources presented in Section 3.2.3, which also mention various forms and components of group interaction as

factors that influence decision quality. Notable examples are groupthink (Janis, 1972; Salazar, 2009) and the aforementioned hidden profile situations (McLeod, 2013).

10.1.2. Effective intercultural workgroup communication theory

Based on the vigilant interaction theory treated earlier and other models of group effectiveness (Hackman, 1990; Larson and LaFasto, 1989), effective intercultural workgroup communication theory was put forward by Oetzel (a PhD-student of Hirokawa's (Hirokawa and University of Hawai'i - Hilo, 2016)) in 1995 as *effective decision-making theory* (Oetzel, 2017, p. 1). As the current name indicates, it pays particular attention to the cultural context of (and possible cultural differences within) a decision-making group. A revised version of the theory that is discussed in this section clarifies that culture "can be indexed by national culture [and] ethnicity" – a 'narrow' definition of culture – as well as by "language, gender, job position, age, or disability" – a much wider description (Oetzel, 2005, p. 352)[2]. This revised edition also opens up the theory to workgroups in general, rather than only decision-making groups (Oetzel, 2005).

The primary dimension used to assess cultural differences is *individualism – collectivism* (Triandis et al., 1990; Triandis, 1995; Hofstede, 1984), first discussed by Parsons and Shils (1951) as *self-orientation – collective-orientation*. Broadly speaking, Western cultures are largely individualist[3]: the individual is more important than the group and persons will strive to attain their own goals, rather than sacrifice some to meet group goals. On the other hand, non-Western (Asian, African and Latin American (Triandis et al., 1990)) cultures are mostly collectivist: group goals are often deemed more important than individual goals and rather than claiming the proverbial spotlight to champion a success to which they only marginally contributed (as an individualist would do), collectivists prefer to let their 'group identity' take centre stage – even if an achievement is largely an individual act (Ting-Toomey, 1988; Ting-Toomey and Kurogi, 1998). Dimensions strongly associated to *individualism – collectivism* are the *independent – interdependent* self construals that affect cognition, emotion and motivation (Markus and Kitayama, 1991), illustrated in Figure 10.1, and *competitive – cooperative* behaviour (Oetzel, 1995).



(a) Independent self construal

(b) Interdependent self construal

Figure 10.1: Independent and interdependent self construals, based on Markus and Kitayama (1991, p. 226). The crosses are representations of (aspects of) the self or the others. In case these are on the boundary of the self and others (as occurs in the interdependent view), this means that (aspect of the) self depends directly on the other. Crosses not on that intersection are relatively independent of the other.

According to Oetzel (1995), these different orientations have an important on decision-making preferences. Whereas individualists are mostly concerned with the "bottom line" ("utility, quality, and correctness" of a decision), collectivists value "not only the quality of the decision but also the appropriateness, process, and acceptability of a decision"[4] (Oetzel, 1995, p. 255). In other words: individualists focus

[2] Formally, Oetzel (2005) adheres to the definition of a culture as "a population of people who have similar attitudes, values, beliefs, and share a system of knowledge through unstated assumptions" (Triandis, 1995).

[3] In order to limit invoking too narrow interpretations of 'culture' as description for just nationality and ethnicity, the terms *individualist(s)* and *collectivist(s)* are used as much as possible in the remainder of this text, avoiding terms as *individualistic culture* or *collectivistic culture*.

[4] These operationalisations are, according to Oetzel (1995, pp. 254-255), defined in a publication by Hirokawa and Salazar (1991, pp. 3-4), of which no further details could be found. *Correctness* is being "free from error", *quality* is based on conforming to "established standards", *utility* is about the cost-benefit-ratio of a decision, *acceptability* depends on agreement within the group, *process* is "the extent to which the group follows acceptable procedures in arriving at a decision" and *appropriateness* takes into account to what extent a decision matches "group goals, task requirements, and informational resources."

on *task* outcomes, whereas collectivists focus on *relational* or *socio-emotional* outcomes (Oetzel, 1995; Bonito, 2009). This *task* – *relationship*-balance finds its origins other historical social theories (Oetzel, 2005), such as interaction process analysis (Bales, 1950). Hackman (1990, p. 7) added to this a third – personal – dimension, as "the degree to which the group experience contributes to the well-being of team members", including them allowing them to fulfil their personal needs.

Effective intercultural workgroup communication theory is based on a number of theoretical assumptions, quoted from Oetzel (2005, pp. 357-359) and listed below. They clearly show the connection to vigilant interaction theory, by assuming (/confirming) the systems perspective and assuming (communication) processes influence output. These assumptions are applicable to groups that are task-oriented, working on a complex task[5] and share a common language (Oetzel, 1995, 2005).

1. Intercultural workgroups can be though of as a system with inputs, processes, and outcomes operating in a particular context.
2. The context of the group frames the relationships among inputs, processes and outputs.
3. The inputs, reflected by members' cultural values and self-conceptions and the diversity among group members, influence the communication processes of a group.
4. Communication processes impact the outcomes of the group.
5. The processes and outcomes serve as feedback for context and input.
6. Intercultural workgroups need to be evaluated in terms of both task and relational effectiveness.
7. Participation, consensus decision making, cooperative conflict, and respectful communication are culturally approprioate communication behaviors in that they relate to both task and relational effectiveness.

Following these assumptions, the theory puts forward a number of propositions that are quoted below (Oetzel, 2005, pp. 360-364). In comparison to the orignial theory (which consists of fourteen propositions) (Oetzel, 1995), the revised and current version is limited to nine. The first seven examine the influence of group inputs on group process and the last two explore the influence of group process on outcomes.

1. The more negative contextual factors [a.o. status differences among members] that a culturally diverse group faces, the less likely the group will experience effective communication.
2. The more culturally heterogeneous a group, the less likely it will experience effective communication.
3. The more individualistic (or independent) a culturally diverse group, the more likely the group will utilize dominating conflict strategies.
4. The more collectivistic (or interdependent) a culturally diverse group, the more likely the group will utilize collaborating conflict strategies.
5. The more individualistic (or independent) individuals in a culturally diverse group, the more likely they will take turns.
6. The more collectivist (or interdependent) a culturally diverse group, the more likely the group will have equal participation.
7. The more members of a culturally diverse group have other- or mutual-face concerns, the more likely the group will have effective communication.
8. The more a culturally diverse group utilizes effective communication processes, the more likely the group will achieve task effectiveness.
9. The more a culturally diverse group utilizes effective communication processes, the more likely the group will achieve relational effectiveness.

Figure 10.2 presents a model of the effective intercultural workgroup communication theory (Oetzel, 2005, 2017).

[5] Having multiple solutions and high information and evaluation demands (Oetzel, 1995, 2005) and/or having unclear goals, little clarity on how to achieve these and a large number of potential barriers on the way (Hirokawa, 1990; Orlitzky and Hirokawa, 2001)

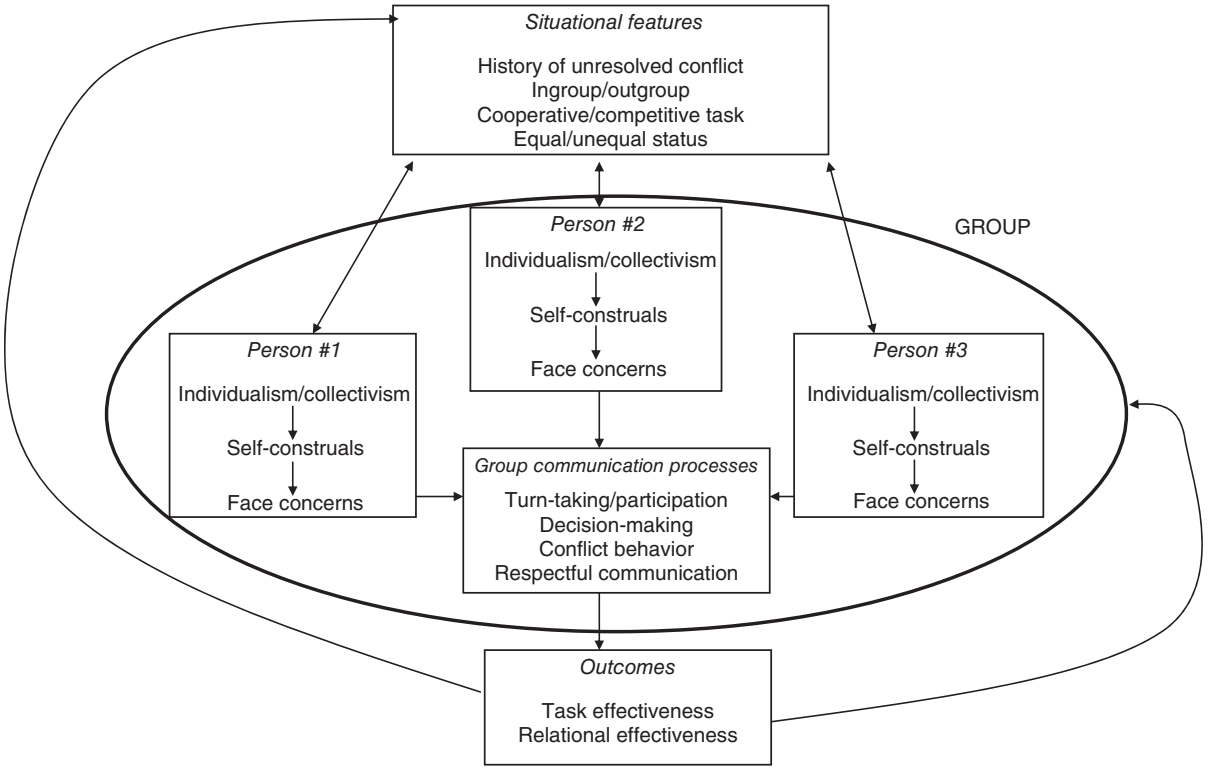


Figure 10.2: Model of the effective intercultural workgroup communication theory (Oetzel, 2017, p. 3)

Especially because of its connection to vigilant interaction theory, effective intercultural workgroup communication theory can be contiguously related to other parts of the current text. This is further supported by the importance of conflict – which can both beneficial as well as disadvantageous – within intercultural small groups (Oetzel, 1995), also mentioned multiple times in Section 3.2.

10.2. Critique and limitations

Having presented the vigilant interaction theory and effective intercultural workgroup communication theory in Section 10.1, this current section voices some critique and discusses limitations. Part of the following comments originates from academic literature, but the majority stems from the present author's critical reflection.

The next sections discuss criticisms regarding the focus on the cultural dimension (Section 10.2.2), the equivalent appreciation for task and relationship-outcomes (Section 10.2.3) and a few remarks regarding the limited operationalisation of the larger theoretical concepts of effective intercultural workgroup communication theory (Section 10.2.4). Section 10.2.5 briefly treats a missed opportunity of more explicitly including uncertainty in the theory. First, however, Section 10.2.1 discusses the potential discrepancy between effective communication and decision quality.

10.2.1. Effective communication versus decision quality

Given the fact that the main topic of interest of this thesis work is decision quality, it might seem counter-intuitive that theories of effective teamwork form the heart of the theoretical framework supporting part of this research. To some extent, that indeed is the case. This is a direct result of the – in the author's opinion – lack of a clear separation of decision quality and team effectiveness in academic literature in

general[6]. This is consistent with observations presented in Section 3.1, where it was concluded that a widely supported definition for decision making does not seem to exist.

However, lacking any theories directly concerned with decision quality, it is argued the two theories presented here do indeed form a sound basis for further work. Especially in the introduction to effective intercultural workgroup communication theory by Oetzel (1995), the two concepts are treated closely related, if not equivalent: "decision-making effectiveness is determined by focusing on whether a group has made a 'good' or a 'bad' decision" (Oetzel, 1995, p. 247). The updated version of the theory moves somewhat further away, defining effectiveness in terms of "satisfaction, decision-making quality, and workgroup productivity" (Oetzel, 2017, p. 1), with the former related to the relationship-dimension, and the latter to the task-dimension Oetzel (2005).

10.2.2. Focus on cultural dimension

The most important point of criticism is the amount of attention paid to the cultural dimension in effective intercultural workgroup communication theory. As discussed previously, many of the differences in decision-making preferences are – in the present author's opinion – not strictly limited to nationality or ethnicity, but applicable to any group of persons. This is confirmed by Markus and Kitayama (1991, p. 226), who state that also "[w]ithin a given culture [...], individuals will vary in the extent to which they are good cultural representatives and construe the self in the mandated way". Ting-Toomey and Kurogi (1998, pp. 189-190), too, note that people in individualistic cultures might be more focused on their "I-identity", but do not equate these concepts. Rather than using individualistic and collectivistic cultures as primary dimension, it seems the dimensions of *independent – interdependent* self construals or *self-orientation – collective-orientation* would have been more suitable. These do as much justice to the personal differences observed, but do not activate the too limited interpretations of the word *culture*.

Interestingly, the revised edition of the theory has actually strengthened this potential bias, as the propositions put forward in the first version of the theory actually did use the *independent – interdependent* dimension (Oetzel, 1995). Similarly, the updated version explicates the cultural focus by incorporating the term *intercultural* in the name of the theory. On the other hand, Oetzel (2005, p. 252) makes attempts to refute the bias ("it has been argued that there are problems with using [individualism – collectivism] to explain behaviour at the individual level") and defines culture in a broader sense. Nevertheless, he still uses (comparisons between) stereotypical Japanese and American groups as illustrations throughout the text.

10.2.3. Prescribing equivalent importance

In a bibliographical note discussing the history of the theory, Oetzel (2005, p. 355) voices his "concern with both mainstream and cultural diversity models of group effectiveness, [which] is that they privilege one particular view of how groups should work. That is, they emphasize work outcomes over relational outcomes". Yet, in overturning this dominant view, Oetzel (2005, p. 366) himself explicitly "emphasizes both task and relationships at an equal level". Even though the theory is limited to workgroups (that both need to maintain a working relationship as well as complete a task), it is instinctively clear that some workgroups (such as a group of friends starting a company) might value the relationship over their work output, whereas others (a group working together on an ambitious project for short time and with no expectation of future collaborations) can be expected to focus on their task rather than their relationship.

Interesting enough, interaction process analysis – one of the theories underlying effective intercultural workgroup communication theory – is much more open about the fact that there should be a *balance* between task and relationship goals. Although Bonito (2009, p. 528) also talks about maintaining an "equilibrium" and Bales (1950, p. 8) describes an ideal interaction process as one placing "alternating emphasis" on task and relationship, they seem to leave more room for the group defining their own equilibrium between task and relationship and – by extension – by individualist and collectivist characteristics.

[6] This is further discussed in Section 16.4.1.

A possible explanation for the cultural dimension and prescribed equivalence
Oetzel (2005) is very open about his personal interests regarding intercultural communication. For example, he admits having "a great interest in social justice and inclusion" (Oetzel, 2005, p. 354), and raises questions on addressing privilege, preventing or reducing segregation and improving race relations. Discussing the metatheoretical assumptions underlying his work, (Oetzel, 2005, p. 357, emphasis added) highlights his belief in societal inequities and his objective to change these, states he sees his theory as a "social construction of intercultural workgroups, [...] that seeks patterns in the world, but from *a social justice and somewhat suspicious lens*" and confirms it not being "value-free or objective". Rather, he characterises the theory as "predominantly normative" (Oetzel, 2005, p. 356).

Based on that strong personal conviction, it might be that Oetzel's focus on culture and his equalisation of the importance of work and relationship output is an overstatement that aims to compensate for the lack of attention given to diversity and collectivist cultural values in prior workgroup research.

As I have argued in the previous sections, I feel this is unnecessary. On the other hand, I am – just as the scholars Oetzel was criticising in the first place – primarily independent and stem from a mostly indivualistic culture. As such, I might take a more utilitarian perspective in this discussion, and therefore think too lightly about the importance of explicitly denoting or stressing culture.

10.2.4. Limiting operationalisation

In addition to the somewhat more fundamental critiques voiced before, a number of smaller comments are made here. They have been grouped here, as they all concern the 'operationalisation' from underlying concepts to concrete propositions.

First, Oetzel (1995) (based on Hirokawa (1980)) strongly advocates consensus decision making. Oetzel (2005) does so even more pronounced, in defining consensus decision making as part of effective communication in his seventh assumption. Although Hirokawa (1980, p. 312) indeed "suggest[s] that members of effective groups tend to interact on substantive matter until agreement is reached", the results of the literature study detailed in Section 3.2.1 do not necessarily agree, instead pointing to e.g. deliberative acceptance (a decision- making strategy that bears resemblance with procedural justice and was introduced by Beatty and Moore (2010)) as a better decision making strategy (Baartmans and Kosolosky, 2015). Closely related is the assumption or view that consensus decision making prevents conflict and thereby improves decision quality, whereas various authors discussed in Section 3.2.3 have shown conflict can have a beneficial impact.

Second, Oetzel (1995) promotes equal levels of contributions as a way to make more effective decisions. Oetzel (2005), again, clusters this in effective communication. Regardless, the present author feels this is too strict. Indeed, Section 3.2.3 notes that it is important for team members to contribute and participate in discussion, but this does not prescribe *how*. In Oetzel's choice to do so, the theory becomes limited – less like a tool, more like a straightjacket.

Third, Oetzel (2005, p. 355) states that "a diverse group is more creative in problem solving that a homogeneous group". Creativity might indeed be an important skill in general problem solving (especially *solution formulation*, as shown in Figure 3.1), but its influence on (high-quality) decision making is not confirmed in the literature review presented in Section 3.2. As such, this critique might be attributed to the somewhat different focus in Oetzel's and the current research discussed in Section 10.2.1.

Fourth and last, the connection between decision quality and the task-dimension on one hand, and group satisfaction and relationship-dimension on the other is seen as too simple. As shown in Figure 3.2, the present author sees these factors interrelated. Although treated in this separate paragraph, this remark is in line with Section 10.2.3, criticising the fact that task- and relationship-output are deemed equally important.

10.2.5. Uncertainty

Last in this section is the lack of attention to uncertainty in both the vigilant interaction theory as well as the effective intercultural workgroup communication theory. Although Oetzel (2005, p. 253) does state that "[d]uring interaction, participants must anticipate others' decision-making styles to predict the effect of various message strategies", this unpredictability in relationship is not explicated. Very similar, the complex tasks these two theories focus on are characterised by low goal and goal-path clarity (Hirokawa, 1990), but that uncertainty is not emphasised further. Rather than a criticism, the present author feels this is a missed opportunity. This is further elaborated and demonstrated in Chapter 11.

10.3. Core concepts

Having presented and critically reviewed vigilant interaction theory and intercultural workgroup communication theory, the objective of this section is to list the core concepts of the theories on which the model to be developed in Chapter 11 will be based. These can be seen as the fundamental assumptions underlying the model.

- Decision quality is improved if the decision-making process is vigilant and people involved in that process show critical thinking. In a vigilant process, groupthink is to be prevented.
- A decision-making process yields both task and relational outcomes. Depending on whether people see themselves as predominantly independent or interdependent, they place more or less emphasis on either task or relational outcomes of a decision-making process. An individual's definition of self can be influenced by cultural and societal backgrounds, as well as by gender, age, job position, seniority level and team role.
- Groups need to achieve a balance between task and relational outcomes. What the exact balance is, depends (among others) on group composition and the needs or preferences of the individuals of which the group is comprised. In a workgroup, it can never be that the balance is such that either one type of outcome is completely neglected.
- Besides a balance between task and relational outcomes, the decision-making process needs to take into account the personal needs of the individuals involved, or the needs of the organisations that are represented by various individuals.

10.4. Applicability

Whereas the previous sections discussed the two theories that are bundled in this theoretical framework in a general sense, this section confirms their applicability to project MANTA, or similar projects meeting the criteria discussed at the end of Section 9.5. As such, this section aims to advocate the applicability of the theoretical framework to the research subject.

Project MANTA clearly fits the description of a complex task: it has multiple solutions, high information and evaluation demands, and there is substantial uncertainty on what the actual project objectives are and how these are to be achieved. Furthermore, the project team is clearly a task-oriented group. Also, the people involved share a common language. Although not all have the same mother-tongue, they are comfortable expressing themselves in English. A difference from traditional groups is the fact that most meetings are not face-to-face and people work in different countries. Given the previously discussed extension of vigilant interaction theory to virtual teams (McLeod, 2013), this does not preclude inter-organisational or international projects from the theory.

The two construals of self that are discussed in effective intercultural workgroup communication theory can also be found in project MANTA, and are likely to appear in comparable projects. Although the entire consortium shares a Western-European culture, differences in seniority and project role, as well as intra-cultural variation, contribute to some people taking a more analytical focus, whereas others are less hard on facts and content. Very closely related to this is the problem statement identified in Chapter 9,

in which disagreement between (the priority of) project goals was found and where it was noted that that situation is not discussed. The tremendous amount of interrelations between stakeholder interests and dependencies, illustrated in Section 9.1.4, further adds to this complexity: should we focus on the project task, or are we better off pursuing individual goals?

Managing that complexity is made more difficult due to the substantial amount of uncertainty involved – both in terms of the process as well as in terms of the content. In addition to the goal-unclarity, the specific outcomes of the research project (as with most, if not all, research projects) are unknown. Similarly, people have to take into account how others will respond (or: how they think others will respond) to particular communications (being plain information or opinionated reasoning) when considering their contributions to the discussion.

11

Model development

In this chapter, the theoretical framework developed in Chapter 10 is used to develop a model. The model aims to transform the insights from the theoretical framework – which are precisely that: theoretical – to a useful and practical representation of the problem. With this, the model subsequently intents to improve understanding and contribute to higher quality decisions in projects like project MANTA. As such, the current chapter answers research question II-d, *How can the insights from these theories or frameworks be combined in a conceptual model?*.

The remainder of this chapter is structured chronologically in order to accurately represent the design and development stages of the model. Section 11.1 presents the starting points used for model development, thereby briefly summarising some of the earlier findings, and sets priorities. Section 11.2 introduces the basic model, how the starting points and theory are incorporated and where it does and does not succeed. Section 11.3 shows an extended version, in which the shortcomings of the basic model are addressed. Practical use of the model is discussed in Chapter 12.

11.1. Requirements and priorities

Following the problem context, the problem statement and the core theoretical concepts identified before, a number of requirements is set up that the model should meet. These are split up into three groups of diminishing priority: *must haves*, *should haves* and *could haves*, based on a slight adaptation of the MoSCoW-method, a prioritisation technique often used in software development projects (International Institute of Business Analysis, 2015, p. 375).

Must haves

Most important, the model must (be able to) accurately describe the situation. That means it has to incorporate the balance between task and relational outcomes and include uncertainty – both related to task and to relationship. Directly related to the problem statement, the model must be able to provide insight into varying individual and group goals.

Should haves

Fitting with the concept of vigilant decision making, the model should include a means to indicate group integration – thereby also providing a signal of increased risk of groupthink. Furthermore, it should be flexible, in the sense that it can help groups to set their own objectives and standards, without prescribing these. This allows the model to be of continued use for various (types of) groups over a prolonged period of time, even if group focus changes as a project progresses. This does not have to be limited to

standards regarding the balance between task and relational outcomes: rather, the model should include the balance between individual and group goals as well.

Could haves

Meeting the aforementioned goals will result in a model. An additional step could be made by extending this to a tool, making it easier for groups to use in evaluating and improving their decision making. Another use of such a tool could be in the hands of an external party, such as a sponsor, who might (as indicated in Section 9.5) also be negatively affected by low quality decision making. In this case, the model could be used to ascertain whether the goals of prospective group members are aligned well-enough to the goals of a group they might be invited or assigned to.

11.2. Basic model

The basic version of the model is shown in Figure 11.1. The blue arrow on the left represents the task; the orange arrow on the right represents the relationship. As long as the two 'legs' of an arrow are apart that dimension can be seen to exist; if the legs coincide on the horizontal marked 0, that dimension does not exist anymore. Furthermore, the extent to which the two overlap (i.e., the size of the diamond in the middle) is a measure for the amount of group integration. As indicated in the figure, uncertainty is shown on the vertical axis.

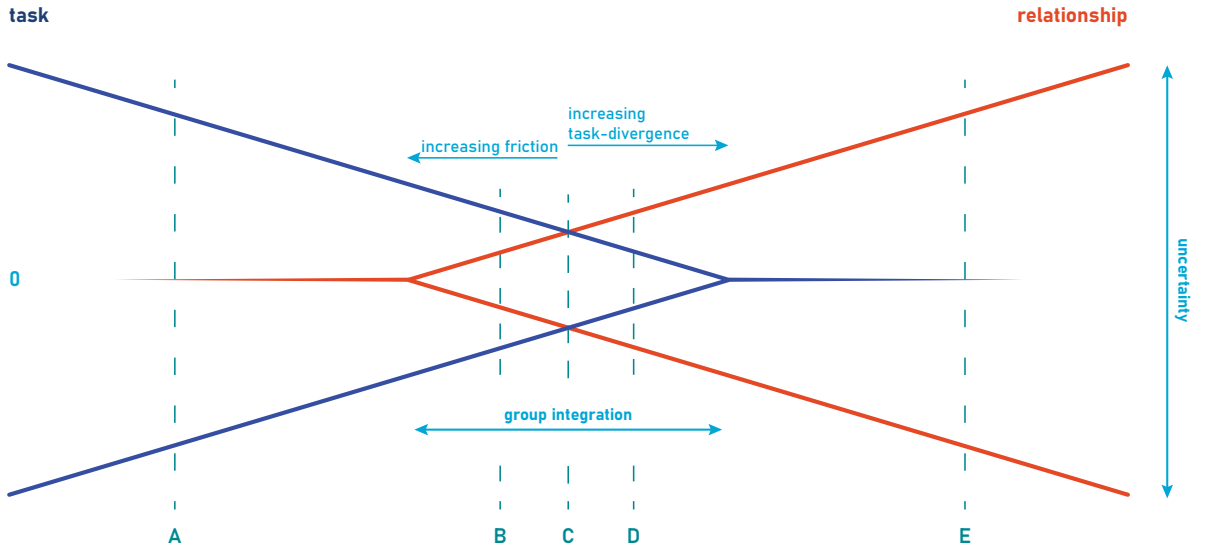
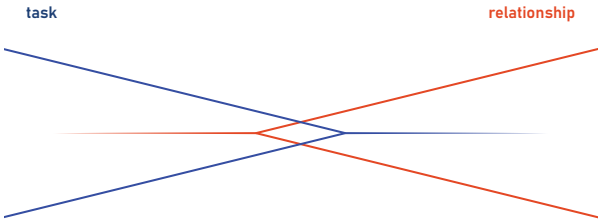


Figure 11.1: Basic conceptual model, showing the inter-relations between group integration and task and relationship uncertainty and balance

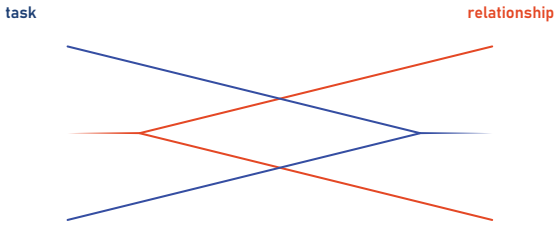
The model is used by mapping the group's current position on the chart. Ultimately, groups should aim to end up in the middle, indicated by line C. There, task and relationship are balanced. If groups are too far left and put too much focus on the task, friction increases. This is indicated by line B. The opposite occurs at line B, where the relationship dominates the task. In lines A and E, the relationship and task, respectively, get no attention anymore. In that case, the work comes to a standstill (A), or the group is reduced to the errand boy of the group member that has most power (E). The influences on decision quality, identified and categorised in Section 3.2, can be used to steer the group towards the intersection of task and relationship.

When the quantities of interest – the amount of group integration, task-related uncertainty or relationship-related uncertainty – change, the model changes as well. This is shown in Figure 11.2. As readily follows from visual inspection, the intersection of the lines representing task and relationship remains constant with changing group integration, but moves with asymmetric changes in uncertainty. In Figure 11.2c, for

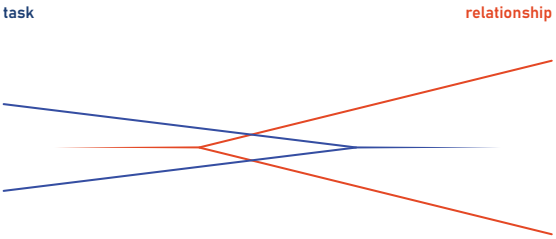
example, it has moved left from centre. Although the model still notes equal amounts of attention paid to both the task and the relationship, it shows that the intersection is closer than before to the point where the relationship diminishes altogether. This is consistent with common everyday experiences that if one focuses most attention on one thing, other items run the risk of getting out of sight.



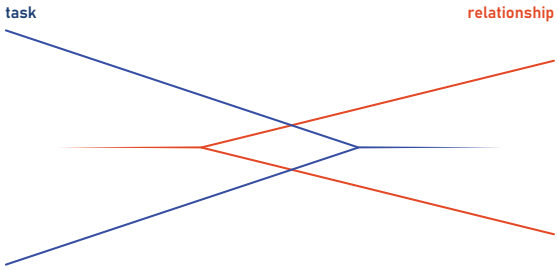
(a) Lower group integration, visualised by reduced overlap between the two arrows



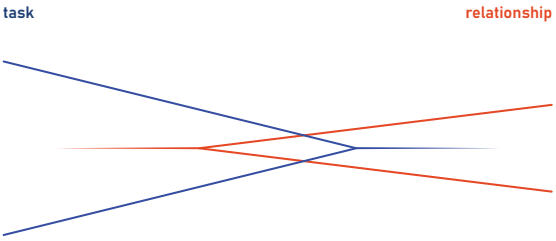
(b) Higher group integration, visualised by increased overlap between the two arrows



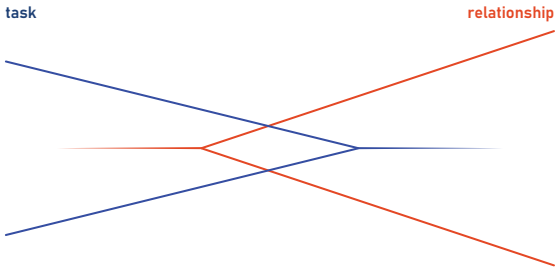
(c) Lower task-related uncertainty, visualised by reduced height of the task-related arrow



(d) Higher task-related uncertainty, visualised by increased height of the task-related arrow



(e) Lower relationship-related uncertainty, visualised by reduced height of the relationship-related arrow

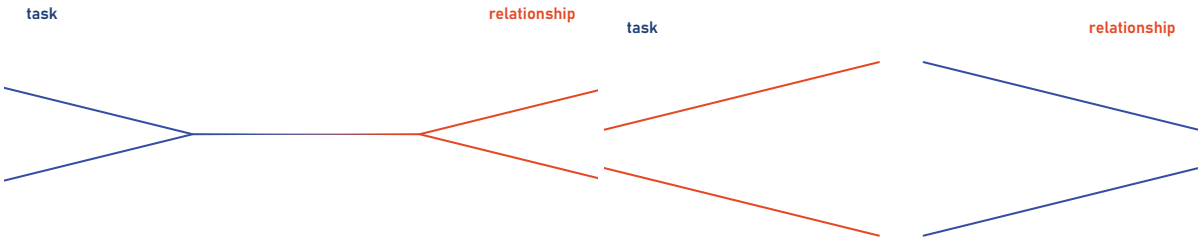


(f) Higher relationship-related uncertainty, visualised by increased height of the relationship-related arrow

Figure 11.2: Variants of the basic conceptual model, showing how group integration, task-related uncertainty and relationship-relationship uncertainty influence the model

The model is limited to workgroups. This means that there is no relationship without a task, as it is the task that keeps the group together. Also, there can be no task without a relationship, for that would leave no incentive to conduct the work in a group. This is also shown in Figure 11.3. In the first situation, dubbed *integration dystopia* and shown in Figure 11.3a, there is no overlap, no shared goal and no mutual interest. Figure 11.3b shows what seems to be *integration utopia*, but in reality is as problematic as the dystopian situation: groups will drown in groupthink, leaving the problem most likely to be solved best by an individual.

Whereas the basic model as presented here forms an interesting first step, it is not free from problems. Comparing the model to the requirements and priorities set out earlier, it must be concluded that the basic model lacks a dimension showing the potential discrepancy between group and individual goals. As this is a core feature of the problem (as defined in Section 9.5), this is an important shortcoming. Additionally,



(a) Complete lack of integration: integration dystopia

(b) Excessive integration: perceived integration utopia, but integration dystopia in reality

Figure 11.3: Variants of the basic conceptual model, showing extreme forms of group integration

the model assumes task and relationship outcomes as equally important, in prescribing groups should aim for the balance where the two arrows intersect. This too is problematic, as that assumption is one of the exact shortcomings in the effective intercultural workgroup communication theory (further detailed in Section 10.2.3) the model set out to solve. Furthermore, discussion with fellow graduate students and research supervisors indicated the y-axis to be ambiguous: it seems to have a double role. On one hand, it shows uncertainty, whereas it also is used to indicate attention (or time, or effort, or focus, or ...?) given to a particular dimension.

11.3. Extended model

After various iterations (shown and shortly discussed in Appendix I), the problems with the basic model are addressed in the extended model presented in this section.

Figure 11.4 shows the first version of the extended conceptual model. It solves a number of the shortcomings of the basic model. First of all, the *sweet spot* is no longer necessarily in the middle of the diagram. Rather, groups themselves can decide on a desired *task-relationship balance* or *exchange rate*. In case that balance is 1, the optimum is located in the centre. Otherwise, it shifts to the left (if the task-concerns should have more impact on the decision than relationship-reasons) or the right (if relationship-outcomes outweigh task-concerns).

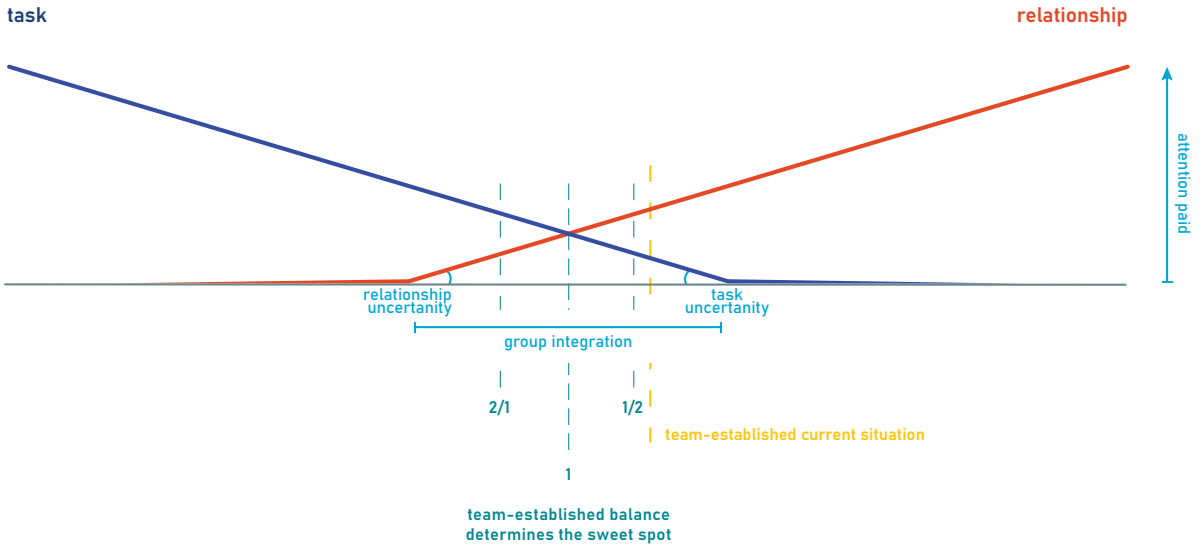


Figure 11.4: Extended conceptual model, first version, showing the inter-relations between group integration, task and relationship uncertainty, and attention paid to task and relationship

In the model as it is shown in Figure 11.4, the team-indicated balance is in the middle, with the team currently spending too much attention to the relationship – ending up at the yellow line. Hence, this group needs to base their decisions less on relationship-related reasons and use more task-related arguments. Furthermore, the annotations *increasing friction* and *increasing task-divergence* are dropped, as they are process-related variables, whereas the task- and relationship-objectives concern the (intended) result of that process.

Other changes with respect to the basic model are the fact that the y-axis is now firmly indicating the attention paid to either task or relationship, following Bales (1950, p. 8)'s original definition in his work on interaction process analysis. With this adjustment, the measure of uncertainty is now represented by the angle either line makes with the horizontal. Although equivalent to the situation in the basic model, the current presentation avoids confusion.

Although the extended model in Figure 11.4 is a clear improvement over the basic model in Figure 11.1, it is still lacking a measure for the (possible) difference between group and individual goals. This is solved in the second version of the extended model, which is shown in Figure 11.5. Rather than single lines for task and relationship, a band is added to this line to show the variation between the group and the various individuals (or individual organisations) that make up that group. This particular representation honours the additional complexity that differing perspectives cause, by visualising it has a particular impact on the uncertainty.

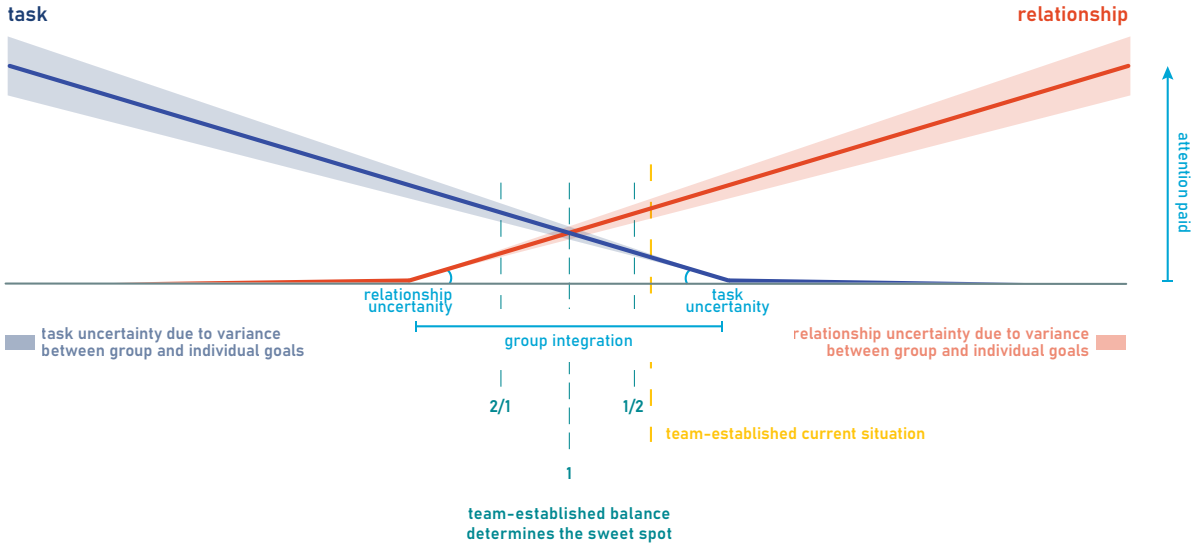


Figure 11.5: Extended conceptual model, second version, showing the addition of the (possible) difference between group and individual goals

As the model shows, the absolute spread increases with uncertainty. This is consistent with the earlier observation that with growing uncertainty, people (wilfully or unknowingly) might work towards increasingly varying outcomes.

A third version, shown in Figure 11.6, includes another improvement in the form of a second band (in both task- and relationship-dimensions) representing the possible misalignment between individual perspectives on the group goal. This band is shown within the earlier band, as individual goals will always differ more from the group objective than do various (mis)interpretations of that group goal.

The model now includes all relevant dimensions specified as requirements, but the concept of uncertainty now effectively appears in multiple scales: both the angle with the horizontal axis is determined by it, as well as the bands. (This problem is somewhat comparable to the ambiguous vertical axis seen in the basic model, which represented both *uncertainty* and *attention paid*.) Put differently: the question what relationship or task uncertainty (the angle with the x-axis) might possibly remain if there everybody perfectly agrees what the respective outcomes should be, is difficult (if not impossible) to answer.

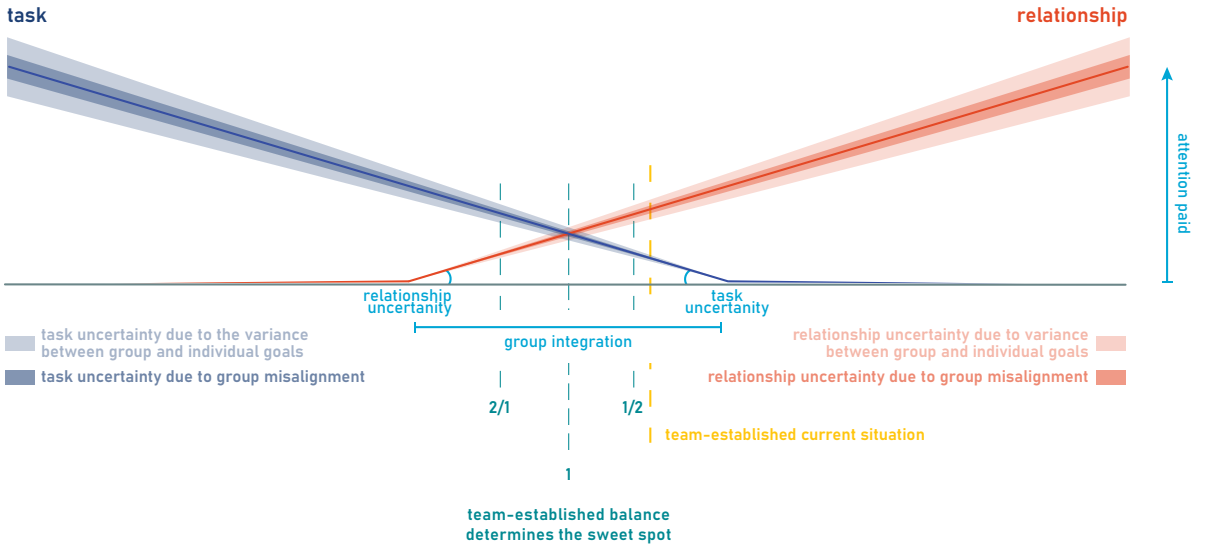


Figure 11.6: Extended conceptual model, third version, showing the addition of (possible) misalignment between individual perspectives on the group goal

A solution is found in the distinction between “goal clarity” and “goal-path clarity”, as defined by Hirokawa (1990, p. 192). Following the definitions put forward by Hirokawa, *goal uncertainty* is here defined as the uncertainty about *what the goal is*, whereas *goal-path uncertainty* is defined as uncertainty about *how the goal can be reached*. These definitions are used to solve the identified problem, resulting in a fourth version of the model shown in Figure 11.7. In comparison to Figure 11.6, the legends and the labels of the angles with the horizontal are changed. The angles previously indicated relationship and task uncertainty (in general) and are now specified to represent respective *goal-path* uncertainties. Similarly, the meaning of the bands is specified to *goal uncertainty*. Besides these change, observant readers might note the slightly thinner solid lines. This makes it easier to distinguish the line from the band, in case that band is particularly narrow.

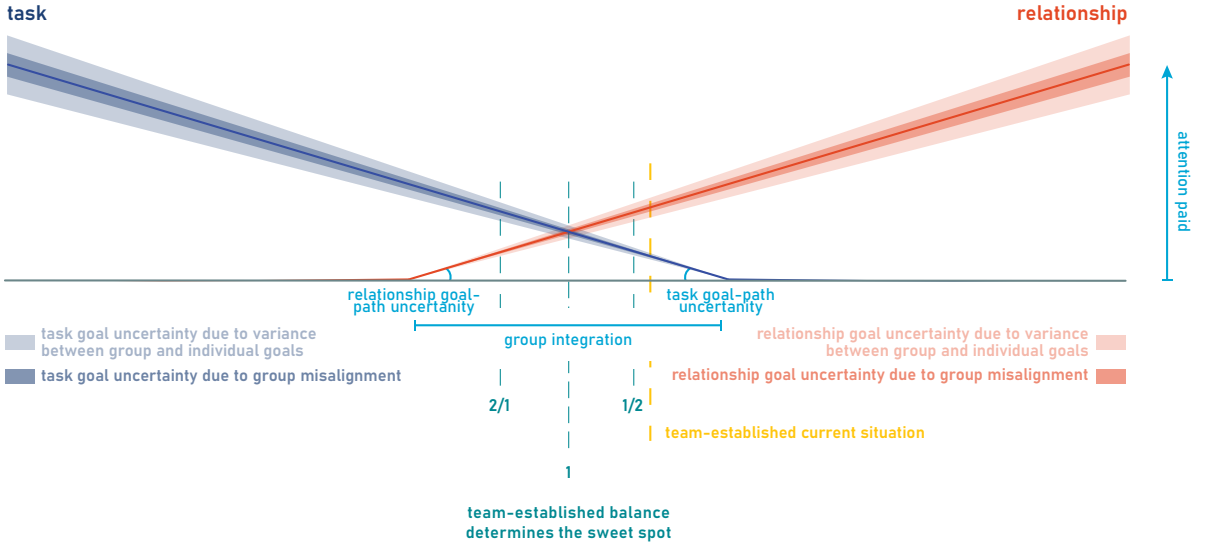


Figure 11.7: Extended conceptual model, fourth and final version, showing the inter-relations between group integration, task and relationship uncertainty, attention paid to task and relationship, the (possible) difference between group and individual goals and the (possible) difference between individual perspectives on the group goal

The various bands that have been added to the model, however, also slightly complicates it: what lines should we compare to determine the balance between attention to task and attention to relationship? It

is argued here that these should be measured based on the solid lines (in the middle of the bands) and that the rest, following Steiner's equation, is to be seen as process loss. The goal uncertainty (i.e., the bands) requires attention to manage or resolve, but does not necessarily (or at least, not completely) contribute to realising the (task or relationship) outcome objectives. This is illustrated in Figure 11.8, a close-up of the centre part of Figure 11.7 that explicitly indicates the useful attention and the attention losses. In this case (for both task- and relationship-components) the goal uncertainty results in attention losses of approximately 25%.

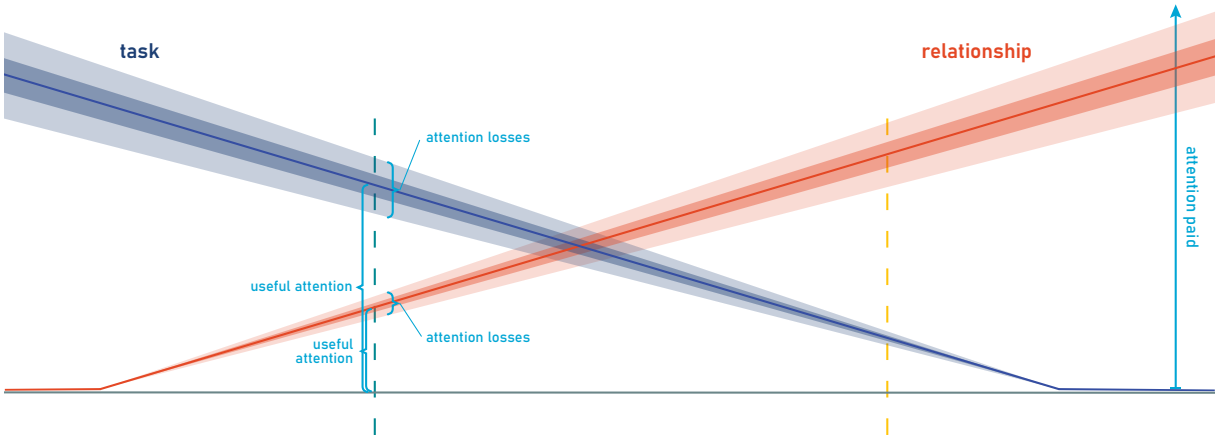
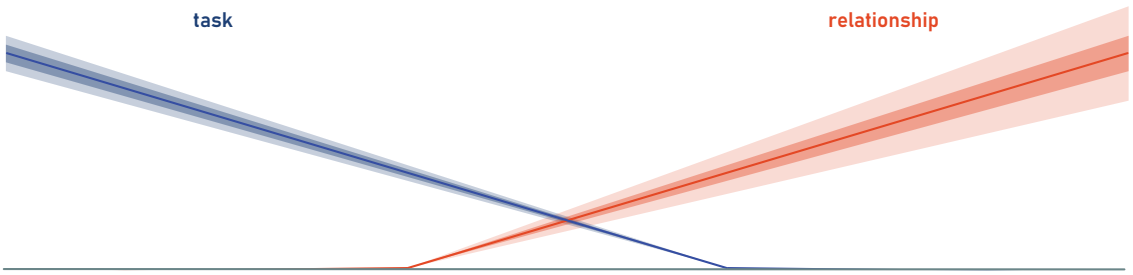


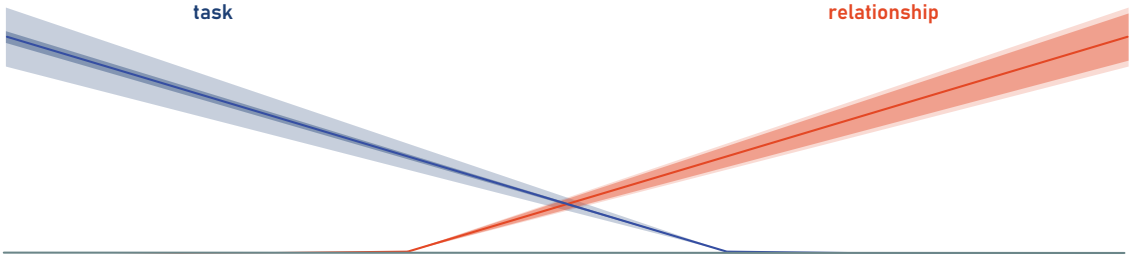
Figure 11.8: Close-up of extended conceptual model, showing attention losses

The models shown in Figures 11.5, 11.6 and 11.7 are all symmetric, whereas this does not have to be the case. Figure 11.9 shows a non-exhaustive set of other possibilities. Figure 11.9c, for example, indicates it is possible for the bands to be distributed asymmetrically about the solid lines. Both in case of misalignment and individual-group-variance, a majority of the group might share a particular view, pushing the band(s) in a particular direction. Misalignment and variance can be offset in the same direction (as is the case for the relationship-dimension in Figure 11.9c), or in opposite direction (as goes for the task-dimension).

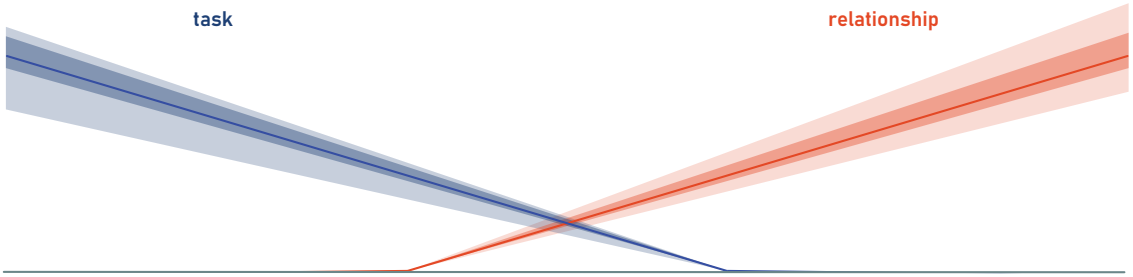
Given completion of the model, it is named: *TARE*, a combination of the words task and relationship. Further significance of that name is found in the concept of tare weight and the tare button on a kitchen scale – used to establish a clearly defined common ground that can support subsequent steps.



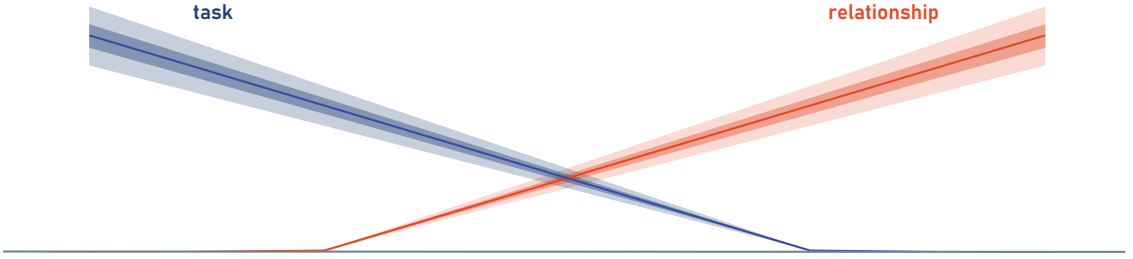
(a) Lower (higher) variance between individual and group task (relationship) objectives, visualised by the lower (higher) spread of the outer-most band



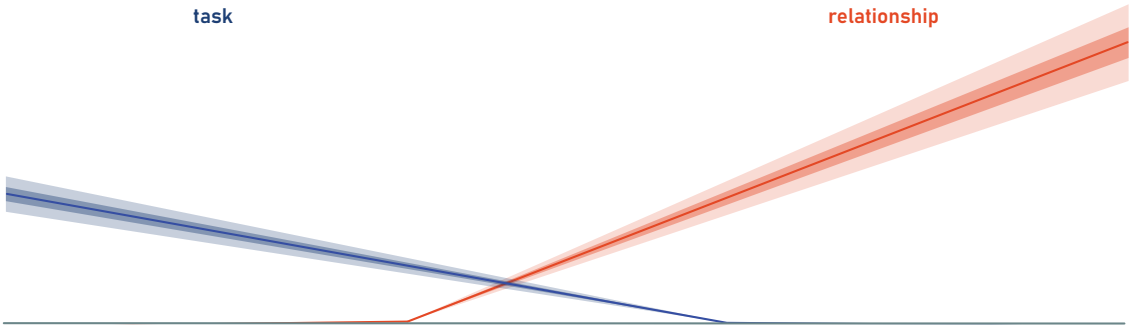
(b) Lower (higher) misalignment between task (relationship) objectives, visualised by the lower (higher) spread of the inner-most band



(c) Asymmetrically distributed variance between individual and group objectives, visualised by the spreads of the inner-most bands extending further above than below the solid line



(d) Higher group integration, visualised by the larger overlap and higher position of the intersection



(e) Lower (higher) task-related (relationship-related) uncertainty, visualised by the smaller (larger) angle the blue (orange) lines make with the horizontal

Figure 11.9: Variants of the extended conceptual model, showing how (mis)alignment of group goals, variance between individual and group objectives, group integration and uncertainty influence the model

12

Model use

Following its devleopment in Chapter 11, the current chapter turns towards anticipated use of the TARE-model. Although the model meets most of the requirements – it can describe the situation, it incorporates uncertainty, shows varying individual and group goals, provides an indication of group integration and does not impose standards, but allows group to set these themselves – it is not readily clear how it can be used, especially over longer periods of time. The current chapter aims to transform the model into a tool and as such, to answer research question II-e (*How can this conceptual model be used, through transformation into a tool?*).

This chapter aims to discuss that use by showing a possible way in which to collect the opinions of the participants of a (hypothetical) group (Section 12.1), aggregate (Section 12.2) and evaluate (Section 12.3) these. Lastly, Section 12.4 hypothesises how the model can be used over the course of a project. As these steps suggest, the anticipated use is as a (periodical) assessment, which in turn can inspire and guide change. This might concern goals and sub-goals, or the amount of attention spend on different topics. In any case, the assessment aims to explicate the situation, fostering (more) vigilant interaction over the remainder of the project. Although the model has descriptive qualities, the present author feels it adds most value when utilised in the aforementioned broader sense.

Before moving on, it is stressed that this chapter outlines only one way of using and implementing the model – whereas their might be many more. The selection in this chapter by no means aims to imply other ways of using the model are impossible, redundant or less successful. Some other ideas are presented in Section 12.5.

12.1. Collection

As a first step, group constituents are queried about their individual perspective and goals. The following six questions should be able to do so:

1. What are the project goals in terms of task and relationship?
2. On a 7-point scale (completely – completely not), please indicate whether you think other participants have answered the previous question in the same way as you did.
3. On a 7-point scale (completely clear – completely unclear), please indicate whether you think it is clear how you can achieve the project goals in terms of task and relationship?
4. What are your individual goals – or those of the organisation you represent – in terms of task and relationship?
5. On a 7-point scale (completely clear – completely unclear), please indicate whether you think it is clear how you can achieve your individual goals – or those of the organisation you represent – in terms of task and relationship?

6. On a 7-point scale (group – team – individual), please indicate whether you feel the consortium is a group (collection of individuals), a team (well-oiled machine) or effectively a individual (without group diversity).

The first and fourth questions are answered by participants choosing particular objectives from a pre-filled list or add their own. Such a pre-filled list can be generated based on the objectives laid out in a project manual (such as the Description of Action, in case of project MANTA). The variance observed in the answers to the first question, combined with the answer to the second question, determines the (mis)alignment of the group goal. The variance observed in the answers to the fourth question determines the variance between group and individual goals. Similarly, the number of group goals versus individual goals might be used as a measure for this spread. As goes for the first question, the pre-filled list used for the fourth question can be based on a project manual or proposal, possibly extended by goals that might be anticipated by a project coordinator, steering committee or higher body.

The third, fifth and sixth question determine the goal-path uncertainties and the group integration, respectively. That yields enough information to construct the basis of the diagram, as shown in Figure 12.1, from the perspective of one project participant. As such, it uses dashed lines rather than bands to indicate goal uncertainties.

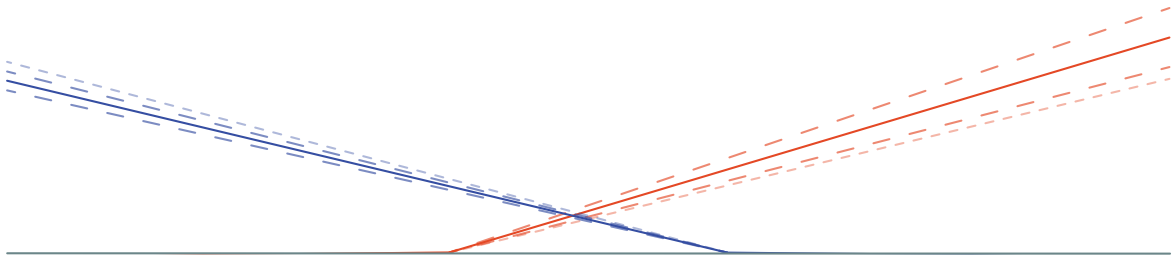


Figure 12.1: Conceptual model halfway through the *collection*-phase, showing one participants' perspective

Next, two more questions are used to determine the current and desired balance between task and relationship – as seen by a single participant:

7. On a 7-point scale (only task – only relationship), please indicate how important you feel the project goals in terms of task and relationship are, relative to each other.
8. On a 7-point scale (completely – not at all), please indicate to what extent you feel the project consortium commits to this balance when making decisions.

Extending Figure 12.1 with this data yields Figure 12.2. The **yellow** dashed line indicates the current situation; the **green** one shows the desired situation.

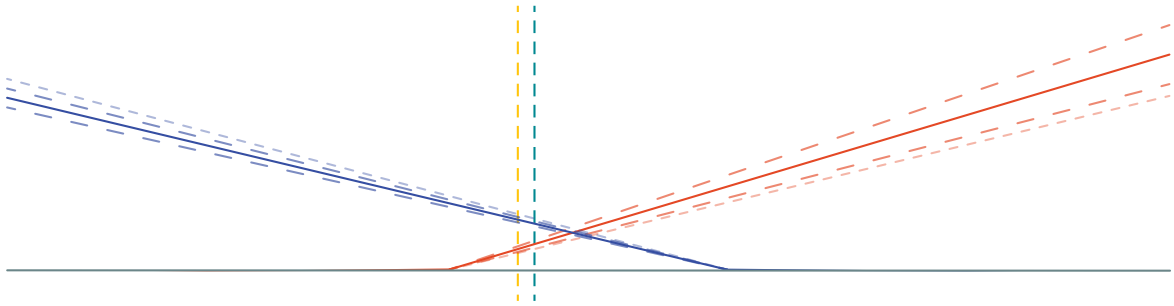


Figure 12.2: Conceptual model at the end of the *collection*-phase, showing one participants' perspective

12.2. Aggregation

Once everybody has completed the *collection*-phase, the individual perspectives can be aggregated. Figure 12.3 shows a stack of four individual perspectives, whereas Figure 12.4 shows the combined model. The goal-path uncertainties are determined by averaging the answers to question 3. The spreads in goal uncertainty – the bands in the diagram – are envelopes of the answers to questions 1 and 2 (group (mis)alignment) and question 4 and 5 (variance between group and individual goals). Group integration, as well as the current balance between task and relationship, are shown as averages in order to limit complexity of the diagram. In case the answers to questions 6 to 8 vary substantially, it can be envisioned that notifications of this accompany the graphical model.

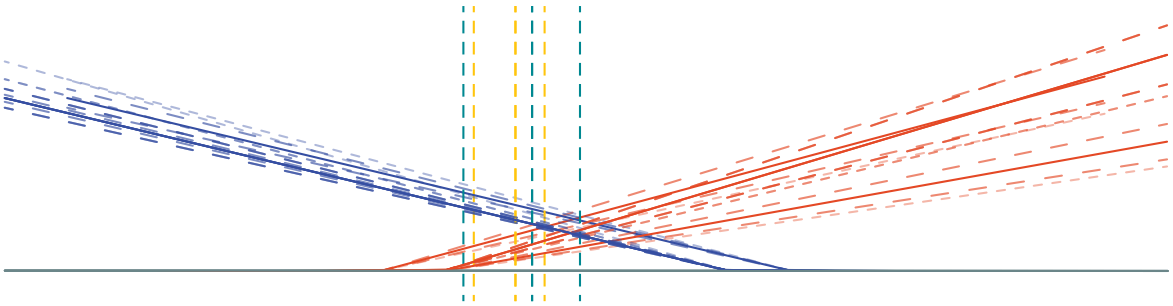


Figure 12.3: Stack over conceptual models at the end of the *collection*-phase, showing the perspectives of all participants

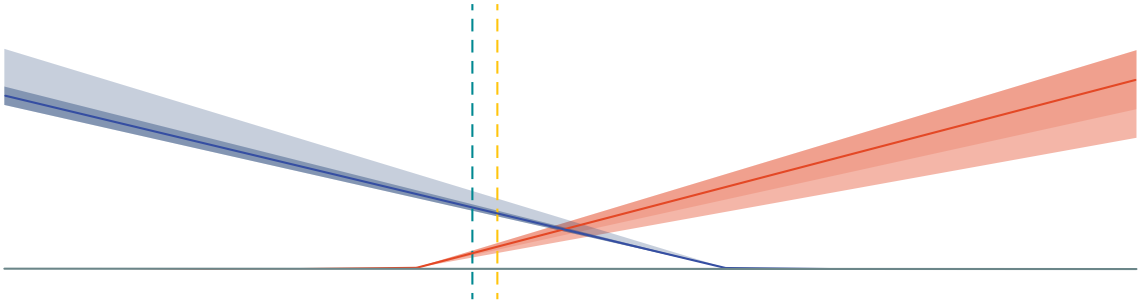


Figure 12.4: Conceptual model at the end of the *aggregation*-phase, showing the combined perspective of all participants

12.3. Evaluation

The *aggregation*-phase is followed by an *evaluation*-phase. This serves two purposes. First of all, the group can determine whether there is a feasible solution space, for example in terms of group integration, limits to the differences between group and individual goals, or limits to a particular task-relationship balance set by a funding agency. In case of project MANTA, it might for example be that the European Commission prescribes that the importance of task (the actual project objective) versus relationship (knowledge transfer, establishing and improving collaboration) goals are $4:1$ and that parties can pursue individual goals that are different from the group objective, but only to a limited extent.

Second, the group can determine the possible difference between the current and desired situation with respect to the balance between task-goals and relationship-goals and use the model to see what variables influence that balance. For example, in the situation as shown in Figure 12.4, the desired balance can be achieved directly by spending more attention on the task and less on the relationship, but also indirectly, by reducing the relationship-related goal-path uncertainty (angle with the horizontal axis).

The group evaluation phase also finds support in literature. Kahneman et al. (2011), for example, notes that whereas awareness of our individual biases does little to mitigate their potentially harmful effects,

this changes in a group setting. Combining a number of individuals, these still might not be able to control their own intuition and irrationality, but "can [...] detect others' faulty intuition and improve *their* jugdment" (Kahneman et al., 2011, p. 55, emphasis in original).

12.4. Over time

The process as described in the previous sections might intuitively seem to be geared mostly towards a project in its start-up phase. However, that does not necessarily have to be: especially when aiming for continued vigilant decision making, there might be value in going to such a process at fixed intervals in time. Especially in conceptual design or research and development project, such as project MANTA, many dimensions included in the model (such as group integration and uncertainty) change over time.

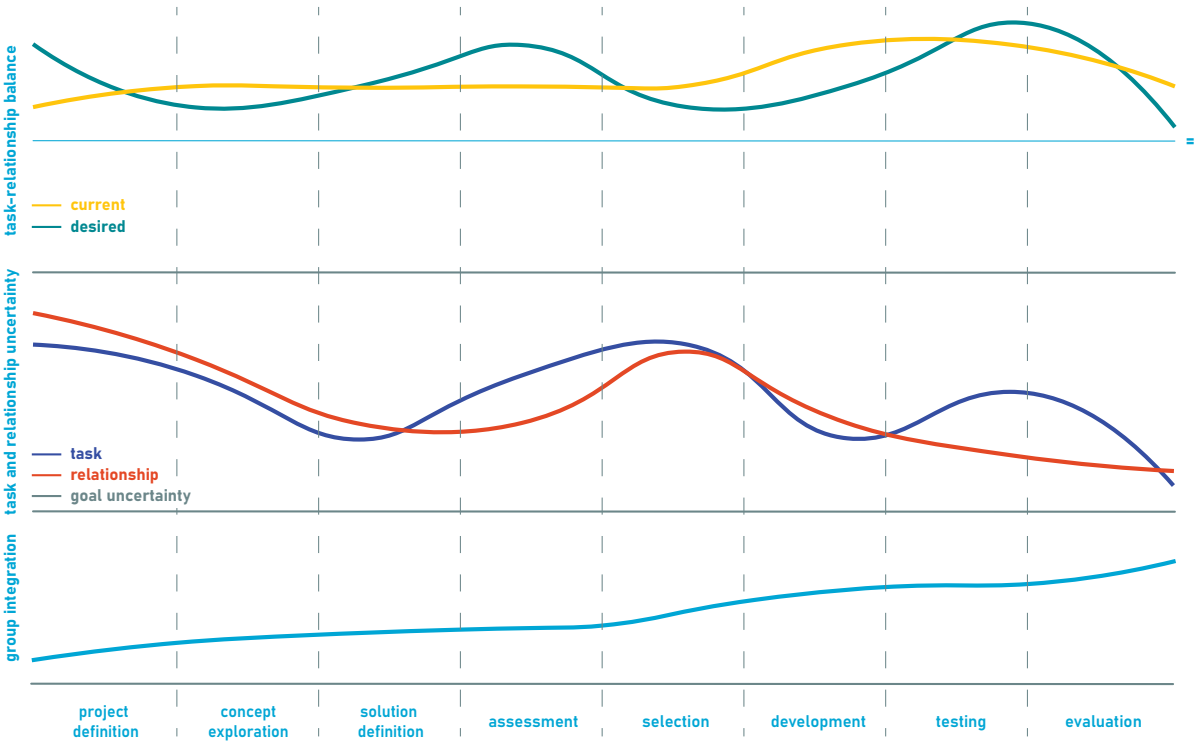
Taking the time to go through this exercise regularly over the course of a project also allows one to map how primary variables change over time. This is illustrated in Figure 12.5. On the horizontal axis, this figure shows eight typical stages of a conceptual design or research and development project: project definition, concept exploration, solution definition, assessment, selection, development, testing and evaluation. Stacked from bottom to top, three indicators are mapped on equally many y-axes. The lowest (in **cyan**) shows group integration. The **blue** and **orange** lines in the middle of the graph, then, indicate task and relationship uncertainties over all these phases (goal-path in Figure 12.5a, goal and goal-path in Figure 12.5b). The topmost set of lines (in **yellow** and **green**) shows the actual and desired task-relationship balance. (The horizontal cyan line splitting the upper half of the figure is a reference line where the same amount of attention is paid to both task and relationship.)

In the figure, one can see a fairly constant desired task-relationship-balance over the first few project phases. The actual balance circles the optimum, managing to meet it during the testing phase. Over the entire course of the project, task outcomes are deemed more important than relationship outcomes: yellow line consistently is positioned about the horizontal reference. One graph down, one can see task- and relationship-related uncertainties to be lowest during the solution definition phase. Similarly, the variance between individual and group goals with respect to task reduces over the course of the project, indicated by the lightest blue band getting smaller and smaller. In this illustration, relationship-related uncertainties peak during the selection phase, before quickly reducing towards the later stages of the project. At the bottom, the group integration is seen to increase relatively steadily over the course of the project. A more substantial increase is visualised during the selection-phase, similar to what was observed in case of project MANTA.

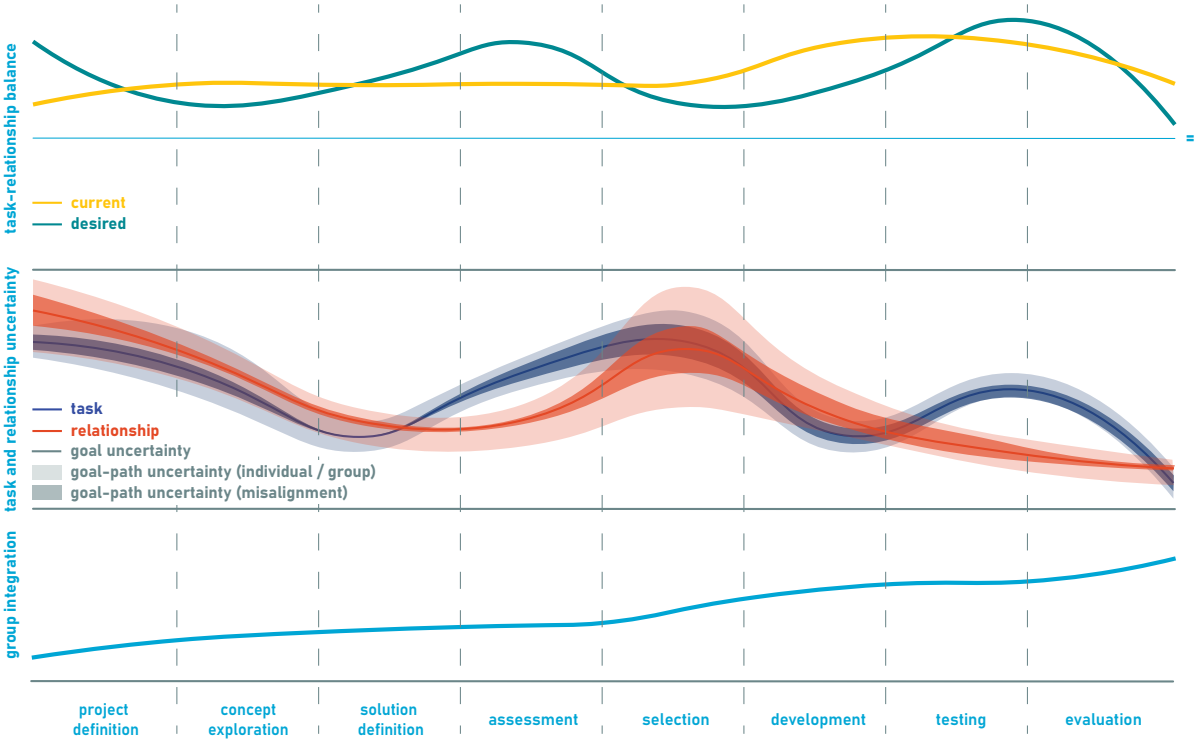
12.5. Other uses

This chapter presented *a* possible way of using the model, which does not necessarily have to be *the* (most useful or effective) way. A few other uses are listed below.

- Assessment of project suitability, in terms of goals and/or consortium partners. For example, if all participants from a prospective project partner indicate substantially different goals, there might be reason to look for another partner – or spend more time negotiating the project goal, and setting limits to the sub-goals individual participants can pursue.
- Systematic analysis of project performance. If application of the model over a number of projects indicates particular difficulties in specific project phases, sponsors (or participating organisations looking for more effective collaboration) might allocate additional resources to that phase, in order to improve project performance. On the other hand, if people notice particular drivers and barriers for project effectiveness during such analyses, they might incorporate these lessons learnt in future projects. In both scenarios, the model might be adopted as an early basis for a standardised assessment framework, to more systematically investigate possible problems or success factors in projects in which forms of goal and goal-path uncertainty play a role.



(a) Without goal-uncertainty, in the form of (mis)alignment and variance between individual and group objectives



(b) With goal-uncertainty, in the form of (mis)alignment and variance between individual and group objectives

Figure 12.5: Illustration of a projects' progress through the conceptual model over time, showing how group integration, uncertainties and task-relationship balance change over the course of the project

13

Closing

With this chapter, Part II comes to a close. Section 13.1 concludes this part and answers the second research question, as well as its sub-questions. Section 13.2 discusses limitations, specifically with respect to validity and reliability. The scientific contributions are re-iterated in the shared discussion at the end of this report (Chapter 16). Recommendations for further research or practical implications are also presented there.

13.1. Conclusions

In this part, project MANTA was found to be a complex project. Although the project only is a relatively small part of the Clean Sky public-private partnership, a substantial amount of stakeholders is involved. Differences in stakeholder type and interests manifest themselves, for example in dilemmas of knowledge protection (industrial parties) versus sharing (academic parties). Moreover, numerous relations between different internal and external parties were identified, which underline the complexity.

Based on a document analysis, interviews and observations, decision making within project MANTA was explored. It was found to be generally consensus-based and conflict-free. Moreover, it was noted that not analytical results, but other (business-related) factors are most prominent in driving decisions. In comparison with factors influencing decision quality found in Chapter 3, it was concluded that various factors negatively impact group decision making in project MANTA. A number of problems with respect to contextual and supportive factors were found, but most notable was the shared impression by project participants that goals and sub-goals are unclear. In addition, this lack of goal clarity was not found to be addressed effectively, leading to the problem statement that *the quality of screening decisions in project MANTA is negatively impacted by the fact that goal uncertainty exists and is not sufficiently explicated, reduced or otherwise managed*. As this problem is caused by project characteristics rather than context-specific factors, it was argued that identical problems are likely to exist elsewhere, provided these projects are of a conceptual or exploratory nature and have an external sponsor, limited resources and varying interests between stakeholders.

Effective intercultural workgroup communication theory and *vigilant interaction theory*, both rooted in systems thinking, were used to improve understanding of this combined problem. It was concluded that higher quality decisions result when the decision-making process is vigilant, that groups need to achieve a balance between both task and relational outcomes of such a process, and that the decision-making process should take into account the personal needs of the individuals involved. Uncertainty about task and relationship goals make this process more difficult and place more emphasis on the need of vigilant interaction.

The insights from aforementioned theories were subsequently combined into a conceptual model con-

necting the central concepts of the theories: TARE. Noting that workgroups by definition require **attention to be paid to** both the **task** as well as the **relationship**, **group integration** enlarges the viable 'solution space' – although very integrated groups are susceptible reduced decision quality (due to groupthink). The attention paid to task and relationship is affected by the corresponding **goal-path uncertainties**. Substantial **goal uncertainty** result in so-called 'attention losses', which are seen as waste.

As a last step, use of the model as a tool was anticipated. A model instantiation specific to the group is created in two phases. First, data is **collected** about the goals and perspectives of the various participants. Second, this input is **aggregated** to yield a group perspective. Once the model has been constructed, it is **evaluated** in and by the group. This phases serves to determine whether a feasible solution space exists for their particular goal and constitution, as well as to indicate the possible difference between how attention is currently spent, and how it should be spent in an ideal situation. Repeating these steps over the course of the project provides insights into how group integration, uncertainty and the balance between task and relationship-goals change with time.

13.2. Limitations

Even though interesting results and conclusions were obtained, there are limitations to this part of the research project. This section discusses these with respect to reliability and validity.

Reliability

"Reliability is concerned with the question of whether the results of a study are repeatable" and "refers to the consistency of a measure of a concept" (Bryman, 2012, p. 46, p. 169). Within qualitative research, this is difficult to achieve (Bryman, 2012). This research forms no exception to that rule. This especially concerns the interviews, which were held in two phases. Given the notion that the passing of time has also relieved some of the problems faced in project MANTA, it is very difficult to ascertain whether participants to later interviews were less critical, or whether earlier problems had indeed largely subsided. As the research was conducted by one person, issues of inter-observer (in)consistency are not applicable.

Validity

"Validity is concerned with the integrity of the conclusions that are generated from a piece of research" (Bryman, 2012, p. 47). Face validity requirements are argued to be satisfied, largely due to the fact that little results were inferred. Rather, interviewees were asked to share their opinion or experience on a particular subject directly. Internal validity of the problem exploration and definition phase was improved by using data from different sources (triangulation), which were found to be in accordance with each other – especially with respect to the main problem statement. This partially offsets the lack of an explicit validation step (in the form of another round of interviews, a survey or a group discussion) to validate the problem definition. Lastly, the choice to record and transcribe interviews reduced the potential for (recall or interpretation) bias, improving internal validity.

Generalisability was shortly discussed and although opportunities are definitely seen, external validity has not been specifically strived for. The fact that the main problem identified indeed matches results from the literature review conducted earlier and can be explained by two selected theories, however, provide support for earlier hypotheses with respect to generalisability. The results are argued to be ecologically valid, as at least part of the data was collected unobtrusively (document analysis) or in the natural setting of the project (observation).

Two important and final limitations with respect to the validity of this research is that it is carried out by one person (which might have introduced a bias) and the fact that research outcomes (such as the conceptual model and tool) were not tested, because of time limitations. As all problem exploration steps were taken carefully and the model and tool are firmly based in literature, it was decided to prioritise further developing the integrated perspective over such tests. Section 16.4.1 provides concrete suggestions for a stepwise validation effort.

End of Part II: Socio-psychological perspective

III

Integrated perspective

Having investigated both the technical and socio-psychological perspectives in isolation, this part sets out to integrate the lessons learnt. This way, it aims to answer the central question and achieve the main goal, both repeated below.

> How can technical and socio-psychological perspectives be integrated in order to improve group decision quality under uncertainty in aircraft conceptual design and technology assessment and selection?
>
> Make a contribution to holistically improving group decisions about technology assessment and selection under uncertainty in aircraft conceptual design, by proposing a way of integrating technical and socio-psychological perspectives on decision making under uncertainty.

This part is much more concise than the two previous ones and therefore works towards a conclusion in a single chapter: Chapter 14. It was nevertheless decided to contain this chapter in a separate part as to indicate it is positioned comparable to Part I and Part II.

14

Synthesis

Part II analysed the decision making process in project MANTA, explored and defined a problem, found theoretical support and combined these insights into a model. Further back, in Chapter 3, decision quality was defined and influences on decision quality were explored. Throughout conducting this research project, the author was struck by the similarity between the factors *task* and *relationship* when it comes to decision goals on one hand (theoretically explored in Chapter 10), and *technical* and *socio-psychological* influences of decision quality on the other (discussed in Chapter 3). That chapter also put forward a definition of decision quality, in which the ideal observer played a role as aiming to strike a balance between *objectivity* and *trust* in its assessment of the decision. This dimension, too, seems closely related.

The current chapter sets out to further explore this possible connection in order to find opportunities to integrate the technical and socio-psychological perspectives. Making this effort is interesting from both an academic as well as a practical point of view. If such a connection can be shown to exist, it might allow insights from one perspective to cross over to another and vice versa, spurring further ideas for research or inspiring concrete actions towards improving decision quality.

In order to explore this notably more conceptual and philosophical idea as structured as possible, Section 14.1 first presents a short recap of the key 'ingredients' to the discussion that follows. Section 14.2 takes these to a more abstract level and explores whether or not these three different classes – objectivity and trust, technical and socio-psychological, and task and relation – are indeed instances of a greater whole. The insights gathered in that discussion are combined to a more refined description of the decision making system in Section 14.3, on which the influence of uncertainty is treated in Section 14.4. Lastly, Section 14.5 closes the chapter.

14.1. Synopsis

This section presents a short synopsis of the three dimensions under consideration in this chapter. Adhering to the structure of this report, the dimension *objectivity – trust* is treated first, followed by *technical – socio-psychological* and *task – relationship*.

Objectivity and trust

In Section 3.1.5, the following definition of decision quality was put forward:

> The extent to which a (group of) decision maker(s) at the decision point can convince an ideal observer that the decision will yield the decision goal, insofar possible.

The ideal observer was introduced to "strike a balance between objectivity and trust" (p. 19) in order to

broaden the applicability of the definition to uncertain situations, where both the decision makers and the ideal observer know there are things they do not know. In the assessment on the likelihood of the decision reaching the decision goal by the ideal observer (and thereby of the quality of the decision), “objective information can influence that confidence, but if that is not enough, other (more emotional) aspects can be used” (p. 19).

Technical and socio-psychological factors

Section 3.2 subsequently investigated a large number of factors influencing decision quality. These were grouped into four categories: contextual and supportive factors, technical factors, socio-psychological factors and implementation factors. Most influences were categorised as either technical or socio-psychological. The technical factors mostly concern “information” (p. 22), factors related to “human interaction, involvement, emotion and needs” are listed as socio-psychological factors (p. 23).

Task and relationship outcomes

In the analysis of decision making within project MANTA, and especially when setting up a theoretical framework to improve understanding of that analysis in Chapter 10, it was found that decision making yields both task and relationship outcomes. Task outcomes concern the “bottom line”, relationship outcomes are about the “process” through which a decision is reached (Oetzel, 1995, p. 255). Whether somebody puts focus on either task or relationship outcomes is related to the extent to which they are individualist or collectivist. The model developed in Chapter 11, then, connected the attention paid to task and relationship outcomes to the uncertainties about what the task and relationship goals are, and how these can be reached.

14.2. Abstraction

Although each of the dimensions discussed in the previous section combines elements that instinctively can be categorised in one of two categories, these dimensions are not identical. Whereas groups can choose to focus on either task or relationship outcomes (or a combination of those), there is no such possibility with regard to factors influencing decision quality: opting to neglect either the technical or socio-psychological factors contributing to a high-quality decision will render a groups’ choices sub-optimal at best. Regardless the objectives of the project, a leader can make or brake the project. Much the same, a group with the ‘right’ composition might be able to more effectively combine, weigh and integrate various perspectives, whereas a group with a ‘wrong’ composition might not, or might actually fail to uncover all pieces of information relevant to the decision. The reverse is true as well: a relationship-focused decision of high quality cannot be made without processing information about how particular actions will influence that relationship, for a decision can only be of high quality if the (group of) decision maker(s) at the decision point can convince an ideal observer that the decision will yield the decision goal.

Conceptualising these categories illustrates their overlap more clearly. Selecting one word for each category proved to be too limiting and could not effectively communicate the underlying idea, because of the richness of concepts such as *emotion* or *ratio* and because specific interpretations vary from person to person. To circumvent this problem, Table 14.1 was constructed, naming these categories *blue* and *orange*. The table was constructed over a longer period of time, aided by helpful discussions with other people on their interpretations of particular words. Each of these discussions helped to sharpen the ‘definition’ of blue and red, resulting in the lists of words shown in the table, which are used to give meaning to these concepts as the present authors perceives these them. It is hoped that the combined set of terms in each category can convey these meanings of blue and orange, refining the interpretation with every new word-pair added to the consideration.

As can be seen, *objectivity*, *technical factors* and *task* are grouped under the blue heading; *trust*, *socio-psychological factors* and *relationship* are categorised orange. The groups of activities in aircraft design – “engineering / mathematical calculations” and “decision making / logical selections” – put forward by Sadraey (2013, p. 2) are included as blue and orange, respectively, following Bottomley and Doyle (2006).

Table 14.1: Blue and orange categories

Blue	Orange
Ratio	Emotion
Explicit	Implicit
Engineering / mathematical calculations	Decision making / logical selections
Functional	Sensory-social
Information	Feelings
Objectivity	Trust
Aware	Unaware
Technical factors	Socio-psychological factors
Discussion	Interpretation
Knowing	Not knowing
Task	Relation
Machine	Human
Testing	Assuming
Transparency	Opaqueness
Rational	Irrational
Certainty	Uncertainty
Text	Thoughts

Over the course of synthesising these blue and orange perspectives, it was noted that although Table 14.1 holds true, it is an overly simplistic representation of reality. The table does not, for example, provide a clear answer to the question whether knowing about the feelings of another person in the group is orange, or blue, and whether it differs if that knowledge was acquired through a statement ("I feel good about this!") or deduced from a particular interpretation (a facial expression).

The following paragraphs aim to further detail these deliberations, focused on information and decision making.

Information

Following other blue concepts – explicit, aware, knowing, transparency – information is regarded as always being blue, while acknowledging it can have both a blue and an orange 'background'. Explicating feelings (orange) essentially means the decision making group receives new information (blue), just as results of a new mathematical calculation (blue) is new information. In making things explicit – transforming it into information – the group can assess it and determine its value and relevance for their decision making process. This also holds for knowledge that individual group members might possess (for example from experience with previous projects or decisions) which is explicated and shared with the group.

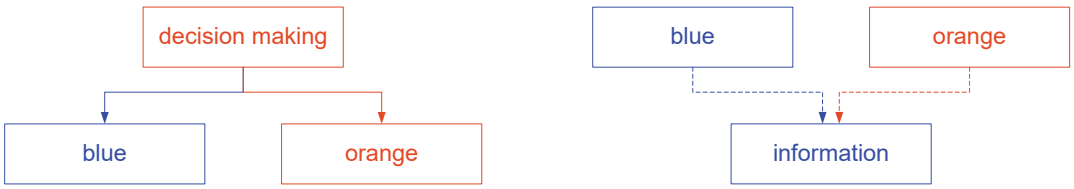
Decision making

On one hand, Table 14.1 classifies decision making as orange – opposed to the mathematical calculations grouped in the blue column. On the other hand, Table 14.1 does not place the technical and socio-psychological factors in the orange column, even though it was previously found that these make

up (most of) the decision making process. This observation draws attention to the fact that decision making exists at multiple levels. When making an important decision, there are smaller sub-decisions in which a (group of) decision maker(s) determines what information to take into account. The same is noted in the model proposed in Part II, which aims to support decision making groups in clearly defining (and thereby choosing) the desired types of outcomes of their decision.

Self-similarity

Adding to the observation that decision making consists of blue and orange inputs, the previous discussion indicated that information can have a blue or orange background. This is depicted in Figure 14.1. Figure 14.1a shows decision making; Figure 14.1b visualises information.



(a) Decision making, splitting up into blue and orange elements

(b) Information, originating in blue and orange elements

Figure 14.1: Schematic representations of decision making and information in terms of blue and orange elements

Interestingly enough, these schematics seem to be mirror images of each other: decision making 'falls apart' into blue and orange, whereas information 'emerges' from blue or orange. There is also a striking self-similarity: while it was previously found that each decision making process involves multiple sub-decisions, a particular piece of information, too, has many 'ancestors' – a logical consequence of the fact that information transfer is far from perfect, and is victim to continuous interpretation, processing and translation.

Fractals and the Droste effect: self-similarity further explored

Self-similarity is the property of an object or pattern to never end. A well-known example from popular culture is the Droste-effect, named after the cacao tin which carried a picture of a woman holding that same cacao tin, which holds the same cacao tin, and so on. Figure 14.2 shows another example, in the form of the Mendelbrot set. Each subsequent images is a further close-up of the previous one, slightly translated to the left. After going through all six images, the first of the set forms the next in line and the loop starts again.

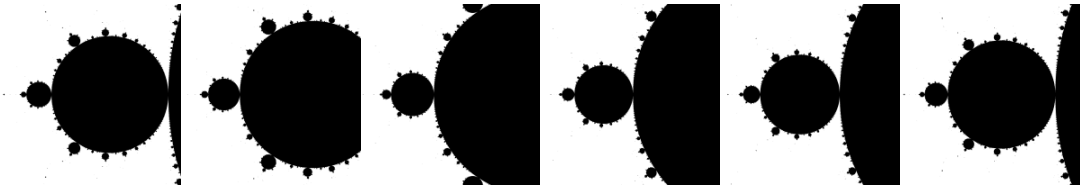


Figure 14.2: Various magnifications of the Mendelbrot set, showing the self-similarity of fractals. Adapted from Wikimedia Commons and Bewareircd (2009)

Besides cultural or mathematical illustrations, self-similar objects can be found in nature as well, such as ice crystals, systems of blood vessels or ferns. Although it is an idealised illustration, Figure 14.3 clearly shows how the two bottom 'leaves' are identical to one another as well as to the entire fern.

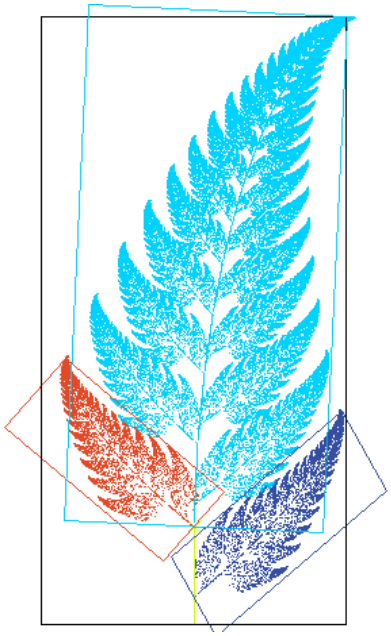


Figure 14.3: A Barnsley fern, showing the (idealised) self-similarity of nature. Adapted from Wikimedia Commons and de Campos

In case this concept would be applied on the schematic shown in Figure 14.1a, a sequence of images as depicted in Figure 14.4 might result. Whereas the first decision might be a universally regarded as 'big' one, it breaks down into 'smaller' choices. Even though these are often thought of as being less important or influential, Figure 2.5 has shown that early decisions in such a staggered process can have major consequences.

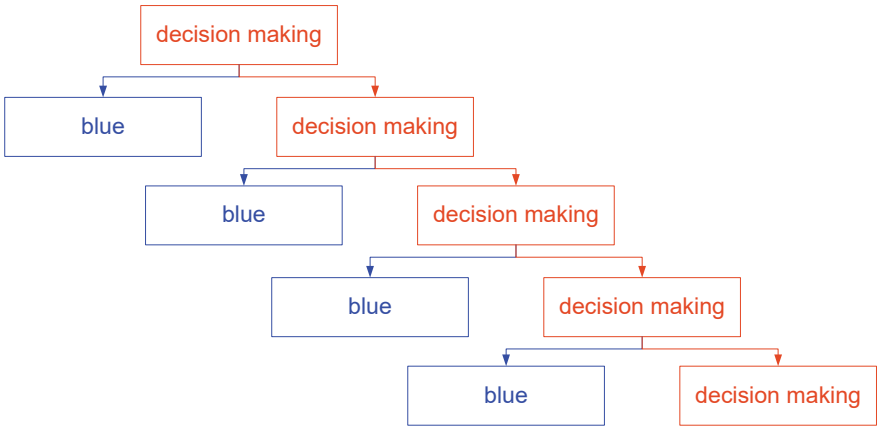


Figure 14.4: Self-similarity of decision making

14.3. Interconnection

The insights gained above result in a partial update to the description of the decision making system outlined at the end of Chapter 3. The schematic shown in Figure 3.2 is partially repeated in Figure 14.5.

This schematic already indicated the interplay of technical factors and socio-psychological factors, noting that "people in a team need to feel comfortable (socio-psychological factor) to share their insight (technical factor)" (p. 25) and "the presentation of information (technical factor) influences how it is discussed (socio-psychological factor)" (p. 25). Figure 14.6 combines these two elements, but no longer classifies

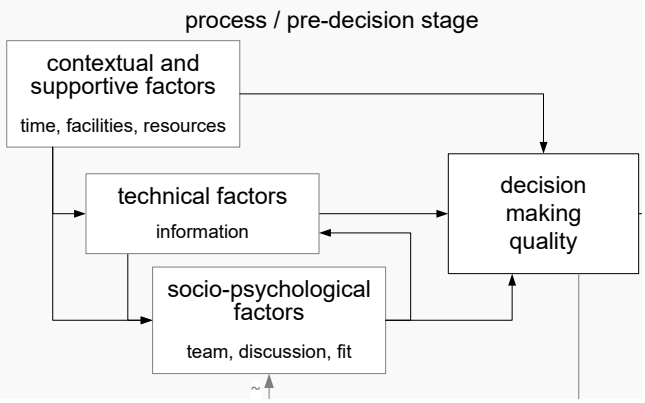


Figure 14.5: Partial copy of Figure 3.2, showing the interrelations between contextual and supportive factors, technical factors and socio-psychological factors

information *processing* a technical factor. Rather, an *information processing unit* – the decision making group – is introduced. Information (either from an external source, or due to the knowledge of an individual in the group being explicated) is input to the information processing unit. The workings of this unit are subsequently shaped by socio-psychological factors, such as leadership and team climate. The influence *group composition*, another socio-psychological factor, can serve as a source of new information. The output of the information processing unit is – as expected – a decision.

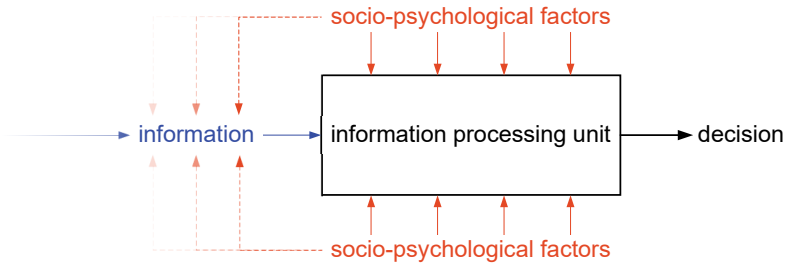


Figure 14.6: Revised representation of the decision making system, showing socio-psychological factors influencing the 'information processing unit'

The above discussion yields the interesting and somewhat paradoxical insight that the information processing unit first requires implicit things (feelings, individual knowledge, ...) to become explicit (information), before it can subsequently combined these explicit things in a rather implicit way. Exactly because the information processing unit (in this thought experiment, at least) is human, it is impossible to know precisely how it operated. The true reasons for making particular choices might not be explicated, the list of arguments supporting a choice might not be exhaustive or a multi-dimensional analysis might be aggregated into a single parameter: a score. Coincidentally, all these 'intransparencies' were observed in decision making in project MANTA.

Having now established the interplay of the two colours, it has to be concluded that although (predominantly) blue or orange perspectives of decision making can be distinguished, it is impossible to isolate them. Doing so only yields a two-dimensional *projection* of decision making, as shown in Figure 14.7, whereas the complete three-dimensional *object* that decision making is, remains hidden from view.

Although decision makers can attempt to reconstruct the three-dimensional figure from the two-dimensional projections, such an approach can never definitively define the shape of the three-dimensional object. Who is to say whether the projections shown in Figure 14.8a stem from the three-dimensional object shown in Figure 14.8b, or from Figure 14.8c?

As such, it is postulated here that asking how the technical and socio-psychological perspectives of

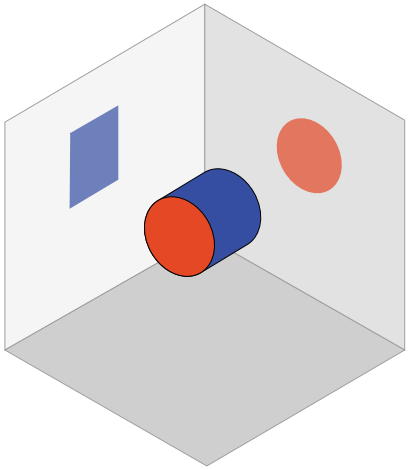
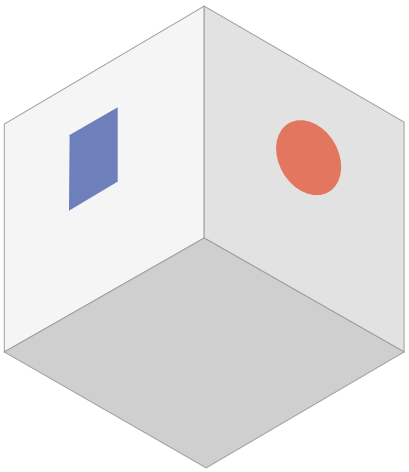
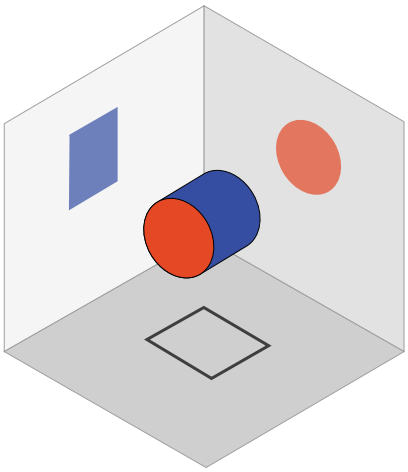


Figure 14.7: Illustration of a three-dimensional object (decison making), casting two two-dimensional projections (the blue and orange perspective), adapted from StareCat.com

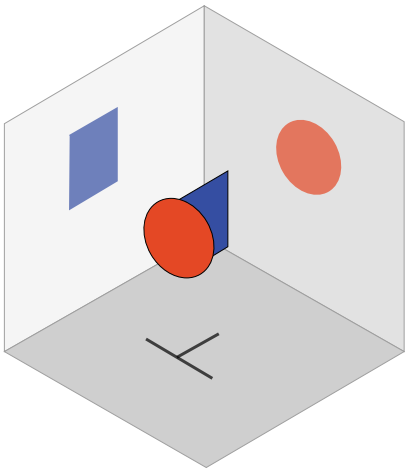
decision making can be integrated is irrelevant. Rather, we should be asking how we can gather more information about the decision making object, or how we can focus our thinking on an integrated rather than an isolated perspective.



(a) Two-dimensional projections of object A and B



(b) Object A



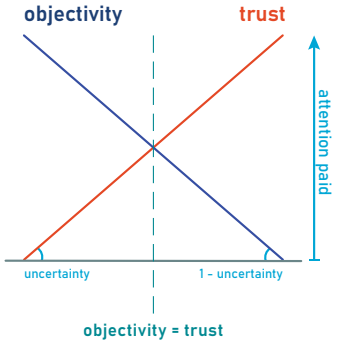
(c) Object B

Figure 14.8: Different three-dimensional objects resulting in the same two-dimensional projections, illustrating that these projections alone do not provide all information necessary to construct the three-dimensional object, adapted from StareCat.com and Curtis (2016)

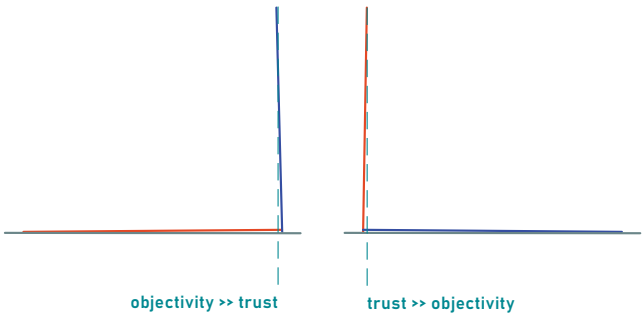
14.4. Under uncertainty

In presenting a revised and interconnected system description, the previous also partially answered the main question of this part and – by extension – of this thesis. That discussion, however, did not yet include the role of uncertainty, even though this was found to be of great importance in aircraft conceptual design as well as in technology assessment and selection processes. The current section corrects that deficiency, by taking another look at the ideal observer.

In a hypothetical and fully deterministic world where uncertainty does not exist, the quality of a decision can be based on objective facts. If a group of decision makers is able to show a document to an ideal observer which states that if the group decides X, it is certain that it will result in outcome Y, this is all the ideal observer needs to know. Similarly, in a completely opposite case where nothing is certain, information has no value: trust in the process is the only remaining measure that influences decision quality. Between these two fictitious extremes, the ideal observer will have to strike a balance between objectivity and trust – between blue and orange. Figure 14.9a shows this in a simple diagram, inspired by the model developed in Chapter 11. Figure 14.9b corresponds to the situation where uncertainty is absent; Figure 14.9c represents the opposite scenario.



(a) Balance between objectivity and trust as a function of uncertainty



(b) Complete certainty (c) Complete uncertainty

Figure 14.9: Balance between objectivity and trust as a function of uncertainty, inspired by Figure 11.7

These ideas can be refined with the discourse presented in this chapter – discerning the background of information: the ideal observer bases its assessment of the decision quality on the information about the desired outcome and the decision making process. The decision making process is defined as visualised in Figure 14.6. Therefore, information about the decision making process includes knowing what information has entered the system, as well as how socio-psychological factors have influenced the way the information was processed.

Combining that analysis with Figure 14.9, it is hypothesised that uncertainty plays a role in the integrated perspective by influencing the information background. Similar to Figure 14.9a, it will be mostly blue

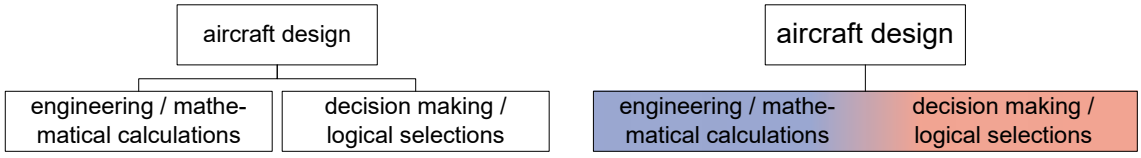
in case there is little uncertainty, but mostly orange in case there is a lot of uncertainty. In affecting the information background, uncertainty also impacts the interwovenness of the technical and socio-psychological perspectives: more apart in a deterministic world and more closely integrated in a more uncertain one.

14.5. Closing

The current part set out to answer the overall question of this thesis: *How can technical and socio-psychological perspectives be integrated in order to improve group decision quality under uncertainty in aircraft conceptual design and technology assessment and selection?*

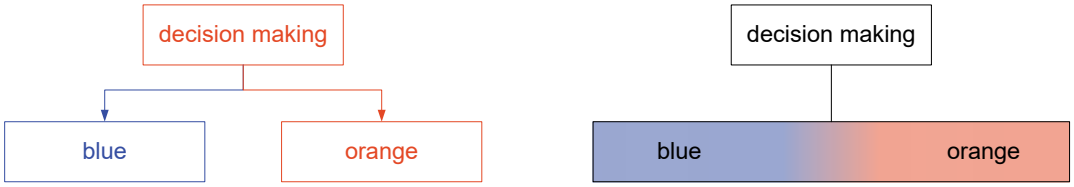
Rather than developing the building blocks to answer this question, this chapter has found that the premise of the question does not hold. Through the comparison of various fundamental dimensions central to the research presented in this report – objectivity and trust, technical and socio-psychological factors and task and relation outcomes – it was found that the technical and socio-psychological perspectives are already integrated, more than we might realise. Rather, it seems we apparently struggle (or maybe even fail) to realise that, and subsequently act upon that realisation. Although both perspectives can be distinguished from each other, they cannot be completely separated. Uncertainty was found to impact the interwovenness of the two perspectives, more tightly integrating them in case uncertainty is higher.

Following this result, two figures presented in this report have to be updated. Figure 14.10a was first shown in Chapter 2 and inspired the two-part approach of the problem, documented in Part I and Part II. Figure 14.11a was based on that figure, and first presented in this chapter. Based on the discussion presented here, these are now replaced by Figure 14.10b and Figure 14.11b.



(a) Original (b) Updated

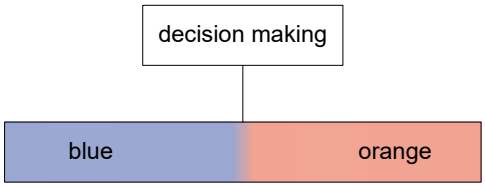
Figure 14.10: Original and updated version of Figure 2.6, based on Sadraey (2013, p. 2)



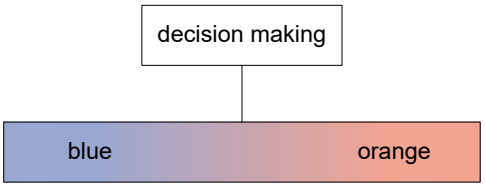
(a) Original (b) Updated

Figure 14.11: Original and updated version of Figure 14.1a

Both cases, as represented in the figures, assume a moderate level of uncertainty. If this would increase, the blue and orange are further intermixed, whereas situations with lower uncertainty show more the two colours more clearly apart. Figure 14.12 illustrates both situations for Figure 14.11b.



(a) Lower degree of uncertainty



(b) Higher degree of uncertainty

Figure 14.12: Original and updated version of Figure 14.1a

End of Part III: Integrated perspective

15

Conclusions

This research aimed to *make a contribution to holistically improving group decisions about technology assessment and selection under uncertainty in aircraft conceptual design*, by *proposing a way of integrating technical and socio-psychological perspectives on decision making under uncertainty*. After having investigated decision making from a technical, a socio-psychological and an integrated perspective, the current chapter draws conclusions. It is done by answering the research questions posed in the introduction. As Chapters 8 and 13 already presented the answers to the sub-questions of research question I and II, this chapter focuses on the main research questions – 0, I and II – as well as the overall question to be answered in this thesis.

Decision quality

To more orderly tackle the problem of improving group decision making, factors contributing to high-quality group decisions were investigated first. Lacking a generally accepted definition in literature, decision quality was defined as *the extent to which a (group of) decision maker(s) at the decision point can convince an ideal observer that the decision will yield the decision goal, insofar possible*. The ideal observer – an idealised entity, completely transparent and unaffected by the decision or its outcome – was introduced to make the definition applicable to situations with both high and low levels of uncertainty. In the former case, the decision quality will be based mostly on trust – for example in the procedure through which the decision was reached. In the latter situation, objectively verifiable facts determine the quality of the decision. A crucial element of the definition is that the decision quality is established at the point at which the decision is made, in order to separate the quality of the decision from the desirability decision outcomes.

Factors influencing decision quality found in literature were categorised in four groups. Contextual and supportive factors 'set the stage' and include factors such as available time and decision procedure. Technical factors group factors relevant to information and information processing: information must be available, adequate, complete and of good quality, and must subsequently be exchanged, interpreted and assessed. Socio-psychological factors were defined as related to human interaction, involvement, emotion and needs and mostly influence the deliberation phase of the decision making process, by team composition, size and integration, or through conflict, leadership and cognitive reasoning. These (interrelated) factors determine the quality of the decision making process. The combination of the quality of the decision making process and factors related to the ability to implement a decision and the commitment to it, then determine the decision quality. Socio-psychological and technical factors were proposed as highly interlinked.

Technical perspective: uncertainty quantification

The need for high-quality information, as well as information about the uncertainty of that information, inspired research question I: *How can model uncertainty be quantified, assessed and propagated bottom-*

up, i.e., starting from model(ling) assumptions, simplifications and limitations? Three two-dimensional aerodynamic solvers – an incompressible panel method, a finite difference full potential solver and a finite volume Euler code – were compared in their ability to predict a number of aerodynamic quantities of interest relevant to the conceptual design process for a variety of geometries and inviscid flow situations. Given a representation (in terms of number and distribution of coordinate points) and grid that is accurate enough, the impact of solution method was found to be much smaller than the impact of flow model for Mach numbers outside the low subsonic regime. Comparing flow models, it was found that the incompressible flow assumption has a notably higher impact than the irrotational flow assumption in the Mach range considered.

Propagating these two-dimensional results to an assessment of impact at wing level using a three-dimensional vortex lattice method and scaling of the lift slope indicated results consistent with the 2D analyses, and scaled by aspect ratio, wing sweep and taper. In a qualitative further extension to aircraft-level parameters, the estimated influence was found to be substantially lower than the uncertainty band associated conceptual aircraft design and analysis tool used for this analysis. As such, the effect of the aforementioned assumptions could not be unambiguously established. Nevertheless, the approach taken to assess the uncertainty caused by particular modelling assumptions – based in systematic one-by-one parameter variations, gradual scope enlargement and using scaling and correction factors – was shown to yield usable results.

Socio-psychological perspective: decision making

Based on the earlier conclusion that a good decision requires more than just information and a quantification of the uncertainty thereof, research question II was put forward: *How can a (combination of) relevant socio-psychological factors negatively impacting group decision quality be combined in a conceptual model and subsequent tool that helps to understand and mitigate that impact?* Based on an analysis of project MANTA, a public-private R&D partnership in which industry, research institutes and academia investigate wing movable concepts in order to reduce fuel consumption, it was found that the quality of screening decisions in project MANTA is negatively impacted by the fact that uncertainty about project goals exists and is not sufficiently explicated, reduced or otherwise managed. The central concepts of Effective intercultural workgroup communication theory and vigilant interaction theory – the relation between task and relationship outcomes, group integration and uncertainty – were combined into a newly developed model called TARE.

It was concluded that workgroups need to pay attention to both task (TA) and relationship (RE) outcomes. The amount of attention each gets depends on uncertainty about how those outcomes could be realised, as well as group preference regarding the balance between the different types of outcome. Uncertainties and misalignment about what the outcomes should be (i.e., what the goals are) were modelled as attention losses, seen as waste. The anticipated use of the model, in the form of a tool, starts with collecting data about the goals of various (individual) project participants and subsequently aggregating these to yield a group perspective. The resulting schematic – essentially a quantification of uncertainties associated to different project goals – is then evaluated by the group. This crucial last step fosters the explication and subsequent management of goal uncertainties that was found to be missing.

Integrated perspective: holistically improving group decisions

Aiming to improve the quality of group decision holistically, the overall question put forward in this thesis asked *how technical and socio-psychological perspectives could be integrated in order to improve group decision quality under uncertainty in aircraft conceptual design and technology assessment and selection*. Comparing the outcomes of earlier research stages – in which *objectivity and trust*, *technical and socio-psychological factors* and *task and relationship outcomes* were identified as key parameters – the previously proposed interrelation between socio-psychological and technical factors was confirmed. At the same time, it was concluded that the premise of the overall question does not hold. Using a thought experiment, it was established that the two perspectives are already integrated, but that we fail to fully appreciate the consequences of that integration. Whereas the perspectives are often separated, this thesis concludes that although the technical and socio-psychological perspectives can be distinguished from

each other, they cannot be taken apart. That holds even more so for uncertain situations, as uncertainty was found to increase the interwovenness of the two perspectives.

16

Discussion

This thesis has investigated ways to improve the quality of screening decisions under uncertainty in aircraft conceptual design and technology assessment from multiple perspectives. Clearly demarcated research questions were put forward to guide that exploration, of which Chapter 15 presented equally specific answers. The appropriate modesty of these questions, however, prevented discussing the more general implications they inspire.

The current chapter aims to change that, by embedding the results in the broader context as it was sketched in Chapter 2. That is the objective of Section 16.1. Following that, Section 16.2 summarises the contributions made by this research project. Then, Section 16.3 discusses limitations of the research as it is presented in this report. These do not concern detailed methodological considerations, as those were already discussed in Sections 8.2 and 13.2. Rather, Section 16.3 contains remarks on a somewhat higher level. Last, Section 16.4 takes a broader outlook and treats opportunities, both for future research as well as for translation into practice.

16.1. Implications

In the introduction to this report, the problem under investigation in this research project was positioned in context: a context of making good decisions about conceptual aircraft design in order to make sure the vehicles we develop in the near future will meet the goals and requirements of the far future. A new phase of rapid innovation – focused on reducing the impact of aviation on the environment – is envisioned, in which (hybrid-)electric aircraft, novel configurations and smarter and more integrated systems are likely to play a role. Design organisations and individual engineers alike will want to make the right choice about all those innovations – and rightly so. That ambition, coupled with the increase of computing power available to aircraft designers, has firmly established computational aerodynamics, computer aided design and multidisciplinary design optimisation as essential elements of the toolkit of a modern-day aerospace engineer.

Available computing power continues to increase – opening up more and more tools that were previously limited to more detailed stages of the design process to the conceptual design phase. The fact that we *can*, however, does not automatically mean we *should*. As Section 4.1.4 indicated, agreement about what tools are best suited for conceptual aerospace design has not yet been reached. Especially given the higher input requirements of higher-fidelity models, and noting the possibility of performing (sub-)system analyses adjacent to (rather than included in) the main design process, it was argued that the conceptual design phase should be limited to using models of fidelity levels no higher than L2.5 (thin-layer Navier-Stokes equations) and L1 (full potential equation) for problems in two and three dimensions.

Using models fitting in that scope, the influence of two fundamental simplifications was assessed: the

incompressible and irrotational flow assumptions. Isolated effects were found to be significant, but when propagating the effects to full-size aircraft-level using the Aircraft Design Initiator, the influence on key performance indicators was found not to exceed the range of uncertainty associated to the Aircraft Design Initiator. Even though that prevented drawing definitive conclusions about the precise effect the aforementioned simplifications have on aircraft-level characteristics *in general*, it does provide information about the effect of these assumptions on the characteristics of *a conceptual aircraft design*. After all, given that the Initiator has been successfully employed as a conceptual design tool and technology assessment platform on previous occasions, and the observation that its sensitivity to the incompressible and irrotational flow assumptions cannot be established, support is found for the hypothesis that the two flow model assumptions considered do not influence the overall characteristics of a conceptual aircraft design.

Even though this is still an hypothesis, its implications are substantial. If making even the most fundamental of aerodynamic simplifications does not significantly impact a conceptual design, there seems to be very little support for the trend described earlier in this section. Moreover, it might warrant an update to the conclusion regarding the applicability of particular fidelity levels to conceptual design, reducing the upper limit in two-dimensional cases to L1 as well. Last, it has implications for early-on aircraft-level performance assessments. Although engineers are wise to investigate synergistic or discordant when assessing performance, the step to key performance indicators might be too large when innovations take place at subsystem level or below.

Zooming out from the purely technical perspective that was the topic of the previous paragraphs, contrasting it to the socio-psychological aspects of making good decisions inspires a further reflection. Analysing decision making with project MANTA, it was found that “decisions are in some cases based more on individual (personal or organisational) goals, interests or opinions, rather than analytical results” (p. 149). Although that was not highlighted as problematic per se, it does put the continued push for additional analyses, computations and quantifiable results in a considerably different light. Supporting the hypothesis put forward at the end of Chapter 14 – that we on one hand know there are blue and orange sides to decision making, but on the other hand struggle to successfully act upon that knowledge – it might be that we do not need a discussion about right fidelity models, but would benefit much more from an open debate on how we can give socio-psychological factors the attention they desire.

16.2. Contributions

Having put the concrete results of this thesis back into its wider context, precisely the results of that effort might be the most significant contribution of this research project. It is most certainly not the most concrete or empirically valid result, but it is argued that a question or hypothesis can sometimes be much more useful than an answer. Even though this report will certainly not end that discussion for good, the author feels that Section 16.1 makes a relevant and valuable contribution to a debate that seems long overdue. If any of the deliberations just presented provide an impulse to such a deliberation, the effort has been absolutely worthwhile.

That grander vision, however, does not negate any of the much more specific contributions made by this research. First of all, the extensive overview of factors that influence decision quality did not previously exist. That also goes for the attempt that was made at clustering and connecting those factors, to a model suggesting how decision quality can be improved and how technical and socio-psychological factors are mutually influenced. Although these models are far from completed (as further treated in Section 16.4.1), this thesis might pave the way to further structured understanding of the position of decision quality and factors influencing it.

In Part I, then, attention was paid on what aerodynamic flow models and mathematical solution methods are suitable for use during conceptual design and analysis projects. An extension was proposed to the fidelity levels proposed by Ciampa et al. (2013) and Gu et al. (2018) and various flow models and solution methods were classified in greater detail. In the main research effort of this part, it was established that the impact of the solution method is much smaller than the effect of the flow model, given an accurate

enough representation and grid – the specifics of which were shown for various solvers, flow cases and quantities of interest. Furthermore, an approach of uncertainty quantification and propagation was proposed and tested, which thereby provides a basis for further systematic research in this interesting area.

Third, in Part II, a model was developed that explicates a number of group decision making difficulties often hidden from view: uncertainty about goals and the way to get their, (mis)alignment between various stakeholders, group integration and – most important of all – the balance between task- and relationship-outcomes. It is hoped that both project MANTA as well as other projects might benefit from the model. On a larger scale, it is felt that this thesis presents a number of fundamental critiques on (most notably) effective intercultural workgroup communication theory, which hopefully can contribute to further refining that theory. More detailed suggestions for that effort are treated at the end of Section 16.4.1.

16.3. Limitations

Although this research started with a broad aim – to improve technology assessment and selection decisions in conceptual aircraft design – the problem scope was progressively refined to arrive at two more manageable sub-problems. As seen in Chapter 15, this made it possible to formulate precise solutions, but also comes with limitations. Since specific methodological shortcomings have already been discussed in Sections 8.2 and 13.2, these are not repeated here.

A first remark must be the disclosure of the fact that this research was performed by one person and might therefore carry a bias. The author has investigated the problem from a particular perspective, using a particular set of knowledge and with a particular set of values, experiences and tools. These more subjective factors especially play a role in Part II, for example when observing one thing, but being blind to the other. This certainly holds for Part III as well, as the results presented in that part were obtained from a (largely individual) thought experiment. In carefully documenting the steps taken, the hope is expressed that they can be retraced whenever necessary. In summary, which holds just as well for Part I, other researchers might have approached this project differently, possibly leading to different results.

A second limitation – or point of attention, for that might be a better term – is the fact that the literature study into influences of decision quality has not been limited to the specific project context of project MANTA, as also documented in Appendix B.1.1. As holds in general, the background of these factors has been documented (in Appendix B.3), thereby allowing readers convinced of the importance of a specific context to filter the results accordingly. The present author, however, is not convinced of that limited scope and would like to argue that – especially after the rounds of grouping, clustering and abstraction done – the results in Section 3.2 holds as much for an aerospace engineering context as for a business or medical setting. Information about co-morbidities might have no literal meaning outside the hospital, but the importance of knowing the content of a problem and how particular aspects of it (might) interact with the wider system certainly has.

Similarly, it proved difficult to position the type of collaboration and decision making that occurs in project MANTA in literature. Classifying these as screening decisions has proven successful and can be easily defended: there is a group of people that starts with a magnitude of concepts, bringing that back to a smaller amount through subsequent go/no-go decisions which are based on relatively limited information. On the other hand, this categorisation can be questioned just as easily: the project runs over a longer period of time than usual for screening processes and committee members are (especially at the time of the second down-selection) highly involved in and possibly attached to the concepts reviewed. Top management team literature was also reviewed, but there too, it was found that some elements match the situation of project MANTA very well – such as more senior decision makers and the fact that the group is of a temporary nature – whereas others – the scope, detail and impact of the decision – do not. Although inspiration was drawn from bodies of literature about both classes to obtain a richer understanding of the problem, results might have been better grounded in theory if a more closely fitting paradigm could have been found.

A more substantial impediment is formed by the early-on decision to place cultural factors outside the research scope. Despite appreciating the differences between Dutch and German culture, for example, the author opted not to consider this in order to reduce the problem to a more manageable size. Especially when starting to develop the theoretical framework underlying Part II, irony struck and effective *intercultural* workgroup communication theory proved to be suitable as academic foundation for subsequent design steps. Although the culture-focus on that theory has been extensively criticised in Section 10.2 and the use of that theory by no means indicates a complete turn in research scope, it does emphasise the limitation of not including other possibly relevant literature on cultural aspects of decision making in this project.

Somewhat related to the previous limitation is the fact that the technical factor selected as main point of interest for Part I – information about the uncertainty of other information – was chosen based on a more general review of literature, than on a specific analysis of project MANTA. Although information (un)certainty was discussed, other problems might have been more pregnant.

The last limitation also marks an opportunity. Over the course of this research project, the author has attained a much wider and more refined understanding of concepts such as decision making, problem solving and team effectiveness. With that knowledge, a number of boundaries defined in this research in hindsight seem somewhat arbitrary. The aforementioned literature study conducted to find contributions to decision quality, for example, might have failed to uncover critical factors categorised as drivers of team or decision making effectiveness. Related is the discussion on how the process of decision making fits within the larger problem solving process. In this text, it was defined as succeeding goal and solution formulation in Figure 3.1, whereas exactly that first element was identified as factor influencing decision quality and indeed discovered to be most problematic in project MANTA. Further deliberation of these topics is presented in Section 16.4.1.

16.4. Opportunities

In addition to the limitations and boundaries of this research, it presents a host of opportunities. To structure that discussion, these opportunities are split up in two groups. Section 16.4.1 treats opportunities for further research or development in academia. Section 16.4.2 presents possibilities of applying the knowledge gained and the models developed in this project in practice.

16.4.1. In research

This section lists a wide array of suggestions for further research. They have been structured chronologically, to follow the structure of this thesis. Academic opportunities regarding design quality are treated first, before moving on to recommendations with respect to the technical, socio-psychological and integrated perspectives.

Decision quality

Continuing the discussion on the differences between decision making and problem solving and decision quality and team effectiveness started in the previous section, the present author sees a major opportunity in more strictly defining and delineating these areas. The quality of decisions made by a team might play an important role in determining their effectiveness, but just as all cows are animals but not all animals are cows, the lack of separation makes it difficult to systematically research and improve particular elements. Well possible *the* most important suggestion for further academic work would be to set a clear definition of decision quality. In the present authors opinion, it truly is bewildering that such an important area of research – repeating Simon et al. (1987, p. 11), making decisions “steers the course of society” – is missing such essential foundations. Closely related is the question where decision making stops and ends, especially in relation to the general problem solving process. Although the inherent interwovenness – agreeing on a goal is the result of a decision making process in itself – of these aspects makes it difficult (if not impossible) to demarcate where one ends and the other starts, the current haziness is noted as a barrier towards more structured research in this field.

Further exploratory opportunities for future research include taking another look at some of the concepts that were put aside in this work. Researching the extent to which top management and new product screening teams, discussed in Section 3.1.4, are (in terms of decision making) indeed comparable to each other or to conceptual designers might be interesting, and possibly allows for currently clearly separated knowledge to cross such a chasm, opening it up to a much wider audience and context. Similar ideas might spur from investigating whether the promise of transactive memory systems (observed in Hammedi et al. in a business context) can also be translated to an engineering or design situation.

With respect to the work done on defining decision quality and structuring its influences, there are also a number of evident recommendations concerning validating the presented results. The representation of the decision making process as shown in Figure 3.1 was already discussed. Moreover, further research required to establish the correctness of Figure 3.2 – the schematic representation of influence on decision quality that was proposed in Chapter 3 – and Figure 14.6 – showing the information processing unit transforming information into decisions, while being influenced by socio-psychological factors in multiple ways. Besides the interplay of technical and socio-psychological factors, the relationships between *regret* and *socio-psychological factors*[1] of decision making and the closed-loop direct influence of *implementation factors* on *decision quality* and vice versa seem especially interesting to test. A related effort is a further validation or refinement of the classification of decision quality influences (contextual and supportive, technical, socio-psychological and implementation-related). The distinction between group and individual socio-psychological factors, made by Pavitt (2014), is a concrete example. In connection to the theoretical framework put forward in Chapter 10, the notion by Hackman (1990) that a third – largely personal – outcome dimension exists in addition to the task- and relationship-related outcomes might provide a way to not only further refine the description of the decision making process, but also inspire an addition to the results obtained in Part II.

Technical perspective

Straightforward recommendations are made to further our understanding of uncertainty quantification and propagation in conceptual design.

Even though the toolkit described in Section 6.2.1 was set up to analyse the influence of viscosity as well as assess a number of drag coefficient components, these flow cases could not be properly investigated within the available time. Possibly as follow-up thesis work, it would be interesting to see the influence of neglecting two-dimensional viscosity on three-dimensional wing and aircraft performance parameters. Reynolds numbers of 3, 6 and 9 million are proposed for such an effort, as that allows comparison with readily available experimental reference data as well[2]. Besides generating the data for different flow models and viscous-inviscid interaction methods, there is an opportunity for assessing the possible influence of various drag computation methods (such as pressure drag integration or momentum-integral methods) – a difference that contributed to the decision to limit the current research to inviscid flows. Circumventing the numerical integration steps in the solver and performing these calculations based on the ‘raw’ output (in terms of e.g. skin friction and pressure coefficients and momentum thickness) will likely be the best way to separate between flow model and solution method.

Related to (and possibly an extension of) the previous suggestion follows from the notion that a number of capabilities of the toolkit were developed partially or completely, but not included in this research due to time limitations. In case the toolkit is further used or developed, it is highly recommended to correct these omissions. They concern the Laitone compressibility correction, a more detailed comparison of shock behaviour (analysing shock location and strength) and the assessment of other quantities of interest identified in Section 4.2.

[1] It was hypothesised that outcome bias – causing people to asses the quality of the decision based on the result it has – has an effect on how people learn from previous decision making experiences. Even though they might have made a high quality decision, following from a high quality decision making process, outcome bias might lead people to believe their process was flawed, leading them to take another (possibly lower quality) approach when making their next decision.

[2] A substantial amount of data from Harris (1981) (NACA0012) and Cook et al. (1977) (RAE2822) was already digitised but not compared, mostly due to time limitations. Furthermore, as the experimental data is of course viscous, the comparison to the inviscid cases analysed here would have been unfair. Doing so might yield a relevant new perspective: if models only vary a few percent between each other but collectively deviate orders of magnitude more, it might be the wrong problem to focus research efforts on.

Extending the analysis into the viscous domain as proposed previously might make the next suggestion even more relevant, but even without that addition it might be interesting to explore the possibilities of using the data generated in this research effort can be used to develop a meta-model. Due to the limited influence of solution method, such a project could save resources by limiting itself to the flow model influence. Figure 16.1 provides a first estimation of the possible relevance of such a model. It shows – for different airfoils, Mach numbers and angles of attack – the difference in lift coefficient as found using an incompressible (XFOIL-U) and compressible (VGK) flow model, normalised to the incompressible result. Even though the fit is relatively poor at low Mach numbers, and in the zero-lift angle of attack region of the RAE2822, the quality of the fit is especially high ($R^2 > 0.97$) at Mach numbers above 0.3. Preliminary analysis of the fitted polynomial in Figure 16.1, described as as $y = ax^2 + bx + c$, indicates the variance of both a and c can be relatively accurately described using an exponential function of freestream Mach number. Comparing compressibility-corrected results with truly compressible data, fourth-order (a logical consequence of the fact that the compressibility corrections depend on M^2) polynomial fits of similar quality were obtained.

Following the previous suggestion, a clear research opportunity is seen in the evaluation of additional airfoil geometries, possibly parameterised. This would allow isolated assessment of the influence of camber, leading edge radius and thickness – to name a few. Initial comparisons between the two airfoil geometries included in Figure 16.1 have sparked the hypothesis that the coefficients a and b strongly depend on the geometry. The lift slope (mostly a function of thickness) affects a, whereas the zero-lift angle of attack (depending on camber) is likely to cause the variation in b.

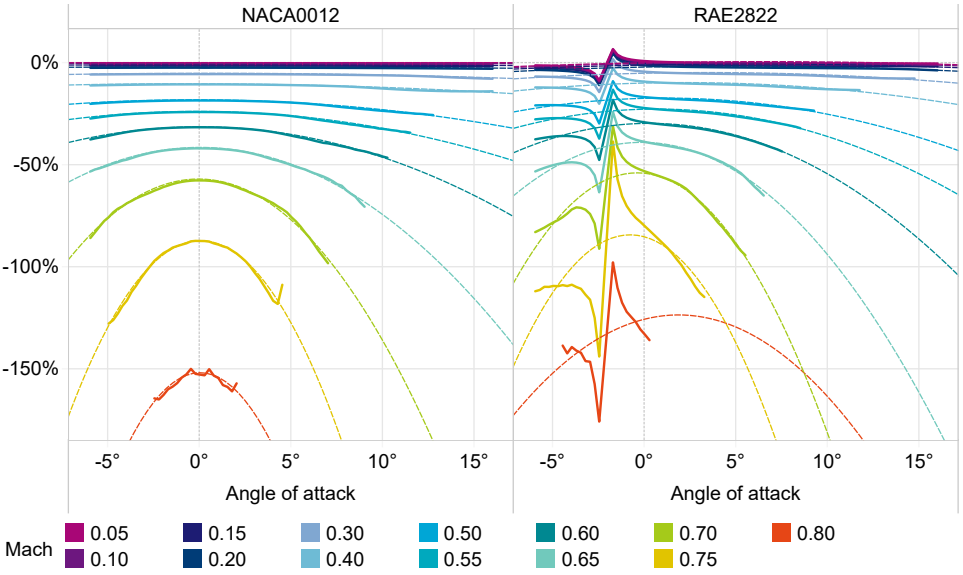
In order to validate and test the results obtained in the uncertainty propagation part of the present research, it is considered a relevant opportunity to perform the same analyses as conducted here using different tools. AVL might be replaced by another vortex lattice method (thereby hopefully also circumventing the problem of the translating supercritical lift slope); the Initiator might be replaced by the Advanced Aircraft Analysis package or RDSwin (DARcorporation, 2005; Raymer, 2016). Such analyses might yield evidence supporting, refuting or limiting the conclusions drawn in this thesis. Especially given the possible implications shown in Section 16.1, such an effort is expected to be significant. Slightly related to this suggestion is the idea to replicate the analyses reported here with different two-dimensional flow solvers. Of the three, replacing MSES is probably most worthwhile, as the problems with seemingly separated flow now limited assessing the impact of the irrotational flow assumption to a relatively narrow domain of angles of attack.

Furthermore, there is a recommendation of work *not* to pursue: developing from scratch a hybrid flow solver in which assumptions can be toggled on and off at will. Although such a code will definitively make it easier to isolate particular simplifications, it will also require to replicate the work that was put into developing XFOIL, VGK and MSES. Based on the results presented here – most notably the very limited impact of solution method – the present author is quite convinced that reinventing the proverbial wheel is not lucrative at all.

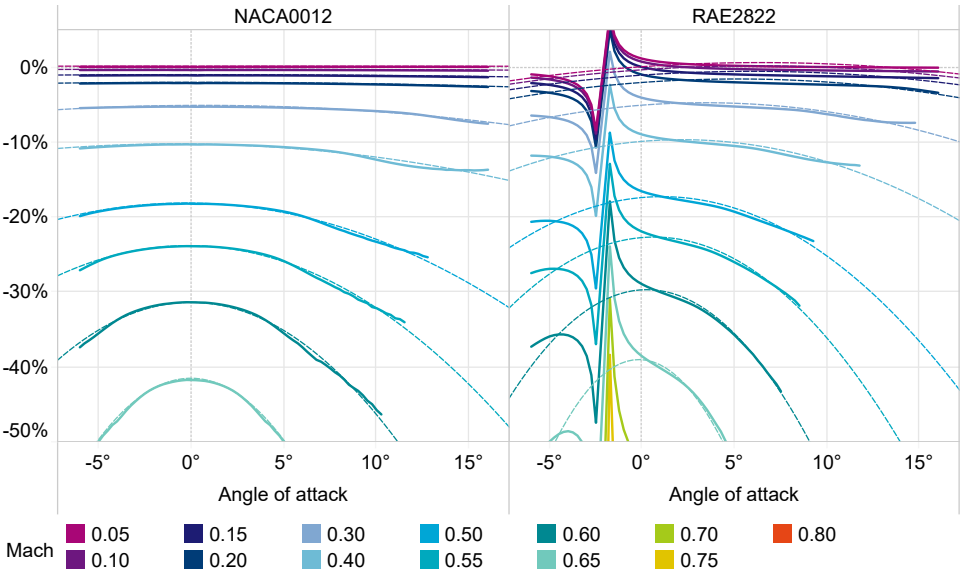
Ending the list of suggestions for further research with respect to the technical perspective is the recommendation to improve the definitions of fidelity level proposed by Ciampa et al. (2013) and Gu et al. (2018), as well as to possibly expand the scale. An intermediate level between the *most detailed* and a *more detailed* representation was already added in this thesis. Similarly, it might be worth considering further refining L1, which now includes a fairly wide range of models: from the simplest panel method to the most advanced potential flow code. The possible future introduction of physics-*based* meta-models furthermore raises the question of how these should be classified.

Socio-psychological perspective

For a variety of reasons, the developed model and subsequently proposed tool were not tested in practice. Specifically because it was argued that although the work conducted in Part II is based in project MANTA, it is not strictly limited to it, it is recommended to make up for this lack of external validation. It is suggested to do so in two stages, focusing on the model first, before moving on to using the tool. The first stage might involve questions that help to determine whether the model is applicable to the group, for example by investigating whether participants recognise the problem the model was designed



(a) Full y-domain



(b) Limited y-domain

Figure 16.1: Difference between compressible (XFOIL-U) and compressible (VGK) lift coefficient for various geometries, Mach numbers and angles of attack, normalised to incompressible result (solid line) and fitted with a 2nd order polynomial (dashed line)

to solve, whether their group fits the underlying theory and whether they understand the interplay of various factors. A second stage could take the form of a test, possibly for a longer period of time. This stage could show whether the model actually helps to solve the problem and/or what practical aspects can be changed to improve user friendliness. Depending on the expected cost associated to developing a prototype or functioning tool (as described in the previous paragraph), the first validation phase could be completed first in order to form initial impressions before committing additional resources. Such efforts should start with projects similar to project MANTA, but can afterwards be extended to projects meeting the criteria listed at the end of Section 9.5.

On a more theoretical level, it would be interesting to continue the reflection process that culminated in the theoretical framework presented in Chapter 10. In Section 10.2 particularly, some critical remarks were raised with regard to effective intercultural workgroup communication theory. Further research will

have to determine whether these critiques hold and justify reconsidering some of the adjustments made in the transition from *effective decision-making theory* to *effective intercultural workgroup communication theory*. Correspondingly, it might be worthwhile to explore if the remarks put forward in this report might add to the theory, furthering understanding of group decision making.

Integrated perspective

A number of other opportunities stem from the path outlined in Part III. First of all, it seems interesting to explore whether single words can be found that accurately convey the meaning of the 'blue' and 'orange' categories presented in Table 14.1. This can greatly enhance communication about these two categories and their roles in decision making. Furthermore, it would be fascinating to explore the extent to which groups that focus on (blue) task-related outcomes undervalue the (orange) socio-psychological influences of decision quality and vice versa.

Moreover, it is felt that gaining further insights as to *why* people struggle to fully appreciate the integrated perspective should be a research priority high up on our list. Closely related to filling this knowledge gap is the recommendation to design an intervention, product or mental cue to help people combine their notions of the technical and socio-psychological perspectives – the projections shown in the figures in Chapter 14 – in order to get a clearer image of the three-dimensional object casting those projections. Given the complexity of this problem, solutions are likely to lie outside the proverbial box. Analogies, works of art or powerful narratives should not be disregarded should be embraced in that endeavour.

16.4.2. In practice

Looking beyond theoretical considerations, the results presented in this report have practical implications, or provide opportunities in that direction.

First of all, the conclusion reached in Part III has reinforced the opinion that engineers should be made more aware of the importance of making good decisions and allow themselves to spend time on that, even if the results of agreeing on who should lead a group might not yield as tangible results as another set of simulations. As the outcomes of this research project clearly show, there is a point where the next elaborate formula does not make a difference anymore. In anticipation of further understanding of why we find it difficult to appreciate the interrelation of the two perspectives – and the way they influence our decisions – simply raising awareness might be a first step towards changing current practise. This might for example be achieved through (professional) engineering education.

With respect to the outcomes of Part II, an obvious recommendation is to further develop the TARE-model into a tool which can be used in the way as proposed in Chapter 12. It is argued that an online implementation will be most suitable, as that provides a user-friendly way of interacting with the model. Also, a database powering such a web application can efficiently collect and aggregate the data. Data can be fed to the tool using a simple questionnaire, which users can each complete online. After all responses have been received, the visualisations can be generated and subsequently discussed in the group. Being able to go back in time and compare the current status with an earlier situation is likely to enhance the usefulness of the model.

In the (applied) research and innovation management domain, it is felt that funding agencies – such as the European Commission / Clean Sky Joint Undertaking in case of project MANTA – would be wise to set more clearly defined goals, or ask consortia to do so themselves. Regardless of which entity sets these objectives (or constraints that they should meet), project tasks should not commence before the desired outcome is clear. If there are multiple goals, they should be ranked and prioritised, or there should be a metric indicating the balance between goals of types of goals – such as the model developed as part of this research project. If consortia set goals themselves – because they are thought to be able to specify more relevant goals, as they have better knowledge of current research efforts and industry challenges – funding agencies should set some ground rules to at least make sure their funds are effectively spent in pursuit of *their* (holistic) goals (such as promoting research, or open innovation or collaboration), rather than those of participating organisations. These measures can contribute to reducing losses and improve

the effectiveness or research and innovation processes. (A more personal and subjective reflection on research funding, especially in the form of public-private partnerships, is part of Chapter 17, to which the interested reader is gladly referred.)

17

Reflection

With this thesis report now coming to an end, the time has come to reflect on product and process. Chapter 16 placed the results that were obtained in a wider context and discussed implications, limitations and opportunities for the future. The current chapter is a much more personal and subjective reflection. It aims to document professionals lessons learnt, contrast former opinions to current ones and show new perspectives gained over the course of working on this project.

Because no day-to-day diary was kept, this chapter cannot present all of the above. Rather, it focuses on the most interesting aspects. Section 17.1 reflects on the project and the lessons learnt as a researcher. Section 17.2, then, continues the discussion started in Section 16.4.2 on public funding of research and development projects, sprouting a further deliberation on professional scientific integrity and societal trust thereof. Section 17.3, lastly, reflects on the added value of multi- or interdisciplinary education and research.

As this reflection is personal and highly opinionated, it is argued that use of the first person perspective is warranted. Put differently: it is 'I' from this point forward.

17.1. On this project

Interrupted by an internship, literature study report and some holidays, I have spent roughly two years researching decision making under uncertainty in aircraft conceptual design. The process was rewarding and I would certainly do it all over again. However, having learnt the lessons I have, there are some things I would do differently the next time. Please consider these reflections as a sign of personal and professional growth as well as a helpful guide to future graduate students working on either the same – or a different – combination of topics.

Just as expected by my supervisors, I presume, I have to conclude that I have been too reserved in scoping my research early on. As deliberations in Section 16.3 show, I feel I could have benefited from a clearer and more bounded definition of my research at the start of the project. From a purely practical point of view, it would have been wise to have conducted my interviews and observations much earlier on. That would have guided me to the specific problem sooner, as it is now defined only in Chapter 9. In turn, that would have allowed me to focus my academic reading on group and team alignment, goal setting, the challenges of collaborating with multiple stakeholders with different agendas and complexity theory. I am sure that would have resulted in a more grounded report than the current one. Writing this, however, I notice contrary thoughts surfacing. Yes, the process just described would have been more efficient. On the other hand, it would probably not have lead to the results documented in this report. For example, it would not have uncovered the existence of both technical and socio-psychological influences of decision quality – which formed the basis for the integrated perspective sketched in Part III.

Despite those upsides, this emergent process also has its drawbacks, notably in structuring the report. Even though it was clear from the start of this project that integrated had to play a role in one of the (research) questions, the current arrangement with an overall question and three main research questions, took a while to set up. Spotting the similarities in research approach between Parts I and II, as discussed in Section 1.4, yielded a major breakthrough and inspired me to set up research questions I and II in a similar manner.

With respect to structure, I have pushed back on suggestions to more clearly split the report into separate parts that stand alone, including a separate introduction, conclusion and discussion sections. Fuelled by the belief that taken together, the two perspectives treated in this report add up to more than the sum of their parts, I decided early on to combine introductory as well as concluding chapters and only split the core of the text. At that point unaware of the final form of Part III, I held on to this approach. Nevertheless, it might in hindsight have been better to follow earlier advice. That would have cleared up the preceding chapter, as opportunities could be located in the parts they applicable to, and might have made this report more accessible to those readers interested in only one aspect.

17.2. On public funding of research and development

Having looked back on this project in terms of process and choices made along the way, this section reflects on project MANTA – and public funding of research and development in a broader sense. I well remember browsing the first set of project documents my research supervisor gave to me, truly astounded by the fact that the commercial interests of major European aerospace companies are included in a research proposal. With topic leaders influencing major decisions and – in my initial impressions – steering away from research and development attempts aiming to realise fuel burn reduction and thereby contributing to cutting back the harmful effects of aviation on the environment, I have openly wondered how project MANTA (and by extension, the entire Clean Sky programme) could not be classified as state aid to a for-profit industry. Over the course of this project and by reading more documents, talking and listening to people involved and observing professionals at work, I have changed my perspective. Yes, commercial organisations might use the contributions from research projects to fund their R&D-work. But also: if a research institute pursues an innovation that the industry cannot sell, it will never reach beyond the walls of academia and make a true contribution. That might well be sub-optimal from an applied research point of view, but until the time we change our profit-driven society, I have grown more convinced it is the best we can do.

That does, however, require utmost vigilance, transparency and integrity from all parties involved in (partially) publicly funded research: both those who receive funds as well as those who reward them. As admitted at the end of Chapter 9, I do not think I should be the one to set those norms, but am sure it should be possible to set norms. Based on what I have observed over the course of this research project, I feel that can be improved. This report provides some specific suggestions for project MANTA, but there are grander challenges. The most notable thereof is setting a balance between task and relationship goals. As long as funding agencies (or: politics or society at large) do not explicate how much stronger connections, more frequent exchanges of ideas and closer integration between academia and industry are actually worth to society (for example, in terms of reduced innovation progress), it is impossible to implement effective audits or enforce change. In my personal opinion, checks like that, or analyses to determine whether a consortium is balanced in terms of power and aligned in terms of agendas, are much more relevant than setting up presumably objective trade-off tables to support a decision that (due to associated levels of uncertainty and complexity) can only be properly made by the explicit judgement of professionals.

Especially when opening them up to a larger political or societal debate, those are difficult questions at a time where they are not easily answered. Science is continuously attacked, especially by populist politicians. I get that. The truths that scientists present to the world are far from comfortable: battling global warming or adapting to it will require massive investments, (again) moving money away from the people who have not seen a raise in years. Complexity and nuance is removed from our debate, which more and more often is limited to an exchange of 140- or 280-character Tweets and five-second

soundbites – if there is a proper exchange at all. I get that, too. People struggling to pay their rent, tuition or medical bills and juggling three jobs to make it to the end of the month will not have the time to spend days reading background articles and op-eds. I also realise that raising in public the questions I have raised here will inspire bad actors to point out the imperfections of science, to support plans to cut further funding until "those researchers figure it out" and to push their own gut-feeling-based agenda. I am convinced that is a worthy price to pay as I deeply feel the fundamental scientific process and the narrative about research and innovation will stand that test in the long run.

However, only few will probably agree. As such, we might be able to start with smaller things that improve the system from within. I think educating junior researchers into the politics of academia and science funding would be a good place to start. People with a more open mind might be able to ask the questions that senior researchers have stopped asking. Another step would be to indeed explicate the importance of task versus relationship outcomes and appoint an independent, external observer to judge whether that balance is met in practice. In order to make time for such an inquiry, we might reduce our effort to rationalise every decision we make. Would it not be refreshing to allow professionals to do what they are convinced is the right thing and periodically question and challenge those decisions, rather than having them game trade-off matrices? The epilogue that follows this chapter tells the story of what such a future might look like.

17.3. On multi- or interdisciplinary (design-based) research and engineering

Before closing this reflection chapter, it is interesting to reflect on the value of multi- or interdisciplinary research and engineering, especially in a design-based context. I would like to do so by sharing the story of going from the initial idea of (the socio-psychological part of) this research project to what it has ultimately become.

When starting this project and finding a way to integrate the technical and the social perspectives from Aerospace Engineering and Science Communication, I knew I wanted to do a project involving decision making and uncertainty – an interest that was sparked by dr. ir. Kwakkel, giving a course in the *Airport of the Future* minor-programme on *Policy Analysis, Uncertainty Management and Model Based Decision Support for Airport Strategic Planning*. It opened my eyes to the difference between *complicated* and *complex*, to bias, to framing effects and human irrationality. Consecutively, that resulted in some initial research ideas and questions. If we present a group of decision makers with a number of concepts, each involving some (quantified) degree of uncertainty, do their decisions change if they are presented with the most uncertain project first, rather than last?[1] What happens if we present decision makers with an indication of the uncertainty of particular values first, before showing those values?[2] Is it possible to make an analysis system, such as the Aircraft Design Initiator, that also controls the process of making decisions based on its output?[3]

Looking back, I still feel these are interesting questions. Nevertheless, they are questions fitting in a scientific paradigm that I feel is becoming more and more dated. They are mono-disciplinary, mostly rooted in psychology and behavioural economics[4]. Also, they provide answers that might explain situations and help us to better understand the world around us, but do not immediately solve any concrete problems we face.

[1] Scientific basis for this question is in the anchoring bias. This bias is at the basis of the Dutch saying "de eerste klap is een daalder waard" and states that whoever is first to set an asking or offering price in a negotiation process will dictate what order of magnitude is reasonable – and thereby steer the outcome much more than the counter-bids or offers that follow. Would that same effect influence people's perception of uncertainty?

[2] This might lead decision makers to take more time to establish what bounds of (un)certainty are reasonable and acceptable for the decision they are about to make.

[3] Would people be more willing to accept process-steering by a tool of which they trust the output of its computational work, compared to the situation where an external process manager steers that process?

[4] Behavioural economics might combine multiple backgrounds – most notably psychology and economics – but has, I think, evolved to a new – single – field of research since.

Combining such a study with the research presented in Part I would have yielded a mostly multidisciplinary project. Coincidentally conducted by the same person, but equally well divisible in two parts. In terms of the three-dimensional graphic shown at the end of the Synthesis-chapter (Chapter 14), it would have resulted in a blue square and an orange circle.

By diving in at the deep end, reading literature, embracing complexity and – a bit more every day – understanding project MANTA, I have substantially deviated from the questions raised before. I have much more profoundly integrated my two backgrounds, rather than simply attaching a social perspective to a technical problem. I could not have anticipated the outcomes of this project all those months back, but feel it is much more relevant than answers to any of the questions raised before. It puts forward a possible solution to a very specific problem of a very specific group in a very specific context, but at the same time raises a wealth of questions, ideas and inspiration – much more than a follow-up *how does X influence Y in context Z*, however relevant these questions sometimes are. I feel that this better than anything demonstrates the true added value of design-based research integrating various disciplines and hope it inspires future scholars to take a similar approach.

Sure, the narrative about T-shaped professionals – one of my earliest memories of Delft University of Technology – changing the world is a nice one. In that model, people have a broad basis of general knowledge that is complemented by detailed insight in one particular field of expertise. Besides the fact that I think it is up for debate whether engineering education provides a basis that is broad enough, the comparison does not tell how lonely it can be on the island at the end of the T. How little you can see of the continent, when you are far out at sea. And (not unlike the current political chaos in the United Kingdom) how easy it is to forget about the beauty of all else that is out there. Business and industry are slowly starting to see the flaw in their earlier reasoning and struggle with breaking free from the silos they have confined themselves to, relentlessly trying to create a more networked community. Academia and society at large, however, do not seem to have caught on.

Fitting with the societal, political and somewhat philosophical reflexions of this past section, allow me to end on a high note. A few years ago, the Washington Post adopted the slogan *democracy dies in darkness* as a testament to the “the dangers of secrecy in government” (Farhi, 2017, citing Bob Woodward). Let me propose another one: *innovation dies in isolation*. And let us remember that collaboration, breaking down boundaries and keeping an open mind are key in tackling the challenges that our world is facing today.

Epilogue

It's the year 2030. The crashes of two Boeing 737 MAX aircraft in 2018 and 2019, taking the lives of many hundreds of people, have left their mark on the aerospace industry. As problems with the jet kept being raised and public trust diminished, the American company decided to kill the program. A tremendously difficult decision for sure, but it also presented the manufacturer with a unique opportunity: starting with a clean slate. Boeing had been improving their 1960s design for almost fifty years and whereas that kept cost down, it also meant dealing with substantial historical debt. A fresh start allowed engineers to do away with all that and make a significant leap into the future. Emission taxes were in place all around the world and customers judged brands – including airlines – much more harshly for their societal and environmental impact.

It made sustainability a top priority. The first thing they changed was the height of the landing gear. When the 737 was first developed, nobody had foreseen the ever-increasing size of new turbofan engines, improving fuel efficiency with each inch of fan diameter. Exactly that design choice proved fatal in the end. They furthermore made a wider and flatter fuselage, allowing to transport more people in one go, while at the same time generating part of the lift to keep the plane in the air. Moreover, they readied it for a next generation of propulsion systems by building a more modular wing and strengthening the fuselage a little extra. They wanted to make sure the structure could support the heavier battery packs. If energy density further improved, a new generation of 909's – as they named the aircraft – might become partial hybrids.

These too were difficult decisions, as not one bit of flexibility came for free. Strengthening the wing-fuselage joint to allow longer future versions increased weight. Designing systems such that they would work when driven by gas generators as well as electric motors increased complexity. And both had an effect on cost. Nevertheless, given the information available at that time and a clearly defined goal which was shared by all, they were good decisions. Even though none of the managers or engineers was sure how the future would unravel exactly, the way they made the decision – open, vigilant, taking into account the ideas of various specialists – instilled trust. Indeed, the future was looking up. Although the first flight has yet to be made, initially hesitant market response turned around after KLM – the company that advocated "responsible flying" back in 2019 in a global PR-campaign marking their 100th anniversary – placed the first fifty orders and put its money where its mouth was.

At the other side of the pond, meanwhile, Airbus realised they had to do something as well. Although their 737-competitor was stemming 'only' from the 1990s, the Europeans knew another incremental improvement would be no match for Boeings new model. Moreover, Airbus also began to feel the additional pressure bearing down on the aviation sector. While fuel consumption was mostly an issue of operating cost twenty years ago, it was no longer possible to avoid fundamental choices: are we going to focus on reducing aviation impact on the environment, or do we stick with the industry's traditional profit-driven business model?

They chose the former, following the European Union's ever-increasing focus on working towards sustainable air travel. Even though earlier Clean Sky programmes were by no means cheap, the massive 15 billion reserved for the fourth and current iteration of the program was – and still is – record-breaking. The fact that emission taxes became common in the early 2020s and that substantial portions of the income generated that way were used to fund research and development work enabled these budgets. Besides increases in budget, the Clean Sky management had implemented some changes in the way it defined goals and monitored progress. 80% of the effort and resources spent was to be directed at reaching the project goal: making aviation sustainable. This increased emphasis on the public outcomes of projects followed the increased public funding through taxation revenues. Nevertheless, Europe realised that participating organisations were investing time and effort as well, and allowing the different

stakeholders involved to explore some of their own interests helped in keeping project groups together. As such, a maximum of 20% could be spend on pursuing goals slightly different from the project goal – as long as the entire consortium agreed.

This was the context Bob was working in. By now, he was a senior project manager at one of Europe's aerospace research institutes. Together with two industrial partners, another research institute and two universities, the organisation he worked for was part of a research consortium investigating ways to improve wing performance for regional aircraft using distributed propulsion. From an enormous list of ideas, his group was to select, build and test the three best concepts. What those would be, Bob did not yet know. The line-up of early ideas included all kinds of concepts, ranging from using highly integrated multi-functional movables to using no movables at all, instead controlling the aircraft using thrust vectoring and increasing lift for take-off and landing by rotating electrically driven fans.

Although it had taken the group – or team, as Bob liked to see the consortium – some effort to come to terms with the levels of uncertainty and complexity of the project, they were well underway. In a first screening, they had gotten rid of some two-thirds of the initial solution ideas. Even though some were truly revolutionary and might have yielded fantastic benefits, no expert in the field realistically expected them to be developed to a high enough technology readiness level in the next decade. Naturally, choosing to not pursue so many ideas was difficult. A number of graduate students doing their thesis work at the participating universities, for example, had hoped to contribute to the further development of the concepts they had been investigating – but which were now cancelled. Similarly, one of the industrial partners had identified a business opportunity in the commercialisation of an idea that did not make the cut. In the end, though, everybody was happy with the selection as they had made it. Bob was glad he took some extra time for that discussion, so all parties could share their concerns and opinions, contributing to an open dialogue. The 80/20-guideline set by the EU also proved useful: being able to blame an external party for getting in the way of individual endeavours prevented possible conflict within the group, negatively impacting the relationship the consortium partners were trying to build. Funding agencies were somewhat reluctant to acknowledge it, but Bob was well aware that forging bonds between industry and academia to further knowledge sharing and innovation was a major secondary objective of the Clean Sky programme.

The way decisions were made was a little different compared to the first project he was involved in, quite some years back. That revolved around scoring tables and trade-off sheets. It even happened that in case the consortium did not like the outcome, weight factors were adjusted a little and some scores were changed from "substantial improvement" to "moderate improvement" in order to make sure the sheets showed the outcome desired by the group. As he was only a junior back then, Bob didn't feel it was his place to speak up. "Apparently, this is how it goes around here", he thought. That was all in the past, though. Rather, when major decisions came along, the consortium split up into two teams: one yellow, one purple. Each team involved representatives of all organisations involved in the project, just as it included subject matter experts from all relevant disciplines. The mornings of such decision days were spent in the separate teams. Based on available information, each would make their own decisions and prepare supporting arguments. After lunch, the teams joined back together to present the decision they had reached. Subsequently, the other team would challenge the result.

Especially when collaborations involved people from different cultural backgrounds, it sometimes took a while before everybody got used to this way of working. It was not only country-related, though: Bob had observed the same initial uneasiness in groups that varied substantially in terms of gender or seniority. This is why a training session was held during one of the introductory meetings. It proved effective in ironing out any differences between group participants, just as the early discussions used to share all participants' background, expertise and – especially – interests did. Hearing why organisations or individuals joined the project provided the entire team with useful information about 'break points'. Striving for open collaboration and innovation, Bob found it important to keep the team together. Not at *all* cost, but it certainly was worth something. It had actually happened during an earlier selection round. The two teams were split on two concepts and – although it was productive – the group discussion that followed didn't manage to resolve the disagreement. Until Rachel, one of the participants, spoke up. "As I've told you before, we are trying to expand our knowledge on using propulsion system components as load carrying elements. Although I think we made a good decision when we binned a few of the earlier and more extreme concepts, we were very much hoping to at least further develop one of them. Actually,

that's mostly why we decided to join. If we can't decide between this inner wing section and that winglet based on technical merits, it would mean a great deal to us to have the inner wing section move on to the next stage." She told she was a bit hesitant to bring it up, but the others welcomed the openness. It was good to have it out there – as most of the team had a hunch something was going on, but didn't feel comfortable directly asking what it was. As she, as well as her direct colleagues, had made valuable contributions to other parts of the project, the group agreed instantly that it would be a pity to have her institute drop out. And so the matter was resolved.

The decision for which the yellow and purple teams parted ways this time, however, was resolved based on technical factors. Within five minutes after returning from their separate offices, both sub-groups indicated the longer flap had more potential for reducing fuel consumption than the shorter flap. Reaching consensus so quickly didn't mean everybody got to go home early, however. Rather, the team joined in a collective effort to think about arguments why they would *not* choose the longer flap. This helped to critically review their decision, uncovering possible weak spots in their reasoning or reveal potential risks they were not aware of yet. If this highlighted major issues, the decision was reconsidered. That too, however, was not necessary this time. The close examination had raised some new points of attention, but nothing caused them to have second thoughts.

When Bob came home to Amy and told her about such screening decisions, she sometimes asked whether this way of working wasn't tremendously error-prone. As she put it, "it's just a bunch of nerds following their gut, making choices that determine on what kind of plane we go on holiday in twenty years". Bob saw it differently, though. Given the fact that the concepts they were evaluating were so new, there were hardly any analysis tools available that managed to accurately model the innovations under consideration, let alone do so in a speedy and cost-effective manner. Trying to analyse and quantify everything is what resulted in the spreadsheet-confusion he remembered from earlier days. It sure seemed more rational, but often just provided a false sense of security. As such, all teams funded by Clean Sky – as did Bob's – made sure to have specialists on board that were knowledgeable in the relevant areas, or ask external parties to advise the project group. Still, Bob couldn't do anything but agree with Amy that their procedures might yield a different outcome different from the one intended. He'd come to terms with that uncertain reality, though. Lacking crystal balls or an in-house fortune teller, there was no way to definitively prevent undesired outcomes. Although it was a long time ago, he was suddenly reminded of the time he took some additional project management courses in university. It was a lot of open doors, he recalled, but one remark his professor kept stressing had stayed with him: not to confuse decision and outcome.

A date in his calendar, a few weeks from now, was marked FINAL SELECTION. That day, they would choose the three concepts for which they would build and test a prototype. Just last week, he received the first aircraft-level performance estimates. The numbers confirmed what his engineering judgement had told him in the first place. "Matthew is not going to like these results", Bob said to himself. The concepts his company was most interested in scored lowest in fuel burn reduction. "Might be best to sit down individually with them, to see whether they can shift their focus to working on one of the other concepts." As they had gotten to know each other pretty well, Bob expected Matthew could be kept on board.

Aside from that difficulty, the performance assessments indicated reductions in fuel consumption ranging from 4% to 7% – more than the consortium had initially strived for. After shortly wondering whether they could have made any decisions differently that might have increased these numbers to 5% and 8%, he stopped his daydream. The project was on its way to meet the stated technical objectives, held the promise to develop technologies enabling a substantial step towards further sustainable flight and forged fruitful relationships between the partners involved.

Exactly as they had all worked towards.

Bibliography

Abbott, I. H. and von Doenhoff, A. E. (1959). *Theory of Wing Sections*. Dover Publications, Inc., New York, United States of America.

ACARE (2002). Strategic research agenda - volume 1. http://www.acare4europe.org/sites/acare4europe.org/files/document/volume1.pdf. Downloaded May 14th, 2018.

Accreditation Board of Engineering and Technology (2012). Abet constitution. https://www.abet.org/.

Açıkgöz, A. and Günsel, A. (2016). Individual Creativity and Team Climate in Software Development Projects: The Mediating Role of Team Decision Processes. *Creativity and Innovation Management*, 25(4):445–463.

Aerospace Technology. Boeing 787 dreamliner long-range, mid-size airliner. https://www.aerospace-technology.com/projects/dreamliner/. Accessed May 21st, 2018.

Ahn, J. and Lee, D. (2012). Airfoil Designs and Free-Flight Tests of a Fixed Wing MAV Design. In *30th AIAA Applied Aerodynamics Conference*, pages 1–8, New Orleans, United States of America. American Institute of Aeronautics and Astronautics.

Air Transport Action Group. Aviation and the paris agreement. https://aviationbenefits.org/environmental-efficiency/our-climate-plan/aviation-and-climate-change/paris-agreement/. Accessed May 15th, 2018.

Air Transport Action Group (2015). Aviation climate solutions. https://aviationbenefits.org/media/125796/Aviation-Climate-Solutions_WEB.pdf. Downloaded May 15th, 2018.

Airbus (2017). From bleriot to e-fan. https://company.airbus.com/company/heritage/now-and-then/Crossing-the-Channel.html. Accessed May 21st, 2018.

Airbus S.A.S. (1985). A320 aircraft characteristics - airport and maintenance planning. Technical report, Blagnac Cedex, France. Revision Jun 01/12.

Airbus S.A.S. (2017). Global market forecast 2017 / 2036 – growing horizons. http://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Airbus_Global_-Market_Forecast_2017-2036_Growing_Horizons_full_book.pdf. Downloaded May 14th, 2018.

Albar, F. M. and Jetter, A. J. (2013). Fast and frugal heuristics for new product screening – is managerial judgment 'good enough?'. *International Journal of Management and Decision Making*, 12(2):165–189.

Amason, A. C. (1996). Distinguishing the Effects of Functional and Dysfunctional Conflict on Strategic Decision Making: Resolving a Paradox for Top Management Teams. *The Academy of Management Journal*, 39(1):123–148.

Analytical Methods (2018). MSES/MISES. https://www.ami.aero/software-computing/amis-computational-fluid-dynamics-tools/msesmises/. Accessed June 29th, 2018.

Andersen, J. A. (2000). Intuition in managers: Are intuitive managers more effective? *Journal of Managerial Psychology*, 15(1):46–63.

Anderson, J. D. (2001). *Fundamentals of Aerodynamics*. McGraw-Hill, New York, United States of America, 3rd edition.

Anderson, J. D. (2002). *Modern Compressible Flow*. McGraw-Hill, New York, United States of America, 3rd edition.

Anderson, J. D. (2005). *Introduction to Flight*. McGraw-Hill, New York, United States of America, 7th edition.

Anderson, J. D., Degroote, J., Degrez, G., Dick, E., Grundmann, R., and Vierendeels, J. (2009). *Computational Fluid Dynamics: An Introduction*. Springer-Verlag Berlin Heidelberg, 3rd edition.

Argyropoulos, C. D. and Markatos, N. C. (2015). Recent advances on the numerical modelling of turbulent flows. *Applied Mathematical Modelling*, 39(2):693–732.

Ariely, D. (2008). *Preditably Irrational*. HarperCollins Publishers, New York, United States of America.

Aronson, E. (1969). The theory of cognitive dissonance: A current perspective. In *Advances in Experimental Social Psychology*, volume 4, pages 1–34. Elsevier.

Atas, M., Felfernig, A., Stettinger, M., and Tran, T. N. T. (2017). Beyond Item Recommendation: Using Recommendations to Stimulate Knowledge Sharing in Group Decisions. In Kling, R. and Penniman, W. D., editors, *Social informatics*, pages 368–377.

Atkin, C. J. and Gowree, E. R. (2012). Recent Developments to the viscous Garabedian and Korn method. In *28th International Congress of the Aeronautical Sciences*, pages 1–9, Brisbane, Australia.

AVL LIST GmbH (2018). AVL - Development, testing & simulation of powertrain systems. https://www.avl.com/. Accessed August 17th, 2018.

Baartmans, T. and Kosolosky, L. (2015). Groepsbeslissingen: kwaliteit, autoriteit en vertrouwen. *Tijdschrift voor Filosofie*, 77(2):335–371.

Bakay, A., Huang, J., and Huang, Y. (2014). Group decision-making processes and group decision quality: moderation of mutual interest. *International Journal of Management and Decision Making*, 13(4):335–355.

Baker, K. G. and Albaum, G. S. (1986). Modeling New Product Screening Decisions. *Journal of Product Innovation Management*, 3(1):32–39.

Bakker, A. (2006). Applied computational fluid dynamics (lecture 5 - solution methods). http://www.bakker.org/dartmouth06/engs150/05-solv.pdf. Downloaded June 5th, 2018.

Baldwin, B. S. and Lomax, H. (1978). Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows. In *AIAA 16th Aerospace Sciences Meeting*, pages 1–8, Huntsville, United States of America. American Institute of Aeronautics and Astronautics.

Bales, R. F. (1950). *Interaction Process Analysis: A Method for the Study of Small Groups*. Addison-Wesley Press, Inc., Cambridge, United States of America.

Banathy, B. H. (2013). What Is Design? Why Do We Need It? In *Designing Social Systems in a Changing World*, chapter 2, pages 11–47. Springer Science & Business Media, New York.

Baron, J. and Hershey, J. C. (1988). Outcome Bias in Decision Evaluation. *Journal of Persona*, 54(4):569–579.

Bauer, F., Garabedian, P., Korn, D., and Jameson, A. (1975). *Supercritical Wing Sections II*, volume 108 of *Lecture Notes in Economics and Mathematical Systems*. Springer-Verlag, Berlin, Germany.

Baumeister, R. F. (1998). The self. In *Handbook of Social Psychology*, pages 680–740. McGraw-Hill.

Beach, L. R., editor (1998). *Image Theory: Theoretical and Empirical Foundations*. LEA'S Organization

and Management Series. Lawrense Erlbaum Associates, Mahwah, United States of America.

Beatty, J. and Moore, A. (2010). Should we aim for consensus? *Episteme*, 7(3):198–214.

Bem, D. J. (1972). Self-perception theory. In *Advances in Experimental Social Psychology*, volume 6, pages 1–62. Elsevier.

Ben Mosbah, A., Botez, R. M., and Dao, T.-M. (2016). New methodology combining neural network and extended great deluge algorithms for the ATR-42 wing aerodynamics analysis. *Aeronautical Journal*, 120(1229):1049–1080.

Bertels, F. G. A., van Dijk, R., Elmendorp, R., and Vos, R. (2016). Impact of pulsed jet actuators on aircraft mass and fuel consumption. *CEAS Aeronautical Journal*, 7(4):535–549.

Bertin, J. J. and Cummings, R. M. (2009). *Aerodynamics for Engineers*. Pearson Prentice-Hall, New Jersey, United States of America, 5th edition.

Bhugra, D., Easter, A., Mallaris, Y., and Gupta, S. (2011). Clinical decision making in psychiatry by psychiatrists. *Acta Psychiatrica Scandinavica*, 124(5):403–411.

Blazeby, J. M., Wilson, L., Metcalfe, C., Nicklin, J., English, R., and Donovan, J. L. (2006). Analysis of clinical decision-making in multi-disciplinary cancer teams. *Annals of Oncology*, 17(3):457–460.

Blazek, J. (2007). *Computational Fluid Dynamics - Principles and Applications*. Butterworth-Heinemann / Elsevier, Oxford, United Kingdom, 3rd edition.

Blockley, R. H. and Hodges, M. D. (1973). Second-Order Method for Estimating the Subcritical Pressure Distribution on a Two-Dimensional Aerofoilin Compressible Inviscid Flow. Technical Report ESDU 72025, United Kingdom.

Blockley, R. H. and Hodges, M. D. (1982). Methods for Estimating the Pressure Distribution on a Two-Dimensional Aerofoil in Viscous Transonic Flow. Technical Report ESDU 81019, Royal Aeronautical Society, United Kingdom.

Blum, S. (2016). How boeing wrung loads of dead weight out of its newest 777 design. https://www.inverse.com/article/10241-how-boeing-wrung-loads-of-dead-weight-out-of-its-newest-777-design. Accessed May 21st, 2018.

Boeing. Boeing launches 787 dreamliner. http://boeing.mediaroom.com/image-gallery?cat=27. Accessed May 21st, 2018.

Boeing (2001). Sonic cruiser in flight. https://www.avgeekery.com/urban-legend-boeings-sonic-cruiser-just-distraction-787-program/. Accessed May 21st, 2018.

Boeing Commercial Airplanes (2017). Current market outlook – 2017-2036. http://www.boeing.com/resources/boeingdotcom/commercial/market/current-market-outlook-2017/assets/downloads/cmo-2018-3-20.pdf. Downloaded May 14th, 2018.

Bonito, J. A. (2009). Interaction Process Analysis. In Littlejohn, S. W. and Foss, K. A., editors, *Encyclopedia of Communication Theory*, pages 528–529. SAGE Publications, Inc., Thousand Oaks, United States of America.

Borches, P. D. (2011). Harvesting Architectural Knowledge to Enhance Evolvability of Embedded Systems. In van de Laar, P. and Punter, T., editors, *Views on Evolvability of Embedded Systems*, chapter 8, pages 121–136. Springer Science+Business Media B.V.

Boschetti, P. J., Cárdenas, E. M., Amerio, A., and Arévalo, Á. (2010). Stability and Performance of a Light Unmanned Airplane in Ground Effect. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, pages 1–17, Orlando, United States of America.

American Institute of Aeronautics and Astronautics.

Bottomley, P. A. and Doyle, J. R. (2006). The interactive effects of colors and products on perceptions of brand logo appropriateness. *Marketing Theory*, 6(1):63–83.

Boyatzis, R. E. (1998). *Transforming qualitative information: Thematic analysis and code development*. SAGE Publications Inc., Thousand Oaks, United States of America.

Bradshaw, P. and Ferriss, D. H. (1971). Calculation of boundary-layer development using the turbulent energy equation: compressible flow on adiabatic walls. *Journal of Fluid Mechanics*, 46(1):83–110.

Brereton, M. and McGarry, B. (2000). An Observational Study of How Objects Support Engineering Design Thinking and Communication: Implications for the design of tangible media. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 217–224. ACM.

Brodbeck, F. C., Kerschreiter, R., Mojzisch, A., Frey, D., and Schulz-Hardt, S. (2002). The dissemination of critical, unshared information in decision-making groups: the effects of pre-discussion dissent. *European Journal of Social Psychology*, 32(1):35–56.

Brown, M. and Vos, R. (2018). Conceptual Design and Evaluation of Blended-Wing Body Aircraft. *2018 AIAA Aerospace Sciences Meeting*, (January).

Bryman, A. (2012). *Social research methods*. Oxford University Press, New York, United States of America, 4th edition.

Bundzel, M., Lacko, J., Zolotová, I., Kasanickỳ, T., and Zelenka, J. (2017). Artificial intelligence aggregating opinions of a group of people. *Computing and Informatics*, 35(6):1491–1514.

Burleson, B. R., Levine, B. J., and Samter, W. (1984). Decision□Making Procedure and Decision Quality. *Human Communication Research*, 10(4):557–574.

Burris, E. R., Rodgers, M. S., Mannix, E. A., Hendron, M. G., and Oldroyd, J. B. (2009). Playing Favorites: The Influence of Leaders' Inner Circle on Group Processes and Performance. *Personality and Social Psychology Bulletin*, 35(9):1244–1257.

Burtscher, M. J. and Meyer, B. (2014). Promoting good decisions: How regulatory focus affects group information processing and decision-making. *Group Processes & Intergroup Relations*, 17(5):663–681.

Buxton, D., Farr, R., and Maccarthy, B. (2006). The Aero-Engine Value Chain Under Future Business Environments : Using Agent-Based Simulation To Understand Dynamic Behaviour. *The Modern Information Technology in the Innovation Processes of the Industrial Enterprises*, pages 11–12.

Campbell, E. Q. (1964). The Internalization of Moral Norms. *Sociometry*, 27(4):391–412.

Carmeli, A. and Schaubroeck, J. (2006). Top management team behavioral integration, decision quality, and organizational decline. *The Leadership Quarterly*, 17(5):441–453.

Carson, S. J., Madhok, A., and Wu, T. (2006). Uncertainty, Opportunism, and Governance: The Effects of Volatility and Ambiguity on Formal and Relational Contracting. *Academy of Management Journal*, 49(5):1058–1077.

Cartwright, T. J. (1973). Problems, Solutions and Strategies: A Contribution to the Theory and Practice of Planning. *Journal of the American Institute of Planners*, 39(3):179–187.

Carty, A. (2002). An Approach to Multidisciplinary Design, Analysis & Optimization For Rapid Conceptual Design. In *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimizaion*, Atlanta, United States of America. American Institute of Aeronautics and Astronautics.

Catherall, D., Foster, D. N., and Sells, C. C. L. (1969). Two-dimensional incompressible flow past a lifting aerofoil. Technical Report 69118, Royal Aircraft Establishment, United Kingdom.

Ceschi, A., Dorofeeva, K., and Sartori, R. (2014). Studying teamwork and team climate by using a business simulation. *European Journal of Training and Development*, 38(3):211–230.

Chan, S. L. and Ip, W. H. (2010). A Scorecard-Markov model for new product screening decisions. *Industrial Management & Data Systems*, 110(7):971–992.

Chang, T.-J. and Yeh, S.-P. (2014). Intra Project Team Disagreement, Conflict Communicatinos, and Team Performance in Cross-Functional New Product Project Teams: A Decision-making Quality Perspective. *South African Journal of Economic and Management Sciences*, 17(1):91–104.

Chang, W.-l. (2011). A Social Network Based CBR System for Quality Group Decisions. In *International Conference on Information and Com Orlando, FL, USA, November 29th to December 2nd*, pages 1–6.

Chaparro, D., Fujiwara, G. E. C., Ting, E., and Nguyen, N. (2017). Transonic and Viscous Potential Flow Method Applied to Flexible Wing Transport Aircraft. In *35th AIAA Applied Aerodynamics Conference*, pages 1–16, Denver, United States of America. American Institute of Aeronautics and Astronautics.

Chen, C.-P. and Chien, C.-F. (2009). What constitutes 'a quality decision'? *Journal of Quality*, 16(2):87–94. cited By 6.

Chen, Y., Chen, S., and Chen, Y. (2013). Decision quality by the loss cost of Type I and Type II errors. *The TQM Journal*, 25(2):202–220.

Chen, Z., Lawson, R. B., Gordon, L. R., and McIntosh, B. (1996). Groupthink: Deciding with the leader and the devil. *The Psychological Record*, 46(4):581–590.

Choi, H. S. and Thompson, L. (2005). Old wine in a new bottle: Impact of membership change on group creativity. *Organizational Behavior and Human Decision Processes*, 98(2):121–132.

Ciampa, P.-D., Nagel, B., and La Rocca, G. (2013). Preliminary Design for Flexible Aircraft in a Collaborative Environment. In *The International Conference of the European Aerospace Societies (CEAS)*, pages 270–281.

Clark, M. A., Anand, V., and Roberson, L. (2000). Resolving meaning: Interpretation in diverse decision-making groups. *Group Dynamics: Theory, Research, and Practice*, 4(3):211–221.

Clean Sky. Members. https://www.cleansky.eu/members-0. Accessed June 6th, 2019.

Clean Sky. Participants and organisation. https://www.cleansky.eu/participants-and-organisation. Accessed June 6th, 2019.

Clean Sky. Partners. https://www.cleansky.eu/partners. Accessed June 6th, 2019.

Clean Sky 2 Joint Undertaking (2018). Participation in clean sky 2. https://www.cleansky.eu/sites/default/files/inline-files/Clean%20Sky%202%20List%20of%20Private%20Members%20-%20R4%2005%20March%202018%20-%20v1%2009.04.2018_3.pdf. Version R4. Downloaded June 6th, 2019.

Clean Sky 2 Joint Undertaking (2019). Third amended bi-annual work plan and budget 2018-2019. https://www.cleansky.eu/sites/default/files/inline-files/CS-GB-2019-04-09%20Third%20Amd%20WP%2018-19%20published.pdf. Downloaded June 6th, 2019.

Clean Sky Joint Undertaking. The european partnerships for cleaner skies. https://www.cleansky.eu/sites/default/files/inline-files/cleansky-infographic-v1.jpg. Downloaded June 6th, 2019.

Cnacino Queirolo, M. A. (2018). *Impact of Morphing Winglets on Aircraft Performance*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

CNN (2019). KLM to fund development of fuel-efficient Flying-V plane. https://edition.cnn.com/travel/article/klm-flying-v-plane-scli-intl/index.html. Accessed June 19th, 2019.

Coder, J. G. and Maughmer, M. D. (2014). Comparisons of Theoretical Methods for Predicting Airfoil Aerodynamic Characteristics. *Journal of Aircraft*, 51(1):183–191.

Coder, J. G., Maughmer, M. D., and Somers, D. M. (2014). Theoretical and Experimental Results for the S414, Slotted, Natural-Laminar-Flow Airfoil. *Journal of Aircraft*, 51(6):1883–1890.

Collyer, M. and Lock, R. (1978). Improvements to the viscous carabedian and korn method for calculating transonic flow past an airfoil. *RAE Technical Report*, 78039.

Cook, P., Firmin, M., and McDonald, M. (1977). *Aerofoil RAE 2822: pressure distributions, and boundary layer and wake measurements*. RAE.

Cook, P. H., McDonald, M. A., and Firmin, M. C. P. (1979). Aerofoil RAE2822 - Pressure Distributions, and Boundary Layer and Wake Measurements. In *Experimental Data Base for Computer Program Assessment - Report of the Fluid Dynamics Panel Working Group 04*, number 138 in Advisory Reports, chapter A6. Advisory Group for Aerospace Research and Development, Neuilly-Sur-Seine, France.

Cooper, R., Edgett, S., and Kleinschmidt, E. (2001). Portfolio management for new product development: results of an industry practices study. *R&D Management*, 31(4):361–380.

Cooper, R. G. (2008). Perspective: The stage-gates® idea-to-launch process - Update, what's new, and NexGen systems. *Journal of Product Innovation Management*, 25(3):213–232.

Cooper, R. G. (2009). How Companies are Reinventing Their Idea-To-Launch Methodologies. *Research-Technology Management*, 52(2):47–57.

Cooper, R. G., Edgett, S. J., and Kleinschmidt, E. J. (1997). Portfolio Management in New Product Development : Lessons from the Leaders — I. *Research-Technology Management*, 40(5):16–28.

Courtney, J. F. (2001). Decision making and knowledge management in inquiring organizations: toward a new decision-making paradigm for DSS. *Decision Support Systems*, 31(1):17–38.

Coutu, D., Brailovski, V., and Terriault, P. (2010). Optimized design of an active extrados structure for an experimental morphing laminar wing. *Aerospace Science and Technology*, 14(7):451–458.

Coyle, S., Conboy, K., and Acton, T. (2015). Investigating Process-Parameters for Decision Quality in Software Development Teams. In *24th International Conference on Information Systems Development*.

Croskerry, P. (2003). The Importance of Cognitive Errors in Diagnosis and Strategies to Minimize Them. *Academic Medicine*, 78(8):775–780.

Cross, R., Thomas, R. J., and Light, D. A. (2009). How 'Who You Know' Affects What You Decide. *MIT Sloan Management Review*, 50(2):34–42.

Cruz, M. G. (2000). The Presence of Norms in the Absence of Groups? The Impact of Normative Influence Under Hidden-Profile Conditions. *Human Communication Research*, 26(1):104–124.

Cummings, R. M., Mason, W. H., Morton, S. A., and McDaniel, D. R. (2015). *Applied Computational Aerodynamics*. Cambridge University Press, New York, United States of America, 1 edition.

Curtis, T. (2016). Phd transfer seminar july 2016. https://www.slideshare.net/curtistim/phd-transfer-

seminar-july-2016/9. Accessed August 10th, 2019.

Dantsker, O. D. and Vahora, M. (2018). Comparison of aerodynamic characterization methods for design of unmanned aerial vehicles. In *2018 AIAA Aerospace Sciences Meeting*, pages 1–19, Kissimmee, United States of America. American Institute of Aeronautics and Astronautics.

DARcorporation (2005). Advanced aircraft analysis. https://www.darcorp.com/advanced-aircraft-analysis-software/.

De Brentani, U. and Dröge, C. (1988). Determinants of the new product screening decision A structural model analysis. *International Journal of Research in Marketing*, 5(2):91–106.

de Dreu, C. K. W. and Beersma, B. (2010). Team confidence, motivated information processing, and dynamic group decision making. *European Journal of Social Psychology*, 40(7):1110–1119.

de Dreu, C. K. W., de Vries, N. K., Franssen, H., and Altink, W. M. M. (2000). Minority Dissent in Organizations: Factors Influencing Willingness to Dissent. *Journal of Applied Social Psychology*, 30(12):2451–2466.

Delft University of Technology (2018). Technology Impact Matrix.

Dennis, A. R. (1996). Information Exchange and Use in Small Group Decision Making. *Small Group Research*, 27(4):532–550.

Deperrois, A. (2011). xflr5 - Analysis of foils and wings operating at low Reynolds numbers - Guidelines for XFLR5 v6.03. Technical report.

Design Council. A study of the design process. https://www.designcouncil.org.uk/sites/default/files/asset/document/ElevenLessons_Design_Council%20(2).pdf. Downloaded August 4th, 2019.

Dewey, J. (1910). *How We Think*. D. C. Heath & Co, New York, United States of America.

Dey, I. (1993). *Qualitative Data Analysis: A User-Friendly Guide for Social Scientists*. Routledge, London, United Kingdom.

Doganis, R. (2010). *Flying Off Course*. Taylor & Francis, Abingdon, United Kingdom, 4th edition.

Drela, M. (1985). *Two-dimensional transonic aerodynamic design and analysis using the Euler equations*. Doctoral dissertation, Massachusetts Institute of Technology.

Drela, M. (1989). XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils. In Mueller, T. J., editor, *Low Reynolds Number Aerodynamics*, pages 1–12. Springer-Verlag.

Drela, M. (1990). Newton Solution of Coupled Viscous/Inviscid Multielement Airfoil Flows. In *AIAA 21st Fluid Dynamics, Plasma Dynamics and Lasers Conference*, Seattle, United States of America. American Institute of Aeronautics and Astronautics.

Drela, M. (1994). MSES Multi-element Airfoil Design / Analysis Software - Summary.

Drela, M. (2003). Implicit Implementation of the Full e^n Transition Criterion. In *21st Applied Aerodynamics Conference*, Orlando, United States of America. American Institute of Aeronautics and Astronautics.

Drela, M. (2007). A User's Guide to MSES 3.05. Technical report, Massachussets Institute of Technology, Massachussets, United States of America.

Drela, M. (2013). Summary of changes made for recent mses versions. http://web.mit.edu/drela/Public/web/mses/version_notes.txt. Accessed August 1st, 2018.

Drela, M. and Giles, M. B. (1987a). ISES - A two-dimensional viscous aerodynamic design and analysis code. In *25th AIAA Aerospace Sciences Meeting*, Reno, United States of America. American Institute of Aeronautics and Astronautics.

Drela, M. and Giles, M. B. (1987b). Viscous-Inviscid Analysis of Transonic and Low Reynolds Number Airfoils. *AIAA Journal*, 25(10):1347–1355.

Drela, M. and Youngren, H. (2001). XFOIL 6.9 User Primer. Technical report.

Drela, M. and Youngren, H. (2010). AVL 3.30 User Primer. Technical report, Massachussets Institute of Technology, Massachussets, United States of America.

Drela, M. and Youngren, H. (2013). XFOIL - Subsonic Airfoil Development System. http://web.mit.edu/drela/Public/web/xfoil/. version 6.99.

Drela, M. and Youngren, H. (2017a). AVL. http://web.mit.edu/drela/Public/web/avl/. version 3.37.

Drela, M. and Youngren, H. (2017b). AVL 3.36 User Primer. Technical report, Massachussets Institute of Technology, Massachussets, United States of America.

Drisko, J. W. and Maschi, T. (2016). *Content Analysis*. Pocket Guids to Social Work Research Methods. Oxford University Press, New York, United States of America.

Driver, J. and Zingg, D. W. (2007). Numerical Aerodynamic Optimization Incorporating Laminar-Turbulent Transition Prediction. *AIAA Journal*, 45(8):1810–1818.

Edmondson, A. C., Roberto, M. A., and Watkins, M. D. (2003). A dynamic model of top management team effectiveness: managing unstructured task streams. *The Leadership Quarterly*, 14:297–325.

Elham, A. (2013). *Weight Indexing for Multidisciplinary Design Optimization of Lifting Surfaces*. Doctoral dissertation, Delft University of Technology.

Elmendorp, R. J. M. (2014). *Synthesis of Novel Aircraft Concepts for Future Air Travel*. Master's thesis, Delft University of Technology.

Elo, S. and Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, 62(1):107–115.

Elwyn, G. and Miron-Shatz, T. (2010). Deliberation before determination: the definition and evaluation of good decision making. *Health Expectations*, 13(2):139–147.

European Space Agency (2008). Technology Readiness Levels Handbook for Space Applications. Technical report.

Evans, J. S. B. T. (2008). Dual-Processing Accounts of Reasoning, Judgment, and Social Cognition. *Annual Review of Psychology*, 59(1):255–278.

Falk, G. (1981). Unanimity versus majority rule in problem-solving groups: A challenge to the superiority of unanimity. *Small Group Behavior*, 12(4):379–399.

Fargason Jr., C. A. and Haddock, C. C. (1992). Cross-functional, integrative team decision making: essential for effective QI in health care. *Quality Review Bulletin*, 18(5):157–163.

Farhi, P. (2017). The Washington Post's new slogan turns out to be an old saying. https://www.washingtonpost.com/lifestyle/style/the-washington-posts-new-slogan-turns-out-to-be-an-old-saying/2017/02/23/cb199cda-fa02-11e6-be05-1a3817ac21a5_story.html. Accessed June 21st, 2019.

Fernandes, G., Make, M., Gueydon, S., and Vaz, G. (2014). Sensitivity to Aerodynamic Forces for the

Accurate Modelling of Floating Offshore Wind Turbines. In *1st International Conference on Renewable Energies Offshore*, pages 24–26.

Ferziger, J. H. and Perić, M. (2002). *Computational Methods for Fluid Dynamics*. Springer-Verlag Berlin Heidelberg, New York, United States of America, 3rd edition.

Florjancic, D. (2015). *Improved Design of a High Lift System for General Aviation Aircraft*. Master's thesis, Delft University of Technology.

Fokker Aerostructures BV, Fokker Technologies Holding, ASCO Industries N.V, Stichting Nationaal Lucht- en Ruimtevaartlaboratorium, Deutsches Zentrum für Luft- und Raumfahrt, and Technische Universiteit Delft (2014). MANTA - MovAbles for Next generaTion Aircraft: Description of Action. Technical report, CleanSky2.

Freeman, K., Field, R. A., and Perkins, G. D. (2015). Variation in local trust do not attempt cardiopulmonary resuscitation (dnacpr) policies: a review of 48 english healthcare trusts. *BMJ open*, 5(1):e006517.

Freestone, M. M. (2004). VGK method for two-dimensional aerofoil sections - Part 1: principles and results. Technical Report ESDU 96028, Royal Aeronautical Society, United Kingdom.

Freestone, M. M. (2010). Transonic data memorandum - VGK method for two-dimensional aerofoil sections - Part 2: User manual. Technical Report ESDU 96029, Royal Aeronautical Society, United Kingdom.

Fujiwara, G. E. C., Chaparro, D., and Nguyen, N. (2016). An Integral Boundary Layer Direct Method Applied to 2D Transonic Small-Disturbance Equations. In *34th AIAA Applied Aerodynamics Conference*, Washington, United States of America. American Institute of Aeronautics and Astronautics.

GAINS (2015). Gains - the green airframe icing novel systems. http://gains.meggitt.com/. Accessed June 6th, 2019.

Garabedian, P. R. and Korn, D. G. (1971). Analysis of Transonic Airfoils. *Communications on Pure and Applied Mathematics*, 24(6):841–851.

Garvin, D. A. and Roberto, M. A. (2001). What You Don't Know About Making Decisions. *Harvard Business Review*, 79(8):108–119.

Gelles, D. and Kitroeff, N. (2019). F.A.A. Leaders Face Scrutiny Over Boeing 737 Max Certification. https://www.nytimes.com/2019/07/31/business/boeing-max-faa-senate.html. Accessed August 14th, 2019.

Genco, N. and Altman, A. (2009). Parametric Study of the Performance of a Biplane Joined at the Tips. In *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, pages 1–11, Orlando, United States of America. American Institute of Aeronautics and Astronautics.

Gerritsma, M. I. (2002). *Computational Fluid Dynamics, Incompressible Flow*. Delft University Press, Delft, The Netherlands.

Ghosh, S., Rancourt, D., Daskilewicz, M. J., Lee, C., and Mavris, D. N. (2014). A Visualization Method for Multidisciplinary System under Uncertainty. In *14th AIAA Aviation Technology, Integration, and Operations Conference*, pages 1–13, Reston, Virginia. American Institute of Aeronautics and Astronautics.

Giles, M. B. and Drela, M. (1987). Two-Dimensional Transonic Aerodynamic Design Method. *AIAA Journal*, 25(9):1199–1206.

Gillet, J., Schram, A., and Sonnemans, J. (2009). The tragedy of the commons revisited: The importance

of group decision-making. *Journal of Public Economics*, 93(5-6):785–797.

Gouran, D. S. and Hirokawa, R. Y. (1983). The Role of Communication in Decision Making Groups: A Functional Perspective. In Mander, M. S., editor, *Communications in Transition*, pages 168–185. Praeger, New York, United States of America.

Green, J. E., Weeks, D. J., and Brooman, J. (1977). Prediction of Turbulent Boundary Layers and Wakes in Compressible Flow by a Lag-Entrainment Method. Technical Report 3791, Aeronautical Research Council, London, United Kingdom.

Green, J. E., Weeks, D. J., and Brooman, J. W. F. (1973). Prediction of turbulent boundary-layers and wakes in compressible flow by a lag-entrainment method. Technical Report 3791, Aeronautical Research Council.

Greenwald, A. G. (1980). The Totalitarian Ego: Fabrication and Revision of Personal History. *American Psychologist*, 35(7):603–618.

Greer, D., Hamory, P., Krake, K., and Drela, M. (2000). Design and Predictions for High-Altitude (Low Reynolds Number) Aerodynamic Flight Experiment. *Journal of Aircraft*, 37(4):684–689.

Griffin, D. W. and Ross, L. (1991). Subjective Construal, Social Inference, and Human Misunderstanding. *Advances in Experimental Social Psychology*, 24:319–359.

Gu, X., Ciampa, P. D., and Nagel, B. (2018). An automated CFD analysis workflow in overall aircraft design applications. *CEAS Aeronautical Journal*, 9(1):3–13.

Guo, Z., Chen, X.-k., Hou, Z.-x., and Guo, J. (2011). Development of a Solar Electric Powered UAV for Long Endurance Flight. In *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, pages 1–13, Virginia Beach, United States of America. American Institute of Aeronautics and Astronautics.

Hackman, J. R., editor (1990). *Groups That Work (and Those That Don't) - Creating Conditions for Effective Teamwork*. The Jossey-Bass Management Series. Jossey-Bass Limited, San Francisco, United States of America.

Hahlweg, P., Didi, S., Kriston, L., Härter, M., Nestoriuc, Y., and Scholl, I. (2017). Process quality of decision-making in multidisciplinary cancer team meetings: a structured observational study. *BMC Cancer*, 17(1):772.

Haimes, R. and Drela, M. (2012). On The Construction of Aircraft Conceptual Geometry for High-Fidelity Analysis and Design. In *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, pages 1–21. American Institute of Aeronautics and Astronautics.

Hambrick, D. C. (1995). Fragmentation and the Other Problems CEOs Have with Their Top Management Teams. *California Management Review*, 37(3):110–127.

Hamilton, J. G., Lillie, S. E., Alden, D. L., Scherer, L., Oser, M., Rini, C., Tanaka, M., Baleix, J., Brewster, M., Craddock Lee, S., Goldstein, M. K., Jacobson, R. M., Myers, R. E., Zikmund-Fisher, B. J., and Waters, E. A. (2017). What is a good medical decision? A research agenda guided by perspectives from multiple stakeholders. *Journal of Behavioral Medicine*, 40(1):52–68.

Hammedi, W., van Riel, A. C. R., and Sasovova, Z. (2011). Antecedents and Consequences of Reflexivity in New Product Idea Screening. *Journal of Product Innovation Management*, 28(5):662–679.

Hammedi, W., van Riel, A. C. R., and Sasovova, Z. (2013). Improving Screening Decision Making through Transactive Memory Systems: A Field Study. *Journal of Product Innovation Management*, 30(2):316–330.

Harris, C. D. (1981). Two-Dimensional Aerodynamic Characteristics of the NACA 0012 Airfoil in the

Langley 8-Foot Transonic Pressure Tunnel. Technical Report NASA-TM-81927, National Aeronautics and Space Administration, Hampton, United States of America.

Hassan, A. A. and Munts, E. A. (2000). Transverse and Near-Tangent Synthetic Jets for Aerodynamic Flow Control. In *18th Applied Aerodynamics Conference*, pages 1–17, Denver, United States of America. American Institute of Aeronautics and Astronautics.

Head, M. R. (1958). Entrainment in the Turbulent Boundary Layer. Technical Report 3152, Aeronautical Research Council, London, United Kingdom.

Helton, J. C., Johnson, J. D., Oberkampf, W. L., and Storlie, C. B. (2007). A sampling-based computational strategy for the representation of epistemic uncertainty in model predictions with evidence theory. *Computer Methods in Applied Mechanics and Engineering*, 196(37-40):3980–3998.

Henningsen, D. D., Henningsen, M. L. M., Jakobsen, L., and Borton, I. (2004). It's Good to Be Leader: The Influence of Randomly and Systematically Selected Leaders on Decision-Making Groups. *Group Dynamics: Theory, Research, and Practice*, 8(1):62–76.

Henrich, J., Boyd, R., Bowles, S., Camerer, C., Fehr, E., Gintis, H., and McElreath, R. (2001). In Search of Homo Economicus: Behavioral Experiments in 15 Small-Scale Societies. *The American Economic Review*, 91(2):73–78.

Hess, J. L. (1988). Development and Application of Panel Methods. In Cruse, T. A., editor, *Advanced Boundary Element Methods - IUTAM Symposium San Antonio, Texas, 1987*, pages 165–177. Springer-Verlag Berlin Heidelberg.

Heuer, G. (2018). MANTA - WP1.3 Synthesis of Solutions. Technical Report D-A-4.2.1-76.1 (B), Fokker Aerostructures BV.

Hirokawa, R. Y. (1980). A comparative analysis of communication patterns within effective and ineffective decision-making groups. *Communication Monographs*, 47(4):312–321.

Hirokawa, R. Y. (1982). Consensus group decision-making, quality of decision, and group satisfaction: An attempt to sort ”fact” from ”fiction”. *Central States Speech Journal*, 33(2):407–415.

Hirokawa, R. Y. (1988). Group Communication and Decision-Making Performance. *Human Communication Research*, 14(4):487–515.

Hirokawa, R. Y. (1990). The Role of Communication in Group Decision-Making Efficacy: A Task-Contingency Perspective. *Small Group Research*, 2(21):190–204.

Hirokawa, R. Y. and Pace, R. (1983). A descriptive investigation of the possible communication□based reasons for effective and ineffective group decision making. *Communication Monographs*, 50(4):363–379.

Hirokawa, R. Y. and Rost, K. M. (1992). Effective Group Decision Making in Organizations: Field Test of the Vigilant Interaction Theory. *Management Communication Quarterly*, 5(3):267–288.

Hirokawa, R. Y. and Scheerhorn, D. R. (1986). Communication in Faulty Group Decision-Making. In Hirokawa, R. Y. and Poole, M. S., editors, *Communication and group decision-making*, chapter 2, pages 63–80. Sage, Beverly Hills, United States of America.

Hirokawa, R. Y. and University of Hawai'i - Hilo (2016). Randy hirokawa's curriculum vitae. https://hilo.hawaii.edu/faculty/randyhirokawa/CurriculumVitae.php. Accessed May 14th, 2019.

Hirsch, C. (2007). *Fundamentals of Computational Fluid Dynamics*, volume 1 of *Numerical Computations of Internal and External Flows*. Butterworth-Heinemann / Elsevier, Oxford, United Kingdom, 2nd edition.

Hoak, D. E. (1978). USAF Stability and Control DATCOM. Technical report, Air Force Flight Dynamics Laboratory, Ohio, United States of America.

Hofstede, G. (1984). *Culture's Consequences - International Differences in Work-Related Values*. SAGE Publications, 2nd edition.

Hollingshead, A. B. (1996). Information Suppression and Status Persistence in Group Decision Making: The Effects of Communication Media. *Human Communication Research*, 23(2):193–219.

Holst, T. L. (1987). Viscous Transonic Airfoil Workshop Compendium of Results. In *AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference*, pages 1–32, Honolulu, United States of America. American Institute of Aeronautics and Astronautics.

House, R. J. (1996). Path-goal theory of leadership: Lessons, legacy, and a reformulated theory. *Leadership Quarterly*, 7(3):323–352.

Howard, R. A. (1988). Decision Analysis: Practice And Promise. *Management Science*, 34(6):679–695.

Hsieh, H.-F. and Shannon, S. E. (2005). Three Approaches to Qualitative Content Analysis. *Qualitative Health Research*, 15(9):1277–1288.

Hsu, Y.-G., Tzeng, G.-H., and Shyu, J. Z. (2003). Fuzzy multiple criteria selection of government-sponsored frontier technology R&D projects. *R&D Management*, 33(5):539–551.

IHS. ESDU Aerospace Package. https://www.esdu.com/cgi-bin/ps.pl?sess=delft_1181011123020mvw&t=col&p=pk_aesp. Accessed October 11th, 2018.

IndianScribes (2018). 4 rules of verbatim transcription. https://www.indianscribes.com/4-rules-of-verbatim-transcription/. Accessed June 12th, 2019.

Innami, I. (1994). The Quality of Group Decisions, Group Verbal Behavior, and Intervention. *Organizational Behavior and Human Decision Processes*, 60(3):409–430.

International Institute of Business Analysis (2015). *BABOK: A Guide to the Business Analysis Body of Knowledge*. Toronto, Canada, 3rd edition.

Jackson, A., Mentzer, N., and Zissimopoulos, A. (2014). Factors of Group Design Decision Making. In *2015 ASEE Annual Conference and Exposition Proceedings*, pages 26.761.1–26.761.14.

Jacobs, E. J., Ward, K. E., and Pinkerton, R. M. (1933). The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel. Technical Report 460, National Advisory Committee for Aeronautics.

Jagdale, V., Patil, A., Stanford, B., and Ifju, P. (2009). Conceptual Design of a Bendable UAV Wing Considering Aerodynamic and Structural Performance. In *50th AIAA Structures, Structural Dynamics, and Materials Conference*, pages 1–10, Palm Springs, United States of America. American Institute of Aeronautics and Astronautics.

Jameson, A. (1976). Numerical computation of transonic flows with shock waves. pages 384–414, Berlin, Germany. Springer-Verlag.

Jameson, A. (1999). Re-Engineering the Design Process Through Computation. *Journal of Aircraft*, 36(1):36–50.

Jameson, A. (2003). CFD for Aerodynamic Design and Optimization: Its Evolution over the Last Three Decades. In *16th AIAA CFD Conference*, pages 1–11, Orlando, United States of America. American Institute of Aeronautics and Astronautics.

Jameson, A. (2004). Aerodynamics. In Stein, E., de Borst, R., and Hughes, T. J. R., editors, *Encyclopedia*

of Computational Mechanics, chapter 11. John Wiley & Sons, Ltd.

Janis, I. L. (1972). Victims of groupthink: a psychological study of foreign-policy decisions and fiascoes.

Janis, I. L. (1989). *Crucial Decisions - Leadership in Policymaking and Crisis Management*. The Free Press / Macmillan, Inc., New York, United States of America.

Jehn, K. A. (1995). A Multimethod Examination of the Benefits and Detriments of Intragroup Conflict. *Administrative Science Quarterly*, 40(2):256–282.

Jenkinson, L. R., Simpkin, P., and Rhodes, D. (1999). *Civil Jet Aircraft Design*. Arnold Publishers, London, United Kingdom.

Johansson, C. (2014). Managing Uncertainty and Ambiguity in Gates: Decision Making in Aerospace Product Development. *International Journal of Innovation and Technology Management*, 11(2):1450012.

Jones, P. E. and Roelofsma, P. H. M. P. (2000). The potential for social contextual and group biases in team decision-making: biases, conditions and psychological mechanisms. *Ergonomics*, 43(8):1129–1152.

Jungo, A., Zhang, M., Vos, J. B., and Rizzi, A. (2018). Benchmarking New CEASIOM with CPACS adoption for aerodynamic analysis and flight simulation. *Aircraft Engineering and Aerospace Technology*, 90(4):613–626.

Kaba, A., Wishart, I., Fraser, K., Coderre, S., and Mclaughlin, K. (2016). Are we at risk of groupthink in our approach to teamwork interventions in health care? *Medical Education*, 50(4):400–408.

Kahneman, D. (2003). Maps of Bounded Rationality: Economicst Psychology for Behavioral. *The American Economic Review*, 93(5):1449–1475.

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

Kahneman, D., Lovallo, D., and Sibony, O. (2011). Before You Make That Big Decision... *Harvard Business Review*, 89(6):50–60.

Kahneman, D. and Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, 47(2):263–291.

Kamis, A. A. and Davern, M. J. (2005). An exploratory model of decision quality and its antecedents for category novices using multiple-stage shopping engines. *E-Service Journal*, 4(1):3–27.

Kane, A. A., Argote, L., and Levine, J. M. (2005). Knowledge transfer between groups via personnel rotation: Effects of social identity and knowledge quality. *Organizational Behavior and Human Decision Processes*, 96(1):56–71.

Katz, J. and Plotkin, A. (1991). *Low-Speed Aerodynamics - From Wing Theory to Panel Methods*. McGraw-Hill, Inc., Singapore.

Kee, F., Owen, T., and Leathem, R. (2004). Decision Making in a Multidisciplinary Cancer Team: Does Team Discussion Result in Better Quality Decisions? *Medical Decision Making*, 24(6):602–613.

Kelly, K. (2010). The Effects of Incentives on Information Exchange and Decision Quality in Groups. *Behavioral Research in Accounting*, 22(1):43–65.

Kerr, N. L., Niedermeier, K. E., and Kaplan, M. F. (1999). Bias in Jurors vs Bias in Juries: New Evidence from the SDS Perspective. *Organizational Behavior and Human Decision Processes*, 80(1):70–86.

Kerr, N. L. and Tindale, R. S. (2004). Group Performance and Decision Making. *Annual Review of*

Psychology, 55(1):623–655.

Kidger, J., Murdoch, J., Donovan, J. L., and Blazeby, J. M. (2009). Clinical decision-making in a multidisciplinary gynaecological cancer team: A qualitative study. *BJOG: An International Journal of Obstetrics and Gynaecology*, 116(4):511–517.

Kim, Y., Hiltz, S. R., and Turoff, M. (1998). Coordination Structure and System Restrictiveness in Distributed Group Support Systems: An Experiment on Coordination Mode and Leadership. In *Proceedings of the Thirty-First Hawaii International Conference on System Sciences, 1998*, volume 1, pages 145–153. IEEE.

Kirchmeyer, C. (1996). Gender roles and decision-making in demographically diverse groups: A case for reviving androgyny. *Sex Roles*, 34(9-10):649–663.

Kotlyar, I., Karakowsky, L., and Ng, P. (2011). Leader behaviors, conflict and member commitment to team-generated decisions. *The Leadership Quarterly*, 22(4):666–679.

Kozlowski, S. W. J. and Ilgen, D. R. (2006). Enhancing the Effectiveness of Work Groups and Teams. *Psychological science in the public interest*, 7(3):77–124.

Kroo, I. (2004). Innovations in Aeronautics. In *42nd AIAA Aerospace Sciences Meeting*, pages 1–11, Reno, United States of America. American Institute of Aeronautics and Astronautics.

Kulfan, B. M. (2008). Universal Parametric Geometry Representation Method. *Journal of Aircraft*, 45(1):142–158.

Kuzmin, D. Introduction to computational fluid dynamics. http://www.mathematik.uni-dortmund.de/%7Ekuzmin/cfdintro/lecture3.pdf. Downloaded June 5th, 2018.

La Rocca, G. (2011). *Knowledge Based Engineering Techniques to Support Aircraft Design and Optimization*. Doctoral dissertation, Delft University of Technology.

La Rocca, G., Visser, H. A., Steenhuizen, D., and Elham, A. (2014). Advanced design methods (mdo, kbe), ae4233 - on parameterization techniques. Lecture notes Delft University of Technology, academic year 2014/2015.

Lamar, J. E. (1976). A Vortex-Lattice for of the Mean Method Shapes of Trimmed Noncoplanar Planforms with Minimum Vortex With. Technical Report NASA TN D-8090, National Aeronautics and Space Administration, Hampton, United States of America.

Lamb, B., Green, J. S. A., Vincent, C., and Sevdalis, N. (2011a). Decision making in surgical oncology. *Surgical Oncology*, 20(3):163–168.

Lamb, B. W., Brown, K. F., Nagpal, K., Vincent, C., Green, J. S. A., and Sevdalis, N. (2011b). Quality of Care Management Decisions by Multidisciplinary Cancer Teams: A Systematic Review. *Annals of Surgical Oncology*, 18(8):2116–2125.

Lamb, B. W., Sevdalis, N., Benn, J., Vincent, C., and Green, J. S. A. (2013). Multidisciplinary Cancer Team Meeting Structure and Treatment Decisions: A Prospective Correlational Study. *Annals of Surgical Oncology*, 20(3):715–722.

Lamb, B. W., Sevdalis, N., Mostafid, H., Vincent, C., and Green, J. S. A. (2011c). Quality Improvement in Multidisciplinary Cancer Teams: An Investigation of Teamwork and Clinical Decision-Making and Cross-Validation of Assessments. *Annals of Surgical Oncology*, 18(13):3535–3543.

Lamb, B. W., Sevdalis, N., Vincent, C., and Green, J. S. A. (2012). Development and Evaluation of a Checklist to Support Decision Making in Cancer Multidisciplinary Team Meetings: MDT-QuIC. *Annals of Surgical Oncology*, 19(6):1759–1765.

Lamb, B. W., Wong, H. W. L., Vincent, C., Green, J. S. A., and Sevdalis, N. (2011d). Teamwork and team performance in multidisciplinary cancer teams: development and evaluation of an observational assessment tool. *BMJ Quality & Safety*, 20(10):849–856.

Lanceley, A., Savage, J., Menon, U., and Jacobs, I. (2008). Influences on multidisciplinary team decision-making. *International Journal of Gynecological Cancer*, 18(2):215–222.

Lang, C., Xi, Y., and Guo, S. (2008). Impact of team conflict on team decision quality and satisfaction: An empirical research in China. *Frontiers of Business Research in China*, 2(1):1–14.

Larson, C. E. and LaFasto, F. M. J. (1989). *Teamwork: What must go right/what can go wrong*. Sage, Newbury Park, United States of America.

Larson Jr., J. R., Christensen, C., Franz, T. M., and Abbott, A. S. (1998a). Diagnosing groups: The pooling, management, and impact of shared and unshared case information in team-based medical decision making.

Larson Jr., J. R., Foster-Fishman, P. G., and Franz, T. M. (1998b). Leadership Style and the Discussion of Shared and Unshared Information in Decision-Making Groups. *Personality and Social Psychology Bulletin*, 24(5):482–495.

Larson Jr., J. R., Foster-Fishman, P. G., and Keys, C. B. (1994). Discussion of Shared and Unshared Information in Decision-Making Groups. *Journal of Personality and Social Psychology*, 67(3):446–461.

Lasauskas, E. (2005). Influence of transition location on airfoil drag. *Aviation*, 9(3):19–22.

Lasauskas, E. and Naujokaitis, L. (2009). Analysis of three wing sections. *Aviation*, 13(1):3–10.

Lebowitz, S. and Lee, S. (2015). 20 cognitive biases that screw up your decisions. https://www.businessinsider.com/cognitive-biases-that-affect-decisions-2015-8?international=true&r=US&IR=T. Accessed June 20th, 2019.

Lee, D., Van Nguyen, N., Tyan, M., Chun, H. G., Kim, S., and Lee, J.-W. (2017). Enhanced multi-fidelity model for flight simulation using global exploration and the Kriging method. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 231(4):606–620.

Leifsson, L., Koziel, S., Tesfahunegn, Y. A., Hosder, S., and Gramanzini, J.-R. (2014). Aerodynamic Design Optimization: Physics-based Surrogate Approaches for Airfoil and Wing Design. In *52nd Aerospace Sciences Meeting*, pages 1–13, National Harbor, United States of America. American Institute of Aeronautics and Astronautics.

Léonard, T., Gicquel, L. Y. M., Gourdain, N., and Duchaine, F. (2015). Steady / Unsteady Reynolds-Averaged Navier-Stokes and Large Eddy Simulations of a Turbine Blade at High Subsonic Outlet Mach Number. *Journal of Turbomachinery*, 137:041001–1.

Leschziner, M. A. (2010). Reynolds-Averaged Navier-Stokes Methods. In *Encyclopedia of Aerospace Engineering*, pages 1–14. John Wiley & Sons, Ltd.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. a., Clarke, M., Devereaux, P. J., Kleijnen, J., and Moher, D. (2009). The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *PLoS Medicine*, 6(7):e1000100.

Lin, C. P., Chen, K. J., Liu, C. M., and Liao, C. H. (2017). Assessing decision quality and team performance: perspectives of knowledge internalization and resource adequacy. *Review of Managerial Science*, pages 1–20.

Lipiec, M. (2019). Beyond the double diamond: thinking about a better design process model. https://uxdesign.cc/beyond-the-double-diamond-thinking-about-a-better-design-process-

model-de4fdb902cf. Accessed August 4th, 2019.

Littlejohn, S. W. and Foss, K. A. (2011). *Theories of Human Communication*. Waveland Press, Incl., 10 edition.

Littlejohn, S. W., Foss, K. A., and Oetzel, J. G. (2017). *Theories of Human Communication*. Waveland Press, Inc., Long Grove, United States of America, 11 edition.

Lock, R. C. (1981). A modification to the method of garabedian and korn. volume 3 of *Notes on Numerical Fluid Mehanics*, pages 116–124, Braunschweig, Germany. Springer Fachmedien Wiesbaden GmbH.

Lock, R. C. (1985). Prediction of the Drag of Wings at Subsonic Speeds by Viscous/Inviscid Interaction Techniques. In *Aircraft Drag Prediction and Reduction*, number 723, chapter 10.

Lock, R. C. (1995). A method of determining the wave drag and its spanwise distribution on a finite wing in transonic flow. Technical Report ESDU 87003, Royal Aeronautical Society, United Kingdom.

Lock, R. C. and Williams, B. R. (1987). Viscous-Inviscid Interactions in External Aerodynamics. *Progress in Aerospace Sciences*, 24(2):51–171.

Lu, L., Yuan, Y. C., and McLeod, P. L. (2012). Twenty-Five Years of Hidden Profiles in Group Decision Making. *Personality and Social Psychology Review*, 16(1):54–75.

Lykins, R., Keshmiri, S., Riley, R., and Garcia, G. (2011). Modal Analysis of 1/3-Scale Yak-54 Aircraft Through Simulation and Flight Testing. In *AIAA Atmospheric Flight Mechanics Conference*, pages 1–7, Portland, United States of America. American Institute of Aeronautics and Astronautics.

Madsen, H. A. and Filippone, A. (1995). *Implementation and Test of the XFOIL Code for Airfoil Analysis and Design*. Risø National Laboratory, Roskilde, Denmark.

Malhotra, V., Lee, M. D., and Khurana, A. (2007). Domain experts influence decision quality: Towards a robust method for their identification. *Journal of Petroleum Science and Engineering*, 57(1-2):181–194.

Mancini, A. (2018). *The Effect of Maneuver Load Alleviation Strategies on Aircraft Performance Indicators*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Mannix, E. and Neale, M. A. (2005). What Differences Make a Difference? The Promise and Reality of Diverse Teams in Organizations. *Psychological Science in the Public Interest*, 6(2):31–55.

Margason, R. J. and Lamar, J. E. (1971). Vortex-Lattice Fortran Program for Estimating Subsonic Aerodynamic Characteristics of Complex Planforms. Technical Report NASA TN D-6142, National Aeronautics and Space Administration, Washington, D.C., United States of America.

Mariens, J. (2012). *Wing Shape Multidisciplinary Design Optimization*. Master's thesis, Delft University of Technology.

Mariens, J., Elham, A., and van Tooren, M. J. L. (2014). Quasi-Three-Dimensional Aerodynamic Solver for Multidisciplinary Design Optimization of Lifting Surfaces. *Journal of Aircraft*, 51(2):547–558.

Markus, H. R. and Kitayama, S. (1991). Culture and the Self : Implications for Cognition, Emotion, and Motivation. *Psychological Review*, 98(2):224–253.

Martin, J. D. and Simpson, T. W. (2006). A Methodology to Manage System-level Uncertainty During Conceptual Design. *Journal of Mechanical Design*, 128(4):959–968.

Maseland, J. E. J. (2017). Technology survey of movables and innovative concepts for future aircraft - Input to the technology development roadmap. Technical Report NLR-CR-2017-289 /, Netherlands Aerospace Centre, Amsterdam, The Netherlands.

Maskew, B. (1982). Program VSAERO: A Computer Program for Calculating the Non-linear Aerodynamic Characteristics of Arbitrary Configurations – User's Manual. Technical report, National Aeronautics and Space Administration, Moffett Field, United States of America.

Mathieu, J. E., Heffner, T. S., Goodwin, G. F., Salas, E., and Cannon-Bowers, J. A. (2000). The Influence of Shared Mental Models on Team Process and Performance. *Journal of Applied*, 85(2):273–283.

Maughmer, M. D. and Coder, J. G. (2010). Comparisons of Theoretical Methods for Predicting Airfoil Aerodynamic Characteristics. Technical Report TR 10-D-106, U.S. Army Research, Development and Engineering Command, Fort Eustis, United States of America.

Mayring, P. (2014). Qualitative content analysis: theoretical foundation, basic procedures and software solution. Technical report, Klagenfurt, Austria.

Mazar, N., Amir, O., and Ariely, D. (2008). The Dishonesty of Honest People: A Theory of Self-Concept Maintenance. *Journal of Marketing Research*, 45(6):633–644.

McLeod, P. L. (2013). Distributed People and Distributed Information: Vigilant Decision-Making in Virtual Teams. *Small Group Research*, 44(6):627–657.

McMasters, J. H. and Cummings, R. M. (2004). Rethinking the Airplane Design Process - An Early 21st Century Perspective. In *42nd AIAA Aerospace Sciences Meeting and Exhibit*, pages 2 – 26. American Institute of Aeronautics and Astronautics.

McNally, R. C., Durmusoglu, S. S., Calantone, R. J., and Harmancioglu, N. (2009). Exploring new product portfolio management decisions: The role of managers' dispositional traits. *Industrial Marketing Management*, 38(1):127–143.

Melin, T. (2000). *A Vortex Lattice MATLAB Implementation for Linear Aerodynamic Wing Applications*. Master's thesis, Royal Institute of Technology (KTH).

Merchant, A. and Drela, M. (1996). Design and Analysis of Supercritical Suction Airfoil. In *14th Applied Aerodynamics Conference*, pages 206–215. American Institute of Aeronautics and Astronautics.

Meyer, B., Burtscher, M. J., Jonas, K., Feese, S., Arnrich, B., Tröster, G., and Schermuly, C. C. (2016). What good leaders actually do: micro-level leadership behaviour, leader evaluations, and team decision quality. *European Journal of Work and Organizational Psychology*, 25(6):773–789.

Miranda, L. R., Elliot, R. D., and Baker, W. M. (1977). A Generalized Vortex Lattice Method for Subsonic and Supersonic Flow Applications. Technical Report NASA CR-2865, National Aeronautics and Space Administration, Hampton, United States of America.

MIT Technology Licensing Office (2018). MSES - software for high lift multielement airfoil configurations. https://tlo.mit.edu/technologies/mses-software-high-lift-multielement-airfoil-configurations. Accessed June 29th, 2018.

Mohanty, R. P., Agarwal, R., Choudhury, A. K., and Tiwari, M. K. (2005). A fuzzy ANP-based approach to R&D project selection: a case study. *International Journal of Production Research*, 43(24):5199–5216.

Moreland, R. L. (2006). Transactive Memory : Learning Who Knows What in Work Groups and Organizations. In Levine, J. M. and Moreland, R. L., editors, *Small Groups*, Key Readings in Social Psychology, chapter 18, pages 327–346. Psychology Press, New York, United States of America.

Morgado, J., Vizinho, R., Silvestre, M. A. R., and Páscoa, J. C. (2016). XFOIL vs CFD performance predictions for high lift low Reynolds number airfoils. *Aerospace Science and Technology*, 52(2016):207–214.

Mouch, T. N. and Lan, C. E. (1993). Computational Fluid Dynamics with Icing Effects. In *Aerotech '93*, SAE Technical Papers, pages 1–12, Costa Mesa, United States of America. SAE International.

Mullen, B., Anthony, T., Salas, E., and Driskell, J. E. (1994). Group Cohesiveness and Quality of Decision Making: An Integration of Tests of the Groupthink Hypothesis. *Small Group Research*, 25(2):189–204.

Mullins, J. and Sabherwal, R. (2014). How Much Information is Too Much? Effects of Computer Anxiety and Self-Efficacy. In *35th International Conference on Information Systems*, pages 1–20.

Murman, E. M. (1974). Analysis of Embedded Shock Waves Calculated by Relaxation Methods. *AIAA Journal*, 12(5):626–633.

Nanda, S. (2016). *Flow past a square-prism: A numerical study*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Nemeth, C. and Rogers, J. (1996). Dissent and the search for information. *British Journal of Social Psychology*, 35(1):67–76.

Norris, G. (2015). Boeing rolls out 777 upgrade plan. https://aviationweek.com/advanced-machines-aerospace-manufacturing/boeing-rolls-out-777-upgrade-plan. Accessed May 21st, 2018.

Norris, G. (2019). Airbus and rolls-royce freeze e-fan x hybrid-electric demo design. https://aviationweek.com/paris-airshow-2019/airbus-and-rolls-royce-freeze-e-fan-x-hybrid-electric-demo-design. Accessed July 18th, 2019.

Norris, G. and Trimble, S. paris air show 2019: Hypersonics, electric aviation and tankers.

Nowak, M. and Pautasso, C. (2013). Team Situational Awareness and Architectural Decision Making with the Software Architecture Warehouse. In *European Conference on Software Architecture*.

Obert, E. (2009). *Aerodynamic Design of Transport Aircraft*. IOS Press BV.

Oetzel, J. (1995). Intercultural small groups: An effective decision-making theory. In Wiseman, R. L., editor, *Intercultural Communication Theory*, volume 19, chapter 10, pages 247–270. SAGE Publications, Thousand Oaks, California, United States of America.

Oetzel, J. G. (2005). Effective Intercultural Workgroup Communication Theory. In Gudykunst, W. B., editor, *Theorizing about Intercultural Communication*, chapter 15, pages 351–371. SAGE Publications.

Oetzel, J. G. (2017). Effective Intercultural Workgroup Communication Theory. In Kim, Y. Y. and McKay-Semmler, K. L., editors, *The International Encyclopedia of Intercultural Communication*. John Wiley & Sons, Inc.

ONERA (2017). Onera participates in racer. https://www.onera.fr/sites/default/files/communiques/pdf/2017-08/20062017-PR-ONERA-participates-in-racer.pdf. Downloaded June 6th, 2019.

Orasanu, J. and Salas, E. (1993). Team decision making in complex environments. In Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E., editors, *Decision making in action: Models and methods*, pages 327–345. Ablex Publishing, Westport, United States of America.

Orlitzky, M. and Hirokawa, R. Y. (2001). To Err is Human, to Correct for it Divine: A Meta-Analysis of Research Testing the Functional Theory of Group Decision-Making Effectiveness. *Small Group Research*, 32(3):313–341.

Padulo, M., Maginot, J., Guenov, M., and Holden, C. (2009). Airfoil Design under Uncertainty with Robust Geometric Parameterization. In *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, pages 1–14, Palm Springs, United States of America. American Institute of Aeronautics and Astronautics.

Palacios, F., Colonno, M. R., Aranake, A. C., Campos, A., Copeland, S. R., Economon, T. D., Lonkar, A. K., Lukaczyk, T. W., Tayler, T. W. R., and Alonso, J. J. (2013). Stanford University Unstructured (SU2): An open-source integrated computational environment for multi-physics simulation and de-

sign. In *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, pages 1–60, Reston, Virigina. American Institute of Aeronautics and Astronautics.

Park, G. G. and DeShon, R. D. (2010). A Multilevel Model of Minority Opinion Expression and Team Decision-making Effectiveness. *Journal of Applied Psychology*, 95(5):824–833.

Parsons, T. and Shils, E. A., editors (1951). *Toward a General Theory of Action*. Oxford University Press, London, United Kingdom.

Pavitt, C. (2014). An Interactive Input-Process-Output Model of Social Influence in Decision-Making Groups. *Small Group Research*, 45(6):704–730.

Peerlings, B. (2017). Thesis project proposal and plan – holistically improving screening decisions under uncertainty in aircraft conceptual design.

Peerlings, B. (2018). A review of aerodynamic flow models, solution methods and solvers – and their applicability to aircraft conceptual design. Technical report, Delft University of Technology, Delft, The Netherlands. Literature study report, print version.

Peeters, P. M. (2017). *Tourism's impact on climate change and its mitigation challenges*. Doctoral dissertation, Delft University of Technology.

Peyret, R. and Viviand, H. (1975). Computation of Viscous Compressible Flows Based on the Navier-Stokes Equations. Technical Report 212, North Atlantic Treaty Organization, Neuilly-Sur-Seine.

Pipistrel Aircraft. Alpha electro, the new 2-seat electric trainer: the greenest way of learning to fly! http://www.pipistrel.si/plane/alpha-electro/overview. Accessed May 21st, 2018.

Poama, A. (2013). Whither equality? securing the lay citizens' place inside the criminal justice system. *Swiss Political Science Review*, 19(4):472–491.

Porter, E. M. (1996). What Is Strategy? *Harvard Business Review*, November -:61 – 78.

Priem, R. L., Harrison, D. A., and Muir, N. K. (1995). Structured Conflict and Consensus Outcomes in Group Decision Making. *Journal of Management*, 21(4):691–710.

Pronk, J. T., Lee, S. Y., Lievense, J., Pierce, J., Palsson, B., Uhlen, M., and Nielsen, J. (2015). How to set up collaborations between academia and industrial biotech companies. *Nature Biotechnology*, 33(3):237–240.

Pulliam, T. H. (1984). Euler and thin layer Navier-Stokes codes: ARC2D, ARC3D. In *Notes for computational fluid dynamics user's workshop*.

Pulliam, T. H. (1986). Solution Methods In Computational Fluid Dynamics. In *Notes for the von Kármán Institute For Fluid Dynamics Lecture Series*.

Pulliam, T. H. and Steger, J. L. (1978). On Implicit Finite-Difference Simulations of Three Dimensional Flow. In *AIAA 16th Aerospace Sciences Meeting*, pages 1–11, Huntsville, United States of America. American Institute of Aeronautics and Astronautics.

QinetiQ. Our History - About us. https://www.qinetiq.com/About-us/Our-History. Accessed July 3rd, 2018.

QSR International (2017). Nvivo 11 for windows. Version 11.4.1.1064 (64-bit).

QSR International (2019). Nvivo 12 plus. Version 12.5.0.815 (64-bit).

Radford, G. P., Morganstern, B. F., McMickle, C. W., and Lehr, J. K. (1994). The impact of four conferencing formats on the efficiency and quality of small group decision making in a laboratory experiment

setting. *Telematics and Informatics*, 11(2):97–109.

Raghunath, K., Rancour, D., and Mavris, D. N. (2014). Uncertainty propagation for a subsonic aircraft in a coupled fluid-structure interaction environment during conceptual design. In *15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, pages 1–10, Atlanta, United States of America. American Institute of Aeronautics and Astronautics.

Rausch, E. and Anderson, C. (2011). Enhancing decisions with criteria for quality. *Management Decision*, 49(5):722–733.

Raymer, D. P. (2002). *Enhancing Aircraft Conceptual Design using Multidisciplinary Optimization*. Doctoral dissertation, Royal Institute of Technology, Stockholm, Sweden.

Raymer, D. P. (2016). Rdswin: Seamlessly-integrated aircraft conceptual design for students & professionals. In *54th AIAA Aerospace Sciences Meeting*, page 1277.

Reckzeh, D. and Wijn, L. (2019). The intelligent wing: Multifunctional flaps on the A350XWB and the way to future concepts. *Leonardo Times*, 23(1):10–11.

Rittel, H. W. J. and Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences*, 4(2):155–169.

Robert, L. P., Dennis, A. R., and Ahuja, M. K. (2008). Social Capital and Knowledge Integration in Digitally Enabled Teams. *Information Systems Research*, 19(3):314–334.

Rochford, L. (1991). Generating and Screening New Product Ideas. *Industrial Marketing Management*, 20(4):287–296.

Roelofs, M. and Vos (2018a). Multi-fidelity multidisciplinary analyses, design and optimization tools. Technical Report D-A-4.1.2.2-1, Delft University of Technology, Delft, The Netherlands.

Roelofs, M. and Vos, R. (2018b). Technology Evaluation and Uncertainty-Based Design Optimization: A Review. In *2018 AIAA Aerospace Sciences Meeting*, pages 1–21, Kissimmee, United States of America. American Institute of Aeronautics and Astronautics.

Ronghui, P. and Jianbiao, L. (2011). The analysis of procedural justice in decision-making teams and decision quality. In *2011 International Conference on E-Business and E-Government (ICEE)*. IEEE.

Rose, M., Yaralian, H., Wagster, J., and Bhandari, S. (2012). Development and Validation of Flight Dynamics Model of a UAV Airplane. In *Infotech@Aerospace 2012*, pages 1–12, Garden Grove, United States of America. American Institute of Aeronautics and Astronautics.

Ruhstaller, T., Roe, H., Thürlimann, B., and Nicoll, J. J. (2006). The multidisciplinary meeting: An indispensable aid to communication between different specialities. *European Journal of Cancer*, 42(15):2459–2462.

Rumsey, C. L. and Slotnick, J. P. (2014). Overview and Summary of the Second AIAA High Lift Prediction Workshop (Invited). In *52nd Aerospace Sciences Meeting*, pages 1–37, National Harbor, United States of America. American Institute of Aeronautics and Astronautics.

Sadraey, M. (2013). *Aircraft Design*. John Wiley & Sons, Ltd, Chichester, West Sussex, United Kingdom.

Salazar, A. J. (2009). Groupthink. In Littlejohn, S. W. and Foss, K. A., editors, *Encyclopedia of Communication Theory*, pages 460–462. SAGE Publications, Inc., Thousand Oaks, United States of America.

Saldaña, J. (2016). *The Coding Manual for Qualitative Researchers*. SAGE Publications Ltd, London, United Kingdom, 3rd edition.

Saldaña, J. (2011). *Fundamentals of Qualitative Research*. Understanding Qualitative Research. Oxford

University Press, Inc., New York, United States of America.

Salichon, M. and Tumer, K. (2013). A neuro-evolutionary approach to control surface segmentation for micro aerial vehicles. *International Journal of General Systems*, 42(7):793–805.

Salim, S. M., Ong, K. C., and Cheah, S. C. (2011). Comparison of RANS, URANS and LES in the Prediction of Airflow and Pollutant Dispersion. In *Proceedings of the World Congress on Engineering and Computer Science 2011*, volume II, pages 1–6, San Francisco, United States of America.

Sandelowski, M. (2000). Whatever Happened to Qualitative Description? *Research in Nursing & Health*, 23(4):334–340.

Sanitioso, R., Kunda, Z., and Fong, G. T. (1990). Motivated Recruitment of Autobiographical Memories. *Journal of Personality and Social Psychology*, 59(2):229–241.

Sassenberg, K., Landkammer, F., and Jacoby, J. (2014). The influence of regulatory focus and group vs. individual goals on the evaluation bias in the context of group decision making. *Journal of Experimental Social Psychology*, 54:153–164.

Sauter, V. L. (1999). Intuitive Decision-Making: Combining advanced analytical tools with human intuition increases insight into problems. *Communication of the ACM*, 42(6):109–115.

Sawyer, J. (1997). Information sharing and integration in multifunctional decision-making groups. In *Society of Judgment and Decision Making Annual Meeting, Philadelphia, PA*.

Schmidt, K. (2013). *A Semi-Analytical Weight Estimation Method for Oval Fuselages in Conventional and Novel Aircraft*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Schultz, B., Ketrow, S. M., and Urban, D. M. (1995). Improving Decision Quality in the Small Group: The Role of the Reminder. *Small Group Research*, 26(4):521–541.

Schulz-Hardt, S., Brodbeck, F. C., Mojzisch, A., Kerschreiter, R., and Frey, D. (2006). Group Decision Making in Hidden Profile Situations: Dissent as a Facilitator for Decision Quality. *Journal of Personality and Social Psychology*, 91(6):1080–1093.

Schulz-Hardt, S. and Mojzisch, A. (2012). How to achieve synergy in group decision making: Lessons to be learned from the hidden profile paradigm. *European Review of Social Psychology*, 23(1):305–343.

Schweiger, D. M., Sandberg, W. R., and Ragan, J. W. (1986). Group Approaches for Improving Strategic Decision Making: A Comparative Analysis of Dialectical Inquiry, Devil's Advocacy, and Consensus. *Academic of Management Journal*, 29(1):51–71.

Schwenk, C. R. and Cosier, R. A. (1993). Effects of Consensus and Devil's Advocacy On Strategic Decision□Making. *Journal of Applied Social Psychology*, 23(2):126–139.

Scott, J. (1990). *A Matter of Record*. Polity, Cambridge.

Scudder, J. N., Herschel, R. T., and Crossland, M. D. (1994). Test of a Model Linking Cognitive Motivation, Assessment of Alternatives, Decision Quality, and Group Process Satisfaction. *Small Group Research*, 25(1):57–82.

Selig, M. S. (2003). Low Reynolds Number Airfoil Design Lecture Notes.

Seretis, C., Mankotia, R., Goonetilleke, K., and Rawstorne, E. (2014). Quality assessment of decision – making in colorectal cancer multidisciplinary meetings. *Journal of B.U.O.N*, 19(4):913–916.

Shah, S., Arora, S., Atkin, G., Glynne-Jones, R., Mathur, P., Darzi, A., and Sevdalis, N. (2014). Decision-making in Colorectal Cancer Tumor Board meetings: Results of a prospective observational assessment. *Surgical Endoscopy and Other Interventional Techniques*, 28(10):2783–2788.

Sheffey, S., Tindale, R., and Scott, L. (1989). Information sharing and group decision-making. In *Midwestern Psychological Association Annual Convention, Chicago, IL*.

Siemens, Airbus and Rolls-Royce. airbus, rolls-royce, and siemens team up for electric future.

Simon, H. A., Dantzig, G. B., Hogarth, R., Piott, C. R., Schelling, T. C., Shepsle, K. A., Thaier, R., and Winter, S. (1987). Decision Making and Problem Solving. *Interfaces*, 17(5):11–31.

Simons, T. (1996). Executive Conflict Management: Keys to Excellent Decisions and Smooth Implementation. *Cornell Hotel and Restaurant Administration Quarterly*, 37(6):34–41.

Sinsay, J. D. and Nuñez, G. (2010). Toward Right-Fidelity Rotorcraft Conceptual Design. In *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, pages 1–14. American Institute of Aeronautics and Astronautics.

Smith, A. M. O. and Gamberoni, N. (1956). Transition, pressure gradient, and stability theory. Technical Report ES 26388, Douglas Aircraft Company.

Smith, G. F. (2003). Beyond Critical Thinking and Decision Making: Teaching Business Students How To Think. *Journal of Management Education*, 27(1):24–51.

Spalart, P. R. (2000). Strategies for turbulence modelling and simulations. *International Journal of Heat and Fluid Flow*, 21(3):252–263.

Squire, H. B. and Young, A. D. (1939). The Calculation of the Profile Drag of Aerofoils. Technical Report 1838, Aeronautical Research Committee, London, United Kingdom.

StareCat.com. This is true this is truth square circle please consider before talking typing. https://starecat.com/this-is-true-this-is-truth-square-circle-please-consider-before-talking-typing/. Accessed August 10th, 2019.

Stasser, G. and Titus, W. (1985). Pooling of unshared information in group decision making. *Journal of Personality and Social Psychology*, 48(6):1467–1478.

Steiner, I. D. (1972). *Group process and productivity*. Academic Press, New York, United States of America.

Stewart, D. D. and Stasser, G. (1995). Expert Role Assignment and Information Sampling During Collective Recall and Decision Making. *Journal of Personality and Social Psychology*, 69(4):619–628.

Stewartson, K. (1949). Correlated Incompressible and Compressible Boundary Layers. In *Proceedings of the Royal Society. Series A, Mathematical, Physical & Engineering Sciences*, pages 84–100.

Stückl, S., van Toor, J., and Lobentanzer, H. (2012). VoltAir - The All Electric Propulsio Concept Platform - A Visio for Atmospheric Friendly Flight. In *28th International Congress of the Aeronautical Sciences*, pages 1–11.

Sullivan, E. E., Ibrahim, Z., Ellner, A. L., and Giesen, L. J. (2016). Management Lessons for High-Functioning Primary Care Teams. *Journal of Healthcare Management*, 61(6):449–466.

Suwarantana, D. and Rodriguez, D. (2011). A More Efficient Conceptual Design Process Using the RAGE Geometry Modeler. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, pages 1–10, Reston, Virigina. American Institute of Aeronautics and Astronautics.

Swafford, T. W. (1980). Analytical Approximation of Two-Dimensional Separated Turbulent Boundary-Layer Velocity Profiles. Technical Report AEDC-TR-79-99, Arnold Air Force Station, Tennessee, United States of America.

Tableau Software, Inc. (2019). Tableau Desktop. https://www.tableau.com/. Professional Edition, Version 2019.2 (20192.19.0718.1543), 64-bit.

Tatineni, M. and Zhong, X. (1998). Numerical Simulations of Unsteady Low-Reynolds-Number Flows Over the APEX Airfoil. In *36th AIAA Aerospace Sciences Meeting and Exhibit*. American Institute of Aeronautics and Astronautics.

Taylor, C., Shewbridge, A., Harris, J., and Green, J. S. (2013). Benefits of multidisciplinary teamwork in the management of breast cancer. *Breast Cancer: Targets and Therapy*, 5:79–85.

Taylor, R. N. and Dunnette, M. D. (1974). Relative Contribution of Decision-Maker Attributes to Decision Processes. *Organizational Behavior and Human Performance*, 12(2):286–298.

The Boeing Company (2011). 737 engine and installation optimization drives lower fuel consumption. https://leehamnews.com/2012/02/10/boeing-max-v-airbus-neo-fan-size-and-optimizing-the-leap-for-max-part-2/. Accessed May 21st, 2018.

The MathWorks (2017). MATLAB. https://nl.mathworks.com/products/matlab.html. Versions R2017a (9.2.0.556344, win64), R2018b (9.5.0.944444, win64), R2018b Update 2 (9.5.0.1033004, win64), R2019a Update 4 (9.6.0.1150989, win64).

The MathWorks / Jan (2014). Filerename. https://nl.mathworks.com/matlabcentral/fileexchange/29569-filerename. Downloaded June 6th, 2019.

Thomas, J. B., Clark, S. M., and Gioia, D. A. (1993). Strategic Sensemaking and Organizational Performance: Linkages among Scanning, Interpretation, Action, and Outcomes. *The Academy of Management Journal*, 36(2):239–270.

Thomas, P. R. and Richardson, T. S. (2012). Estimation of Stability and Control Derivatives for a Piper Cub J-3 Remotely Piloted Vehicle. In *AIAA Modeling and Simulation Technologies Conference*, pages 1–26, Minneapolis, Minnesota. American Institute of Aeronautics and Astronautics.

Thorne, S., Kirkham, S. R., and Macdonald-Emes, J. (1997). Interpretive Description: A Noncategorical Qualitative Alternative for Developing Nursing Knowledge. *Research in Nursing & Health*, 20(2):169–177.

Thwaites, B. (1949). Approximate Calculation of the Laminar Boundary Layer. *Aeronautical Quarterly*, 1(3):245–280.

Tindale, R. S., Smith, C. M., Thomas, L. S., Filkins, J., and Sheffey, S. (1996). Shared representations and asymmetric social influence processes in small groups. *Understanding group behavior: Consensual action by smaill groups*, pages 81–103.

Ting-Toomey, S. (1988). Intercultural conflict styles: A face-negotaition theory. In Kim, Y. Y. and Gudykunst, W., editors, *Theories in intercultural communication*. Sage, Newbury Park, United States of America.

Ting-Toomey, S. and Kurogi, A. (1998). Facework Competentce in Intercultural Conflict: An Updated Face-Negotiation Theory. *International Journal of Intercultural Relations*, 22(2):187–225.

Toma, C. and Butera, F. (2009). Hidden profiles and concealed information: Strategic information sharing and use in group decision making. *Personality and Social Psychology Bulletin*, 35(6):793–806.

Torenbeek, E. (1982). *Synthesis of Subsonic Airplane Design*. Springer-Science+Business Media, B.V., Dordrecht, The Netherlands.

Torenbeek, E. (2013). *Advanced Aircraft Design - Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes*. John Wiley & Sons Ltd, Chichester, West Sussex, United Kingdom, 1st edition.

Triandis, H. C. (1995). *Individualism & Collectivism*. New Directions in Social Psychology. Westview Press / Perseus Books Group, Boulder, United States of America.

Triandis, H. C., McCusker, C., and Hui, C. H. (1990). Multimethod Probes of Individualism and Collectivism. *Journal of Personality and Social Psychology*, 59(5):1006–1020.

Tversky, A. and Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases. *Science*, 185(4157):1124–1131.

Um, K.-H. and Kim, S.-M. (2018). Collaboration and opportunism as mediators of the relationship between NPD project uncertainty and NPD project performance. *International Journal of Project Management*, 36(4):659–672.

Urquhart, R., Porter, G. A., and Grunfeld, E. (2011). Reflections on Knowledge Brokering Within a Multidisciplinary Research Team. *Journal of Continuing Education in the Health Professions*, 31(4):283–290.

U.S. Department of Defense (2002). Dod news briefing - secretary rumsfeld and gen. myers. http://archive.defense.gov/Transcripts/Transcript.aspx?TranscriptID=2636. Retrieved on March 8th, 2019.

van Bogaert, J. (2015). *Assessment of Potential Fuel Saving Benefits of Hybrid- Electric Regional Aircraft*. Master's thesis, Delft University of Technology.

van Craenenbroeck, J. (2016). *Boundary layer suction configurations with minimal pump requirements for multi-element airfoils*. Master's thesis, Delft University of Technology.

van de Vliert, E. and de Dreu, C. K. (1994). OPTIMIZING PERFORMANCE BY CONFLICT STIMULATION. *International Journal of Conflict Management*, 5(3):211–222.

van den Dungen, N. H. M. (2017). *Synthesis of an Aircraft Featuring a Ducted-Fan Propulsive Empennage*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Van Der Vegt, G. S. and Bunderson, J. S. (2005). Learning and Performance in Multidisciplinary Teams: The Importance of Collective Team Identification. *Academy of Management Journal*, 48(3):532–547.

van der Wees, A. J. and van Muijden, J. (1992). A robust quasi-simultaneous interaction method for a full potential flow with a boundary layer with application to wing/body configurations.

van Dommelen, J. and Vos, R. (2014). Conceptual design and analysis of blended-wing-body aircraft. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 228(13):2452–2474.

van Goozen, H. and Bastiaansen, A. (2017). MANTA project Technical KOM.

van Haver, S. F. G. and Vos, R. (2015). A Practical Method for Uncertainty Analysis in the Aircraft Conceptual Design Phase. In *53rd AIAA Aerospace Sciences Meeting*, number January, pages 1–14. American Institute of Aeronautics and Astronautics.

van Ingen, J. L. (2008). The e^{N} method for transition prediction. Historical review of work at TU Delft. In *38th Fluid Dynamics Conference and Exhibit*, pages 1–49, Seattle, United States of America. American Institute of Aeronautics and Astronautics.

van Riel, A. C. R., Semeijn, J., Hammedi, W., and Henseler, J. (2011). Technology-based service proposal screening and decision-making effectiveness. *Management Decision*, 49(5):762–783.

Van Swol, L. M., Savadori, L., and Sniezek, J. A. (2003). Factors That May Affect the Difficulty of Uncovering Hidden Profiles. *Group Processes & Intergroup Relations*, 6(3):285–304.

Verschuere, B., Meijer, E. H., Jim, A., Hoogesteyn, K., Orthey, R., McCarthy, R. J., Skowronski, J. J., Acar, O. A., Aczel, B., Bakos, B. E., Barbosa, F., Baskin, E., Bègue, L., Ben-shakhar, G., Birt, A. R., Blatz, L., Charman, S. D., Claesen, A., Clay, S. L., Coary, S. P., Crusius, J., Evans, J. R., Feldman, N., Ferreira-Santos, F., Gamer, M., Gomes, S., González-Iraizoz, M., Holzmeister, F., Huber, J., Isoni, A., Jessup, R. K., Kirchler, M., Selle, N., Koppel, L., Kovacs, M., Laine, T., Lentz, F., Loschelder, D. D., Ludvig, E. A., Lynn, M. L., Martin, S. D., McLatchie, N. M., Mechtel, M., Nahari, G., Özdog, A. A., Pasion, R., Pennington, C. R., Roets, A., Rozmann, N., Scopelliti, I., Spiegelman, E., Suchotzki, K., Sutan, A., Szecsi, P., Tinghög, G., Tisserand, J.-C., Tran, U. S., van Hiel, A., Vanpaemel, W., Västfjäll, D., Verliefde, T., Vezirian, K., Voracek, M., Warmelink, L., Wick, K., Wiggins, B. J., Wylie, K., and Yıldız, E. (2018). Registered Replication Report on Mazar, Amir, and Ariely (2008). *Advances in Methods and Practices in Psychological Science*, 1(3):299–317.

Vos, R. (2016). *FPPWiki - Synthesis/Initiator*. Delft, The Netherlands.

Vos, R. (2017). Aircraft Design Initiator: Some background information. https://brightspace.tudelft.nl/d2l/le/content/43778/viewContent/427651/View. Accessed September 28th, 2017.

Vos, R. and Farokhi, S. (2015). *Introduction to Transonic Aerodynamics*. Springer Science+Business Media B.V., Dordrecht, The Netherlands.

Vroom, V. H. and Yetton, P. W. (1973). *Leadership and Decision-Making*. University of Pittsburgh Press.

Waddell, B. D., Roberto, M. A., and Yoon, S. (2013). Uncovering hidden profiles: advocacy in team decision making. *Management Decision*, 51(2):321–340.

Walker, G. and Weber, D. (1984). A Transaction Cost Approach to Make-or-Buy Decisions. *Administrative Science Quarterly*, 29(3):373–391.

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P., and Krayer von Krauss, M. P. (2003). Defining Uncertainty: A Conceptual Basis for Uncertainty Management. *Integrated Assessment*, 4(1):5–17.

Wanous, J. P. and Youtz, M. A. (1986). Solution Diversity and the Quality of Group Decisions. *The Academy of Management Journal*, 29(1):149–159.

Wegner, D. M. (1987). Transactive Memory: A Contemporary Analysis of the Group Mind. *Theories of Group Behavior*, pages 185–208.

Weick, K. E. (1995). *Sensemaking in Organizations*. SAGE Publications, Thousand Oaks, California, United States of America.

Wenger, E. (2000). Communities of Practice and Social Learning Systems. *Organization*, 7(2):225–246.

Wikimedia Commons and Bewareircd (2009). Feigenbaumzoom.gif. https://commons.wikimedia.org/wiki/File:Feigenbaumzoom.gif. Downloaded July 28th, 2019.

Wikimedia Commons and de Campos, A. M.

Wikipedia (2008). Md-12-2. https://en.wikipedia.org/wiki/File:Md-12-2.png. Released under CC BY-SA 4.0. Downloaded May 22nd, 2018.

Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. The Free Press / Macmillan, Inc.

Winquist, J. R. and Larson Jr., J. R. (1998). Information Pooling: When It Impacts Group Decision Making. *Journal of Personality and Social Psychology*, 74(2):371–377.

Wittenbaum, G. M. (1998). Information Sampling in Decision-Making Groups: The Impact of Members' Task-Relevant Status. *Small Group Research*, 29(1):57–84.

Wittenbaum, G. M. (2000). The Bias Toward Discussing Shared Information: Why Are High-Status Group Members Immune? *Communication Research*, 27(3):379–401.

Wittenbaum, G. M., Hollingshead, A. B., and Botero, I. C. (2004). From cooperative to motivated information sharing in groups: Moving beyond the hidden profile paradigm. *Communication Monographs*, 71(3):286–310.

Wood, J. J., Metcalfe, C., Paes, A., Sylvester, P., Durdey, P., Thomas, M. G., and Blazeby, J. M. (2008). An evaluation of treatment decisions at a colorectal cancer multi-disciplinary team. *Colorectal Disease*, 10(8):769–772.

Yaniv, I. (2011). Group diversity and decision quality: Amplification and attenuation of the framing effect. *International Journal of Forecasting*, 27(1):41–49.

Zang, T. A., Hemsch, M. J., Hilburger, M. W., Kenny, S. P., Luckring, James, M., Maghani, P., Padula, S. L., and Jefferson Stroud, W. (2002). Needs and Opportunities for Uncertainty-Based Multidisciplinary Design Methods for Aerospace Vehicles. Technical Report TM-2002-211462, National Aeronautics and Space Administration, Hampton, United States of America.

Zhou, H., Xiao, L., Liu, Y., and Chen, X. (2018). The effect of prediscussion note-taking in hidden profile tasks. *Journal of the Association for Information Science and Technology*, 69(4):566–577.

Zohlandt, C. N. (2016). *Conceptual Design of High Subsonic Prandtl Planes*. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Ávila Filho, S., Costa Da Silva, C., and Oliveira De Sousa, C. (2013). Worker behavior changing by dynamic culture. In *AIChE 2013 - 2013 AIChE Spring Meeting and 9th Global Congress on Process Safety*.

A

Basic aerospace concepts and aircraft nomenclature

This appendix aims to provide readers unfamiliar with aerospace engineering with some basic concepts and corresponding nomenclature, useful for a better understanding of this thesis report. It is split up into two sections. Appendix A.1 treats the aircraft geometry and nomenclature and Appendix A.2 provides a basic understanding of the most important aerodynamic forces and moments.

A.1. Aircraft geometry and nomenclaure

This section treats the aircraft geometry and nomenclature, starting with the entire aircraft in Appendix A.1.1 and zooming in on the wing (in Appendix A.1.2) and wing cross-section or airfoil (in Appendix A.1.3).

A.1.1. Aircraft

Figure A.1 shows the primary components of a conventional airplane – one would use for travelling from The Netherlands to a holiday destination in the Mediterranean, for example.

Please note that – contrary to popular speech – the aircraft pictured has only one wing, which is composed from two half-wings extending on either side of the fuselage. A wingtip device is mounted on each wing tip.

The rearward part of the vertical stabiliser is the rudder; the rearward parts of the horizontal stabiliser are the elevators. The wing is equipped with ailerons, spoilers, slats and flaps, further discussed in the next section.

A.1.2. Wing

Figure A.2 shows the same aircraft as pictured in the previous section from above, indicating the components located on the wing and the two most important dimensions.

The **leading edge** (LE) is the ‘front’ of the wing; the **trailing edge** (TE) the ‘rear’. **Slats**, which increase lift during take-off and landing, are located at the leading edge. **Flaps**, used for the same purpose, are located at the trailing edge. **Ailerons** are also found at the trailing edge and are used for inducing a rolling moment (about the longitudinal axis of the aircraft), which is used to turn. On top of the wing, **spoilers** are located which come up after landing and are intended to disturb the flow (hence the name)

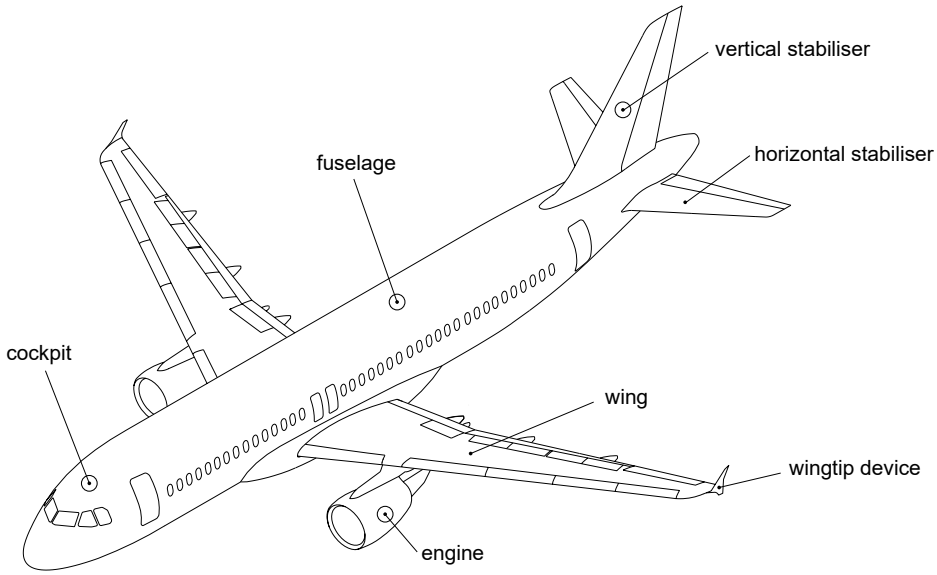


Figure A.1: Schematic 3D-view of an Airbus A320-200 with primary parts indicated (adapted from Airbus S.A.S. (1985))

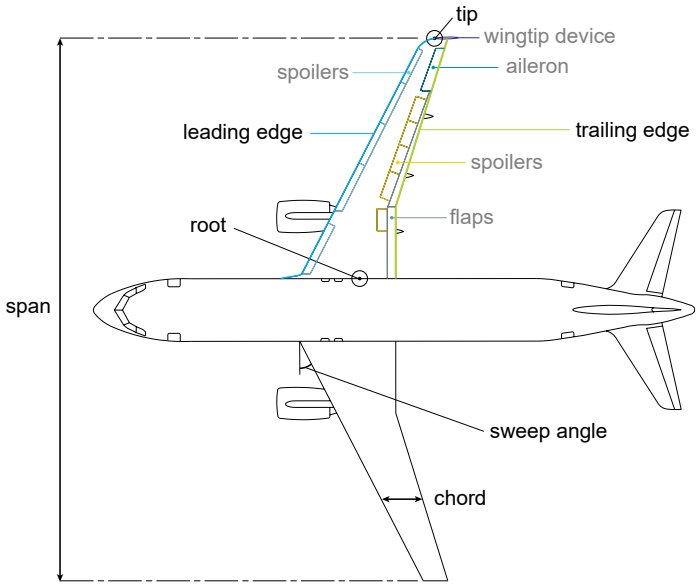


Figure A.2: Schematic top view of an Airbus A320-200 with wing components and dimensions indicated (adapted from Airbus S.A.S. (1985))

and thereby reduce lift. Sometimes, the spoilers are also used for changing direction (in addition to the ailerons). Larger aircraft often feature two ailerons per half-wing: one inboard (towards the fuselage) and one outboard (towards the tip). All these components together are indicated as the **wing movables**. At the tip, a **wingtip device** can be found, which aims to decrease drag by preventing higher-pressure air from below the wing to spill to the lower-pressure upper size – yielding a wing tip vortex.

The lower half-wing is simplified, in order to better show the relevant dimensions. Measuring a wing from tip to tip, the **span** (or wing span) is found. Measuring between leading and trailing edge – parallel to the fuselage – yields the **chord**. The chord at the root (where the half-wing connects to the fuselage) is the root chord; the chord at the tip is the tip chord. Connecting all points that are at 25% of the local chord length (measuring from the leading edge) yields the **quarter-chord line**. If the tip and root chord are divided by each other, the **taper ratio** is found.

In this case, the wing is swept. The **sweep angle** can be expressed at various locations. In the figure, the leading edge sweep angle is indicated. If no location is explicitly specified, the quarter-chord sweep angle (i.e., the sweep angle measured at the quarter-chord line) is meant. In case of an untapered wing (i.e., equal root and tip chord lengths), the sweep angle is the same – irrespective of whether it is measured at the leading edge, quarter-chord line or trailing edge. The use of sweep is that it delays the onset of shock waves and thereby reduces drags at high speeds.

The wing **surface** is the entire surface area of the wing, including the part that sits inside the fuselage. The **aspect ratio** (the slenderness of the wing, abbreviated as AR) is found by dividing the square of the wing span by the surface area.

A.1.3. Airfoil

The cross-section that is obtained when cutting a wing along a particular chord is the airfoil. An example of such an airfoil is shown in Figure A.3.

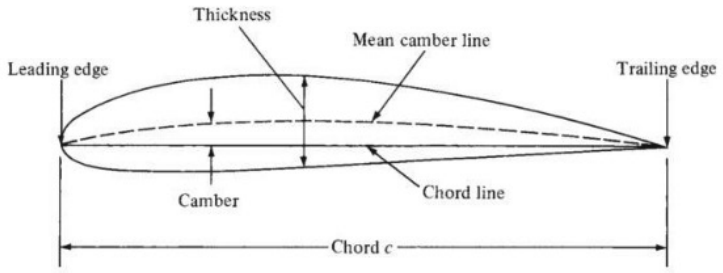


Figure A.3: Airfoil nomenclature (Anderson, 2005, p. 291)

It shows the already familiar leading and trailing edges, as well as the chord. Furthermore, it shows the **thickness** and the **camber**. The mean camber line is the geometrical middle between the bottom and the top; the chord line always is perpendicular to the leading edge. If an airfoil does not have any camber, it is called symmetrical. Airfoils with a thickness-over-chord ratio of 12% or less are generally regarded as **thin airfoils**.

Supercritical airfoils are a special type of cambered airfoils with a relatively flat upper section and a sharply curved trailing edge. Their geometry delays the onset of a shock wave. Because of this, supercritical airfoils produce less shock wave related drag compared to traditional (symmetrical or cambered) airfoils.

A.2. Aerodynamic forces

When an object moves through a fluid, the fluid exerts a force due to the pressure distribution of the fluid around the object. The component of this force that is perpendicular to the direction of the flow is called lift. In flight, it is equal and opposite to gravity, which points downward.

Similarly, an aircraft in slight sees drag, a force pointing rearward. This has to be overcome by thrust (pointing forward) in order to maintain a positive velocity. The ratio between lift and drag is a primary aerodynamic performance indicator, often referred to as aerodynamic efficiency.

Lift and drag on an airfoil are shown in Figure A.4.

As lift is generated by a pressure distribution and force is define as pressure times area, the lift depends on the surface area of the object. Moreover, the lift depends on the velocity and density of the flow, the shape of the object (in this case: the airfoil) and the angle of attack. The angle of attack is the angle

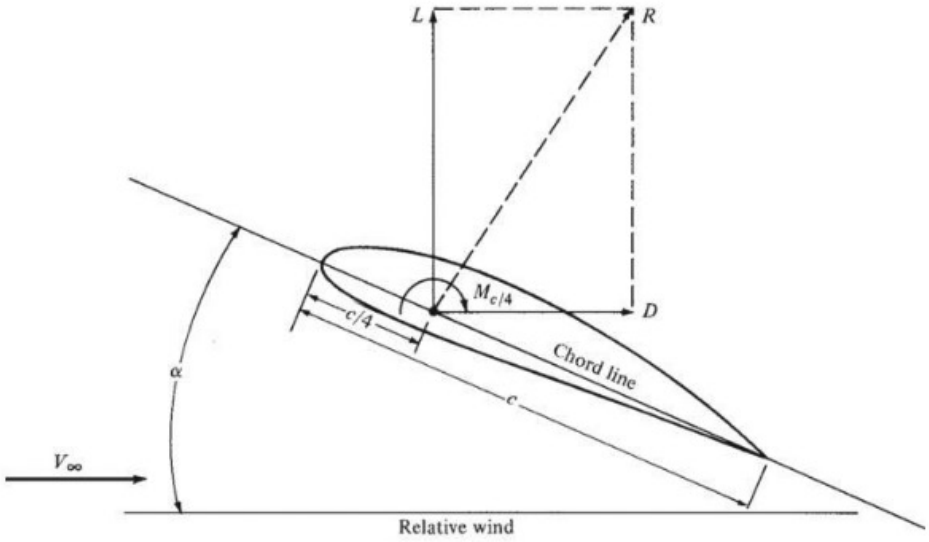


Figure A.4: Definition of lift, drag, moments and angle of attack (Anderson, 2005, p. 292)

between the direction of the flow and the local chord. As goes for the other parameters, a higher angle of attack yields more lift – until the flow separates. This is called the critical angle of attack.

Given the fact that aerodynamic forces result from a pressure distribution, there are also aerodynamic moments – caused by the shape of that pressure distribution relative to the point about which the aircraft rotates. For two-dimensional airfoils, the pitching moment – also indicated in Figure A.4 – is relevant. It is usually computed about the quarter-chord point. If it is positive, it means that an increase of angle of attack will generate a nose-up moment, increasing the angle of attack further. As that is an unstable situation, airfoils are generally designed to have a negative pitching moment coefficient. In that case, an increase in angle of attack yields a nose-down moment with reduces the angle of attack.

B

Literature review into influences on decision quality

In Section 3.2 a multitude of influences on decision quality is treated, answering *Which (kind of) flow models, solution methods and combinations thereof (i.e., solvers) are suitable for aerodynamic analysis in a conceptual design process?* This appendix documents the process used to gather, select and integrate results from literature and shows the 'raw data' that was retrieved. Appendix B.1 discusses the search and reading strategy (including search queries and exclusion criteria), Appendix B.2 treats how the found literature was processed and Appendix B.3 presents the data that was found.

B.1. Search and reading strategy

Aiming to yield a clearly demarcated yet complete set of influences into (group) decision making, it was decided to conduct a systematic literature review. This section discusses the search and reading strategy, detailing search queries and exclusion criteria.

B.1.1. Literature review 1

A first systematic literature review was done by searching both Scopus and Web of Science using the search query shown below, applied to the title, keywords and abstract[1].

```
(
    ( decision OR choice OR selection )
   W/3 ( quality OR performance OR effect* OR result )
)
AND ( multidisciplinary OR "multiple discipline*" )
W/5 ( team OR group OR shared OR panel OR workgroup )
```

230 results were retrieved using Scopus and 146 using Web of Science. After comparing document titles between the results of the two databases, 110 duplicates were removed, leaving 36 additions to the Scopus-set and yielding a total of 266 documents.

[1] The specific search operators vary between the two search engines. `X W/n Y` indicates that terms `X` and `Y` must appear within `n` words of each other.

Exclusion

Based on a review of title, keywords and abstract, 193 papers were excluded. The following exclusion criteria were used:

- too focused on subject content (e.g. factors that a physician uses to choose between two treatment options);
- objectives, aims or purposes not matching the area of interest, insofar as these were explicitly shown in the abstract (e.g. “Objectives: To explore Do Not Attempt Cardiopulmonary Resuscitation (DNACPR) policies from English acute, community and ambulance service” (Freeman et al., 2015));
- poorly written (e.g. “If quality of task performed in chemical industry is inadequate, a severe negative impact can happen [...]”, taken from the abstract of Ávila Filho et al. (2013)); and/or
- publication withdrawn.

It was explicitly decided not to exclude sources from other subject areas (such as medicine) in order to allow ideas from one discipline to cross over to the next. A prime example is the amount of research done into the effectiveness of multidisciplinary cancer care teams, which might not be applicable to an engineering and technology context one-to-one, but might very well give rise to new ideas.

Reading

During the review, publications that were not excluded were marked ‘green’ (21) or ‘yellow’ (52), depending on their estimated relevance (high or medium/partial). When searching for the content of these 73 remaining articles, 11 more were excluded because the full text could not be accessed, was not in the English or Dutch language, discussed a research setup rather than its results or documented the same research twice (a conference paper and a resulting article). According to the classification displayed in the Scopus/Web of Science records, the final set of 62 publications consisted of 44 articles, 9 conference papers, 6 reviews, 2 notes and 1 book section, of which 16 green and the remainder yellow.

The reviews were all read completely. Of the (other) green publications at least the abstract, introduction (or background) and conclusions were read, reading intermediate sections when deemed relevant or when looking for specific details (such as information on the amount of research participants). Based on the first results of this reading effort – relatively many recent publications, research is mainly done on specific case, *decision* quality and *decision making* quality are used interchangeably, research into the benefits of multidisciplinary decision making (in cancer care) shows heterogeneous results, leadership seems to play an important role in decision making – and the time this took, the reading strategy was adjusted. Rather than also reading the yellow texts in greater detail, this set of 46 documents was reduced to 17 titles based on discipline (only non-medical sources) and/or a second review of initial screening notes.

Follow-up snowball search

Of the 33 articles read in total, 18 sources referenced articles possibly relevant for further reading. Moving to a snowball search strategy, these sources led to three concepts suitable for follow up (but not linked to a direct reference) and 60 references. Of these 60, 6 sources could not be accessed and 9 sources were referenced by multiple source (yielding duplicates). Of the remaining 45 publications, 4 were already included in the initial literature search (and thoroughly read in that process), resulting in 41 new sources.

After screening the titles and reviewing the abstracts, a total of 25 articles was excluded based on title (13) or abstract (12), leaving 16 results. These were then read, focusing on abstract and introduction, conclusion and discussion sections. Ultimately, 10 sources were included.

Schematic overview

Figure B.1 shows a schematic overview of the review process documented above. It is inspired by the PRISMA-flowchart (Liberati et al., 2009), but extended to include the follow-up snowball search and visually adapted based on (Lamb et al., 2011b).

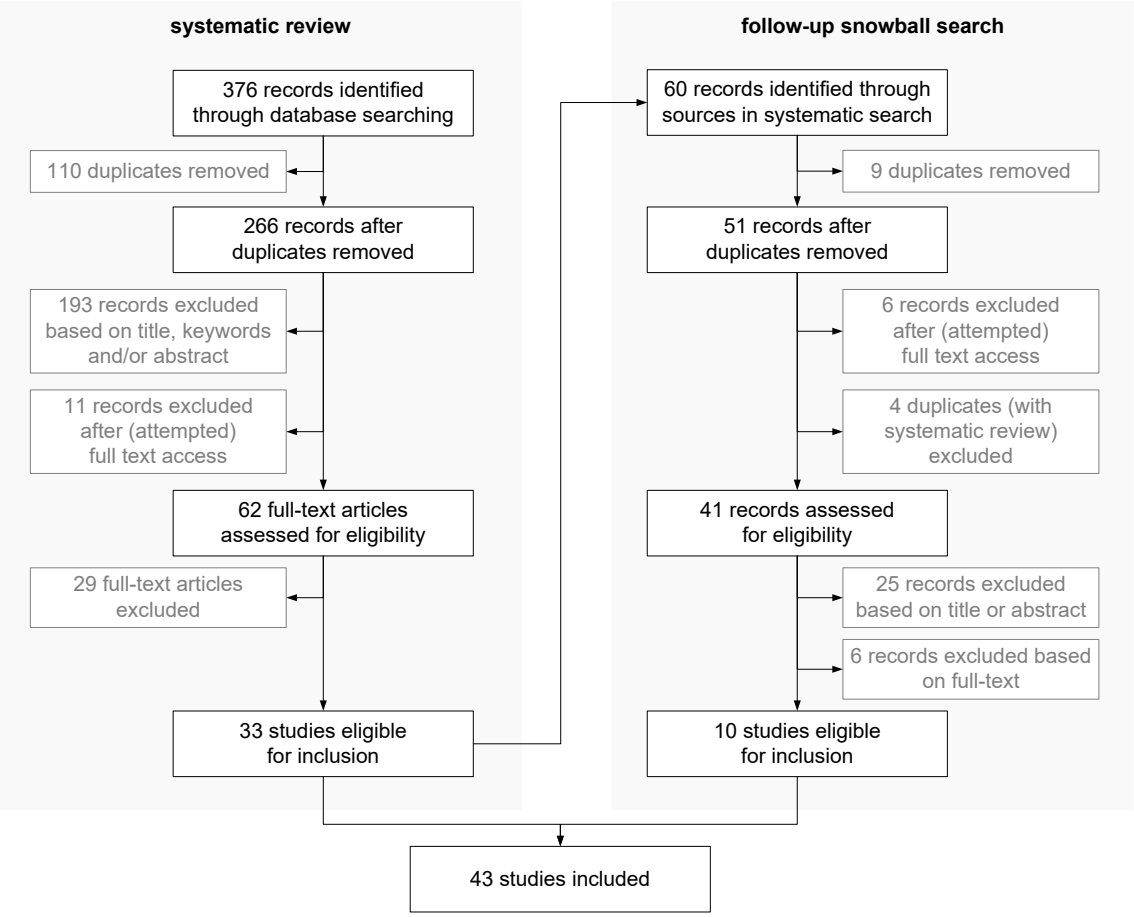


Figure B.1: Schematic representation of first literature review into influences on decision quality

B.1.2. Literature review 2

With a discussion of the differences between *teams* and *groups*, one of the articles following from the snowball search, Jones and Roelofsma (2000), inspired a new (structured) literature search. Orasanu and Salas (1993) explain the difference as "[t]eams consist of highly differentiated and interdependent members; groups, on the other hand, consist of homogeneous and interchangeable members, like juries", which Jones and Roelofsma further specify to *command and control team*, which is characterised by "specialist and interdependent roles" performing a "complex decision-rich task" (Jones and Roelofsma, 2000, p. 1132). With this, the term `AND (multidisciplinary OR "multiple discipline*")` from the initial structured search query might be redundant. As making that change results in multiple thousands of search results in Scopus[2], the query was simplified to the query below:

```
(
    ( decision W/2 quality )
    W/2 ( team OR group )
)
```

Furthermore, the subject fields were limited to exclude areas such as health care, nursing and medicine[3].

[2] `TITLE-ABS-KEY ( ( ( decision OR choice OR selection ) W/3 ( quality OR performance OR effect* OR result ) ) AND ( team OR group OR shared OR panel OR workgroup ) )` yielded 29.229 results on February 5th, 2018.

[3] In Scopus, `EXCLUDE ( SUBJAREA , "MEDI " ) OR EXCLUDE ( SUBJAREA , "NURS " ) OR EXCLUDE (`

In Scopus, this yielded 177 results, divided in 145 results for `group` and 32 for `team`. In Web of Science, 119 results were found, of which 97 for `group` and 22 for `team`. From the results for keyword `team`, 16 duplicates were found between the two search engines, in addition to 70 duplicates in the results for keyword `group`, leaving 172 and 38 unique results, respectively.

Exclusion

Based on title, keywords and abstract, 98 publications were rejected, based on the following exclusion criteria:

- research questions, objectives, aims or purposes not matching the area of interest, insofar as these were explicitly shown in the abstract;
- too small research populations, very specific case-studies or evaluations of particular (industry) tools;
- too different context (e.g. the influence of artificial intelligence for opinion aggregation (Bundzel et al., 2017), publications in the fields of law (Poama, 2013) or in a medical setting);
- too different group settings (e.g. a group that keep working together over multiple projects, initial meetings, temporary versus permanent group membership, online communities or virtual collaboration);
- too old, especially in case the set of publications contained more recent literature on the topic (e.g. about hidden profiles) or a study was deemed too exploratory;
- out of the research scope (e.g. the influence of gender (Kirchmeyer, 1996) or culture); and/or
- publication withdrawn or corrected.

Reading

Just as in the first literature review, papers were colour-coded during the review process. 39 papers were marked green, 49 yellow and a total of 24 publications was marked blue to flag these as possibly relevant for a later research phase. When searching for the content of these 88 remaining articles, 17 more were excluded because the full text could not be accessed or was not in the English or Dutch language. According to the classification displayed in the Scopus/Web of Science records, the final set of 71 publications consisted of 55 articles (including 2 in press), 11 conference papers, 2 reviews, 1 note and 2 book sections, of which 30 green and the remainder yellow.

Also similar to the previous part of this literature review, the reviews were read completely. Of the green papers, abstract, introduction and conclusion sections were read. Of the yellow publications, this was limited to only the abstract – unless the abstract did discuss relevant results (i.e., influences into decision quality) but was not immediately and completely clear. This was the case for 6 articles.

Follow-up snowball search

Following the publications read in the second literature review, 19 references were included in the review by means of a snowball search. After reading through these, 10 records were excluded, leaving 9.

Schematic overview

Figure B.2 shows a schematic overview of the review process documented above. It is inspired by the PRISMA-flowchart (Liberati et al., 2009), but extended to include the follow-up snowball search and visually adapted based on (Lamb et al., 2011b).

B.1.3. Additional references

Besides the systematic literature review conducted and described before, literature was gathered using three other sources or means: the research proposal (Peerlings, 2017), a further semi-systematic

`SUBJAREA , "AGRI " ) ` , in Web of Science, `NOT SU=(HOSPITALITY LEISURE SPORT TOURISM OR HEALTH POLICY SERVICES OR NURSING OR SOCIAL SCIENCES BIOMEDICAL OR HEALTH CARE SCIENCES SERVICES ) .`

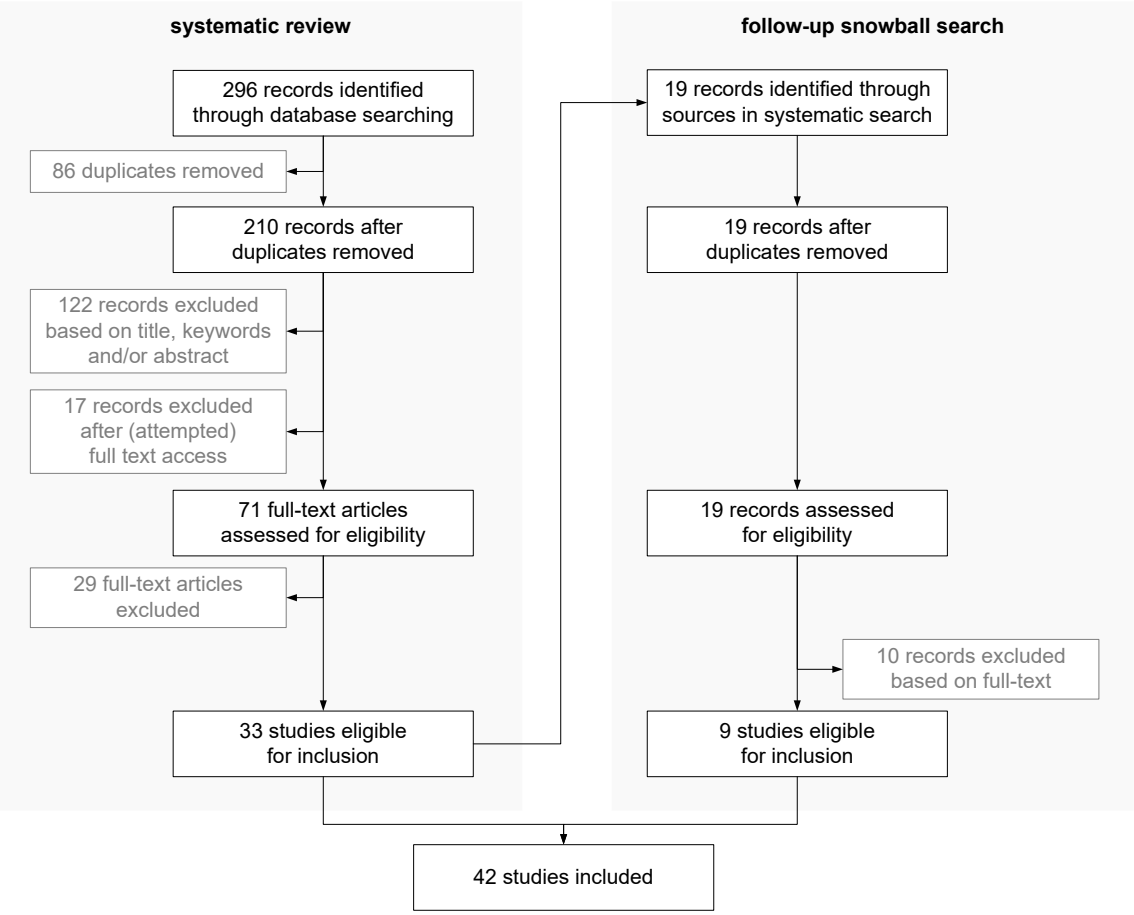


Figure B.2: Schematic representation of second literature review into influences on decision quality

review focusing on screening decisions and top management teams and the book *Theories of Human Communication* by Littlejohn et al. (2017, pp. 263-301).

Literature from research proposal

A total of 9 sources from the proposal underlying this research project (Peerlings, 2017) was re-read.

Literature review 3: Screening decisions

Based on specific information of project MANTA, an additional literature search was conducted to further zoom in on screening decisions (defined in Section 3.1.4 and top management teams (often the groups that make screening decisions) in particular. Results were found using a snowball search from Hammedi et al. (2011) (yielding 11 results), found when writing the research proposal cited above, and a literature search in Scopus. Given the earlier experience of this database providing most results, other databases were not consulted. The following query was used, which excluded medicine and nursing subject areas in order to remove research into e.g. cancer screening from the results.

```
TITLE-ABS-KEY ( "screening decision*" ) AND ( EXCLUDE ( SUBJAREA , "MEDI" ) )
AND ( EXCLUDE ( SUBJAREA , "NURS" ) )
```

This search yielded 146 search results. Given the relatively small amount of results, it was not deemed necessary to filter for *decision quality* in the query. Rather, it was decided to do this manually in the reading phase. Articles were excluded for treating any other topic than R&D portfolio management, new

product development and/or similar. This resulted in 13 publications, of which 2 documents could not be accessed (leaving 11). Edmondson et al. (2003) inspired to consult 4 additional sources.

Given the smaller amount of included literature, no colour-coded classification or reading strategy was used. Rather, the abstract, introduction and conclusion sections of all articles was read. In case these were found to be promising, other sections were read as well.

Textbook review

Lastly, the chapter focusing on group communication in the textbook *Theories of Human Communication* by Littlejohn et al. (2017, pp. 263-301) was reviewed for potentially relevant literature dealing with (the role of communication) in group decision making. This left 9 new documents. It also validated the inclusion of various theories and publications found through other means documented in this appendix.

B.2. Processing

All documents were read in NVivo (QSR International, 2017, 2019). Relevant portions of text were highlighted and coded into relevant categories, such as 'definition' (further split up into e.g. 'decision making', 'decision quality' and 'hidden profile') or 'factor of influence'. After each review (and associated follow-up search), the latter code (and sub-code) was accessed in order to build the results table shown in Appendix B.3.

B.3. Results

Appendix B.3 shows the findings of the literature search, which are summarised and analysed in Section 3.2. The following groups were assigned, using an open classification process:

- Contextual and supportive factors (abbreviated C)
- Technical factors (abbreviated T)
- Socio-psychological factors (abbreviated S)
- Implementation factors (abbreviated I)

Additional clustering is done using categories and sub-categories. Furthermore, each reference has been classified as shown by the symbols between square brackets.

Character 1: Context of the study. M for medical; E for engineering; B for business; G for general.

Character 2: Type of the reference. R for review (followed by the number of studies included, if explicitly specified); A for article; P for conference paper; B for book (or book section); E for essay or other opinionated piece.

Character 3: (optional) Type of the study. S for survey; I for interview; O for observation; E for experiment. Number(s) succeeding the letter(s) indicate the number of participants, if explicitly specified.

A word of caution regarding the number of sources is in place. As both (primary) articles as well as reviews have been included, some findings might appear multiple times. Due to time constraints, it was decided not to correct for this.

The column *Search* indicates whether the result was found in the first (1) or second (2) systematic literature review or the associated snowball searches following these, or included from the research proposal (P), the third literature review (3), or the book by Littlejohn et al. (2017) (T). For the second literature review, the *Search*-column also shows whether the result was found on the *team* (T) or *group* (G) keyword.

At the end of this appendix, Appendix B.3 shows a summarised version of the table, indicating the number of times factors in specific groups, categories and sub-categories were mentioned.

Table B.1: Results of literature search into influences on decision quality

Group	Category	Sub-category	Factor	Search	Reference	Notes
C	Facilities		Facilitating equipment	1	Taylor et al. (2013) [M; R]	For tele- / videoconferencing. Meeting results are comparable with face-to-face.
C	Facilities		Facilities	1	Lamb et al. (2011a) [M; R]	ICT equipment, tele- or videoconferencing equipment.
C	Medium		Communication medium	2G	Hollingshead (1996) [G; A; E159]	"Computer-mediated communication suppressed information exchange" (p. 193). Communication medium is *not* an influence according to Lu et al. (2012, p. 54).
C	Medium		Conferencing format	2G	Radford et al. (1994) [G; A; E204]	Face-to-face, audio or video versus computer channels
C	Procedures		Decision-making procedure	2G	Baartmans and Kosolosky (2015) [E; A]	Comparison of consensus, aggregation and deliberative acceptance. "We conclude that the last alternative […] is the most promising […] as this approach focuses on the quality of the discussion and therefore renders the greatest chance for making right decisions" (p. 371)
C	Procedures		Decision-making procedure	2G	Burleson et al. (1984) [G; A; E120]	
C	Procedures		Decision-making procedure	2G	Gillet et al. (2009) [B; A; E]	"in an environment with other players groups deciding by majority rule act more competitively than individuals while unanimous groups become more competitive with repetition" (p. 794)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
C	Procedures		Decision-making procedure	2G	Hirokawa (1982) [G; A; E162]	"hierarchically structured groups trained to use a majority rule strategy for decision-making tended to produce higher quality solutions than groups trained to use a consensus rule strategy for decision making" (p. 409, citing Falk (1981)). The relationship however depends "on whether or not consensus is reached through the use of a 'vigilant' decision-making strategy" (p. 413)
C	Procedures		Decision-making process	2G	Bakay et al. (2014) [B; A; S115]	"Satisfaction on decision process is expected to impact the group decision quality." (p. 349)
C	Procedures		Decision-making process	2G	Garvin and Roberto (2001) [B; A], in Coyle et al. (2015) [E; P]	"a process characterized by inquiry rather than advocacy tends to produce decisions of higher quality" (p. 2)
C	Procedures		Decision-making process	2G	Schweiger et al. (1986) [B; A; E120] in Waddell et al. (2013) [B; A; E100]	"the dialectical inquiry method led to higher quality decisions than the consensus method of group decision-making" (p. 324)
C	Procedures		Group decision processes	2G	Bakay et al. (2014) [B; A; S115]	
C	Procedures		Model ease-of-use	3	Baker and Albaum (1986) [G; A]	"there appears to be substantial resistance by new product decision makers to use complex models that are not easily understood or used" (p. 39).
C	Procedures		Procedural justice	2T	Ronghui and Jianbiao (2011) [B; P]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
C	Procedures		Procedural rationality	3	McNally et al. (2009) in Hammedi et al. (2011) [G; A; S126]	Through reflexivity (Hammedi et al., 2011).
C	Procedures		Structure of decision-making process	3	Priem et al. (1995) and Schweiger et al. (1986) in Edmondson et al. (2003) [G; A]	
C	Procedures		Task agreement	3	Mathieu et al. (2000) in Kerr and Tindale (2004) [G; R]	
C	Procedures		Task splitting	3	Kerr and Tindale (2004) [G; R]	Splitting into information search and integration / decision making.
C	Procedures		Team processes	1	Sullivan et al. (2016) [M; R]	"e.g., team meetings, clear goals and objectives, and audits to evaluate team effectiveness" (p. 454)
C	Resources		Resources	1	Hahlweg et al. (2017) [M; A; O]	"limited [...] resources make[s] patient-centered MDTM work hard to achieve" (p. 9)
C	Resources		Resources	1	Hamilton et al. (2017) [M; A]	"e.g., [...] financial support" (p. 55)
C	Resources		Resources	2T	Lin et al. (2017) [B; A; S264]	"defined as the extent to which teams have tangible means (e.g., tools and equipment) at their disposal in their immediate teamwork situation […]" (p. 2)
C	Time		Available time	3	Larson Jr. et al. (1994) in Kerr and Tindale (2004) [G; R]	Improves "the chance that unshared information is brought up during discussion" (p. 637).
C	Time		Time	1	Hahlweg et al. (2017) [M; A; O]	"limited time [...] make[s] patient-centered MDTM work hard to achieve" (p. 9)
C	Time		Time	1	Kidger et al. (2009) [M; A; I]	Time available for discussion.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
C	Time		Time	1	Lamb et al. (2011b) [M; R37]	Time available for preparation and discussion, excessive caseload. Higher workload and time pressure reduces attendance.
C	Time		Time	1	Lamb et al. (2012) [M; A]	Time pressure
C	Time		Time	1	Lamb et al. (2013) [M; A]	"longer time per case also was associated with higher contribution scores" (p. 718), "better-prepared cases are linked to better discussion and decision-making" (p. 720)
C	Time		Time	1	Taylor et al. (2013) [M; R]	Time pressure, excessive caseload
C	Time		Time pressure	T	Various, in Pavitt (2014) [G; R]	
C			Decision characteristics	1	Hamilton et al. (2017) [M; A]	"e.g., the urgency of the decision" (p. 55)
C			Importance of portfolio management	3	Cooper et al. (2001) [G; A]	
C			Incentive	2G	Kelly (2010) [B; A: E220]	Reward, based on either individual contribution or group result.
C			Pre-discussion note-taking	2G	Zhou et al. (2018) [G; A; E192]	"could facilitate information sharing but could not alleviate the biased information pooling in hidden profile tasks" (p. 566)
T	Information	Amount	Information amount	2G	Scudder et al. (1994) [G; A; E134]	"a larger pool of information about alternative choices leads to increased decision quality" (p. 77)
T	Information	Amount	Information load	2T	Mullins and Sabherwal (2014) G; P; S276]	Increase of information load has a positive effect unless the "information processing capacity of the decision maker is exceeded" (p. 3)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Availability	Access to comprehensive information	1	Lamb et al. (2013) [M; A]	
T	Information	Availability	Access to information during discussion	3	Sawyer (1997) and Sheffey et al. (1989) in Kerr and Tindale (2004) [G; R]	"rather than relying on memory" (p. 637).
T	Information	Availability	Data	3	Sauter (1999) and Smith (2003) in Albar and Jetter (2013) [G; A]	"do not have access to the type of input data that is required for advanced decision models" (p. 166)
T	Information	Availability	Inadequacy of sufficient information	3	Rochford (1991), Hsu et al. (2003) and Mohanty et al. (2005) in Chan and Ip (2010) [G; A]	
T	Information	Availability	Information availability	1	Seretis et al. (2014) [M; A; O64]	
T	Information	Availability	Information availability	1	Lamb et al. (2011b) [M; R37]	
T	Information	Content	Clinical characteristics	1	Hamilton et al. (2017) [M; A]	"e.g., education, counseling style" (p. 55)
T	Information	Content	Co-morbidities	1	Blazeby et al. (2006) [M; A; O]	Factor for not implementing a decision in 18/273 decisions.
T	Information	Content	Co-morbidity	1	Wood et al. (2008) [M; A; O201]	Factor for not implementing decision (9/201)
T	Information	Content	Demonstrated expertise	T	Various, in Pavitt (2014) [G; R]	
T	Information	Content	General health condition	1	Wood et al. (2008) [M; A; O201]	Factor for not implementing decision, "new clinical information" (p. 769) (2/201)
T	Information	Content	Information	1	Lamb et al. (2011c) [M; A; O164S47]	Imaging (radiological) and histopathological information.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Content	Information	1	Lamb et al. (2011d) [M; A; O112]	Imaging (radiological) and histopathological information.
T	Information	Content	Information about patients	1	Lamb et al. (2011a) [M; R]	
T	Information	Content	Information on patient co-morbidities	1	Lamb et al. (2011c) [M; A; O164S47]	
T	Information	Content	Information on patient co-morbidities	1	Lamb et al. (2011d) [M; A; O112]	
T	Information	Content	Knowledge about health situation	1	Hamilton et al. (2017) [M; A]	
T	Information	Content	Knowledge about treatment	1	Hamilton et al. (2017) [M; A]	Regarding options as well as outcomes.
T	Information	Content	More clinical information	1	Blazeby et al. (2006) [M; A; O]	Factor for not implementing a decision in 8/273 decisions.
T	Information	Content	Patient characteristics	1	Hamilton et al. (2017) [M; A]	“e.g., age, gender” (p. 55)
T	Information	Content	Relevant expertise	2G	House (1996) [G; A] in Bakay et al. (2014) [B; A; S115]	
T	Information	Content	Understanding of the problem situation	T	McLeod (2013) [G; A; E196]	
T	Information	Context	Case familiarity	1	Lanceley et al. (2008) [M; A; O53]	“whether a patient is known to the team” (p. 512)
T	Information	Context	Decision perspective	3	van Riel et al. (2011) [G; A; O251]	e.g. time horizon.
T	Information	Context	Information on patient preferences	1	Lamb et al. (2011c) [M; A; O164S47]	
T	Information	Context	Information on patient preferences	1	Lamb et al. (2011d) [M; A; O112]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Context	Support	1	Hamilton et al. (2017) [M; A]	"e.g., family opinions" (p. 55)
T	Information	Exchange	Exchange of hidden information	2G	Waddell et al. (2013) [B; A; E100]	
T	Information	Exchange	Exchange of unique information	T	McLeod (2013) [G; A; E196]	
T	Information	Exchange	Information asymmetry	3	Edmondson et al. (2003) [G; A]	
T	Information	Exchange	Information coverage	2G	Lu et al. (2012) [G; R65]	"the percentage of unique information mentioned out of total available information" (p. 54)
T	Information	Exchange	Information distribution	3	Edmondson et al. (2003) [G; A]	"asymmetric distributions of situation-specific information and interests will reduced TMT decision-making effectiveness" (p. 297)
T	Information	Exchange	Information distribution	2G	Lu et al. (2012) [G; R65]	Hidden profile or manifest profile
T	Information	Exchange	Information exchange amount	1	Kee et al. (2004) [M; A; SIO]	
T	Information	Exchange	Information repetition and emphasis	3	Larson Jr. et al. (1998b) in Edmondson et al. (2003) [G; A]	In hidden profile situations.
T	Information	Exchange	Information sampling rate	2G	Zhou et al. (2018) [G; A; E192]	Positive correlation with decision quality.
T	Information	Exchange	Information sharing	3	a.o. Winquist and Larson Jr. (1998) in Kerr and Tindale (2004) [G; R]	"pooled (discussed) unshared information did impact positively on group decision quality when groups were given a sufficient amount of time to reach consensus" (p. 637).

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Exchange	Intensity of knowledge exchange	2G	Atas et al. (2017) [G; B; E256]	"The more frequent information is exchange among group members, the higher the quality of the corresponding decision." (p. 368)
T	Information	Exchange	Knowledge sharing	2G	Stasser and Titus (1985) [G; A; E156] in Scudder et al. (1994) [G; A; E134]	
T	Information	Exchange	Processing intensity	2G	Schulz-Hardt and Mojzisch (2012) [G; R]	In hidden profiles.
T	Information	Exchange	Systematic attempts to combine task information	T	McLeod (2013) [G; A; E196]	
T	Information	Exchange	Task information exchange	T	Cruz (2000) and Van Swol et al. (2003) in McLeod (2013) [G; A; E196]	"the volume of task information exchanged over preference advocacy" (p. 630).
T	Information	Forecasting	Evidence-based practice	1	Bhugra et al. (2011) [M; A; I31]	
T	Information	Forecasting	Expectations about health situation	1	Hamilton et al. (2017) [M; A]	
T	Information	Forecasting	Expectations about treatment	1	Hamilton et al. (2017) [M; A]	Regarding options as well as outcomes.
T	Information	Forecasting	Forecasts	1	Chen et al. (2013) [G; A]	"Precise forecasting model"; "control of key forecasting parameters and random factors" (p. 207)
T	Information	Forecasting	Interaction with researcher	1	Urquhart et al. (2011) [M; A]	Interaction between decision-maker and researcher (knowledge brokering) supports evidence-based decision making.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Forecasting	Knowledge about options and outcomes	1	Elwyn and Miron-Shatz (2010) [M; A]	
T	Information	Forecasting	Outcome probabilities	1	Elwyn and Miron-Shatz (2010) [M; A]	
T	Information	Forecasting	Time	1	Chen et al. (2013) [G; A]	"Distance from the forecasting point and the current time point" (p. 207)
T	Information	Format	Information exchange format	1	Lamb et al. (2013) [M; A]	
T	Information	Format	Information presentation	1	Lamb et al. (2013) [M; A]	
T	Information	Multiple domains	Adequate specialist contributions	1	Shah et al. (2014) [M; A; O267]	
T	Information	Multiple domains	Information domains	1	Lamb et al. (2012) [M; A]	"coverage of all relevant domains of information for all patients" (p. 1760)
T	Information	Processing	Argument-based discussion	3	Hammedi et al. (2011) [G; A; S126]	
T	Information	Processing	Assessment of alternatives	2G	Hirokawa (1988) [G; A; E126]	Effective assessment of positive and negative qualities of the alternatives.
T	Information	Processing	Assessment of alternatives	2G	Hirokawa and Scheerhorn (1986) [G; B] in Schultz et al. (1995)	
T	Information	Processing	Assessment of choice-making situations	2G	Hirokawa and Scheerhorn (1986) [G; B] in Schultz et al. (1995)	
T	Information	Processing	Assessment of decision requirements	2G	Hirokawa (1988) [G; A; E126]	
T	Information	Processing	Assessment of the situation	2G	Hirokawa (1988) [G; A; E126]	Including problem analysis.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Processing	Attention to information mentioned by others	T	McLeod (2013) [G; A; E196]	
T	Information	Processing	Discussion of negative aspects of worst option	T	McLeod (2013) [G; A; E196]	
T	Information	Processing	Discussion of positive aspects of best option	T	McLeod (2013) [G; A; E196]	
T	Information	Processing	Evaluation of alternatives	2G	Hirokawa and Pace (1983) [G; A; E150]	
T	Information	Processing	Evaluation of negative aspects	T	Orlitzky and Hirokawa (2001) in McLeod (2013) [G; A; E196]	
T	Information	Processing	Evaluation of opinions and assumptions	2G	Hirokawa and Pace (1983) [G; A; E150]	
T	Information	Processing	Evaluation of positive/negative aspects of options	T	McLeod (2013) [G; A; E196]	
T	Information	Processing	Formal and systematic evaluation approach	3	De Brentani and Dröge (1988) in Chan and Ip (2010) [G; A]	
T	Information	Processing	Group assessment of alternatives	2G	Scudder et al. (1994) [G; A; E134]	Effect on decision quality and process satisfaction
T	Information	Processing	Group information processing	2G	Burtscher and Meyer (2014) [G; A; E180]	
T	Information	Processing	Information	2G	Nemeth and Rogers (1996) [G; A; E86]	Searching for information and processing available information

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Processing	Information interpretation	2G	”Weick (1995) [G; B] and Thomas et al. (1993) [M; A; S210] in Clark et al. (2000) [G; A]”	“Interpretation is an important component of the decision-making process and strongly influences decision quality” (p. 211)
T	Information	Processing	Information processing	T	Orlitzky and Hirokawa (2001) in McLeod (2013) [G; A; E196]	
T	Information	Processing	Information use	3	van Riel et al. (2011) [G; A; O251]	
T	Information	Processing	Processing alternatives	2G	Jackson et al. (2014) [G; P; S]	e.g. benefits and trade-offs of alternatives
T	Information	Processing	Processing information	2G	Jackson et al. (2014) [G; P; S]	e.g. search and analysis of information
T	Information	Processing	Subjective and inaccurate judgment	3	Chan and Ip (2010) [G; A]	
T	Information	Quality	Decisional premises	2G	Hirokawa and Pace (1983) [G; A; E150]	“groups which arrived at a high-quality decision tended to base their decisions on facts, assumptions, and inferences which appeared to be ‘grounded’ […], while groups which arrived at a low-quality decision tended to base their decisions on facts, assumptions, and inferences which were inaccurate and/or highly questionable” (p. 378)
T	Information	Quality	Inadequacy of concrete information	3	Rochford (1991), Hsu et al. (2003) and Mohanty et al. (2005) in Chan and Ip (2010) [G; A]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information	Quality	Information quality	1	Lamb et al. (2013) [M; A]	"specifically, improved information from case history, radiological, and pathological investigations" (p. 719)
T	Information	Quality	Quality of information	1	Hahlweg et al. (2017) [M; A; O]	
T	Information		Adequate information	1	Shah et al. (2014) [M; A; O267]	
T	Information		Data set with expert review of information	1	Lamb et al. (2011a) [M; R]	Radio- and pathological information.
T	Information		Information	1	Chen et al. (2013) [G; A]	"Immediate and rich information, including complete data from the past" (p. 207)
T	Information		Information	2G	Hirokawa and Scheerhorn (1986) [G; B] in Schultz et al. (1995)	
T	Information		Information	1	Lamb et al. (2012) [M; A]	
T	Information		Information	1	Taylor et al. (2013) [M; R]	
T	Information		Information gathering	1	Bhugra et al. (2011) [M; A; I31]	"Gathering accurate and detailed information was seen as the most important process in psychiatric decision making." (p. 406)
T	Information		Knowledge	1	Borches (2011) [E; B]	"companies need to take advantage of the knowledge they already have" (p. 122)
T	Information		Knowledge internalisation	2T	Lin et al. (2017) [B; A; S264]	"defined as the team process in which team members can discover relevant professional knowledge, obtain it, and then apply it in their teamwork" (p. 2)
T	Information		Reminders of varying information	T	McLeod (2013) [G; A; E196]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
T	Information		Training in information exploration	3	Larson Jr. et al. (1994), Wittenbaum (1998) and Wittenbaum (2000) in Kerr and Tindale (2004) [G; R]	
S	Cognitive reasoning	Bias		P	Kahneman et al. (2011) [B; A]	E.g. self-interested bias, affect heuristic, groupthink, saliency bias, confirmation bias, availability bias, anchoring bias, halo effect, sunk-cost fallacy, endowment effect, overconfidence, planning fallacy, optimistic biases, competitor neglect, disaster neglect, loss aversion. "knowing you have biases is not enough to help you overcome them" (p. 52)
S	Cognitive reasoning	Bias	Bias	1	Simon et al. (1987) [G; A]	"the empirical finding that decision makers often overreact to new information, in violation of Bayes's rule" (p. 17)
S	Cognitive reasoning	Bias	Bias	3	Tindale et al. (1996) and Kerr et al. (1999) in Kerr and Tindale (2004) [G; R]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Cognitive reasoning	Bias	Cognitive bias	1	Croskerry (2003) [M; A]	Aggregate bias, anchoring, ascertainment bias, availability, base-rate neglect (also Evans (2008)), commission bias, confirmation bias, diagnosis momentum, feedback sanction, framing effect, fundamental attribution error, gambler's fallacy, gender bias, hindsight bias, multiple alternatives bias, omission bias, order effects, outcome bias, overconfidence bias, playing the odds, posterior probability error, premature closure, psych-out error, representativeness restraint, search satisfying, Sutton's slip, sunk costs, triage cueing, unpacking principle, vertical line failure, visceral bias and Yin-Yang out.
S	Cognitive reasoning	Bias	Discussion bias	2G	Dennis (1996) [B; A; E126] and Stasser and Titus (1985) [G; A; E156] in Schulz-Hardt and Mojzisch (2012) [G; R]	In hidden profiles, discussion bias leads to more (less) introduction and repetition of shared (unshared) information. Furthermore, people value preference-consistent information more than preference-inconsistent information.
S	Cognitive reasoning	Bias	Evaluation bias	2G	Sassenberg et al. (2014) [G; A; E53]	
S	Cognitive reasoning	Bias	Information sampling / repetition bias	2G	Zhou et al. (2018) [G; A; E192]	Negative correlation with decision quality.
S	Cognitive reasoning	Bias	Processing bias	2G	Schulz-Hardt and Mojzisch (2012) [G; R]	In hidden profiles. People "tend to stick to their suboptimal initial preferences" (p. 327).

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Cognitive reasoning	Framing	Framing	1	Simon et al. (1987) [G; A]	Framing as a loss or as a gain.
S	Cognitive reasoning	Framing	Regulatory focus	2G	Burtscher and Meyer (2014) [G; A; E180]	"groups in a promotion focus [accomplishing rewards] solved more tasks correctly than groups in a prevention focus [avoiding punishment]" (p. 663)
S	Cognitive reasoning		(Managerial) heuristics	3	Albar and Jetter (2013) [G; A]	"managerial judgment seems to provide a quick and no-cost decision gate that is 'good enough'" (p. 183), but "[t]he reliance on managerial heuristics is recognised as a source of systematic decision errors" (p. 167), citing Andersen (2000) and Garvin and Roberto (2001)
S	Cognitive reasoning		Cognitive reasoning	1	Bhugra et al. (2011) [M; A; I31]	Including bias.
S	Cognitive reasoning		Groupthink	1	Jones and Roelofsma (2000) [G; R]	On social, organisational and individual level. Groupthink at higher levels can trickle down to teams, but can also arise directly at the team-level.
S	Cognitive reasoning		Groupthink	1	Kaba et al. (2016) [M; E]	
S	Cognitive reasoning		Groupthink	T	Salazar (2009) [G; B], based on Janis (1972)	
S	Cognitive reasoning		Intuition	1	Bhugra et al. (2011) [M; A; I31]	"Expert clinicians were more likely to rely upon intuition [...], novices described a more analytical approach." (p. 403)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Cognitive reasoning		Reasoning	2G	Hirokawa and Scheerhorn (1986) [G; B] in Schultz et al. (1995)	
S	Cognitive reasoning		Reasoning orientation	2G	Innami (1994) [G; A; E168], in Coyle et al. (2015) [E; P]	"the quality of group decisions increases to the extent that group members exchange facts and reasons (defined as 'reasoning' orientation of group verbal behavior) and decreases to the extent that group members stick to their positions (defined as a 'positional' orientation" (p. 409)
S	Discussion	Format	Discussion format	1	Kee et al. (2004) [M; A; SIO]	
S	Discussion	Format	Discussion format	1	Lamb et al. (2013) [M; A]	
S	Discussion	Openness	Debate with top management	2G	Simons (1996) [B; A; S183]	"nonconfrontation impedes [decision quality" (p. 41)
S	Discussion	Openness	Open and inclusive team discussion	1	Lamb et al. (2011c) [M; A; O164S47]	
S	Discussion	Openness	Open and inclusive team discussion	1	Lamb et al. (2011d) [M; A; O112]	
S	Discussion	Openness	Open discussion	1	Lamb et al. (2011a) [M; R]	
S	Discussion	Openness	Open expression of difference in an executive group	2G	Simons (1996) [B; A; S183]	
S	Discussion	Structure	Discussion structure	1	Kee et al. (2004) [M; A; SIO]	
S	Discussion	Structure	Discussion structure	1	Lamb et al. (2012) [M; A]	
S	Discussion		Constructive discussion	1	Seretis et al. (2014) [M; A; O64]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Discussion		Discussion focus	2G	Lu et al. (2012) [G; R65]	"the percentage of unique information out of total discussion" (p. 54)
S	Discussion		Discussion intensity	2G	Schulz-Hardt and Mojzisch (2012) [G; R]	In hidden profiles. Introduction and repetition of information, especially of unshared information.
S	Discussion		Discussion type	1	Kee et al. (2004) [M; A; SIO]	
S	Discussion		Effective group discussion	2G	Wanous and Youtz (1986) [G; A; E594]	
S	Discussion		Team discussion	2T	Park and DeShon (2010) [G; A; E171]	"Team discussion […] relates to minority influence, greater decision quality and team satisfaction" (p. 1)
S	Experience		Experience	1	Bhugra et al. (2011) [M; A; I31]	"Expert clinicians were more likely to rely upon intuition [...], novices described a more analytical approach." (p. 403)
S	Experience		Training in decision processes	2G	Schultz et al. (1995) [G; A; E262]	
S	Experience		Training in psychiatry	1	Bhugra et al. (2011) [M; A; I31]	
S	Fit	Client	Patient agreement	1	Elwyn and Miron-Shatz (2010) [M; A]	"agreement between patients' values and choices" (p. 142)
S	Fit	Client	Patient choice	1	Blazeby et al. (2006) [M; A; O]	Factor for not implementing a decision in 14/273 decisions.
S	Fit	Client	Patient preferences	1	Wood et al. (2008) [M; A; O201]	Factor for not implementing decision (7/201)
S	Fit	Client	Patients' holistic needs	1	Taylor et al. (2013) [M; R]	
S	Fit	Client	Personal values and preferences	1	Hamilton et al. (2017) [M; A]	Also called *value dis- or concordance*.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Fit	Organisation	Importance of compliance with policy initiatives	1	Lanceley et al. (2008) [M; A; O53]	
S	Fit	Organisation	Organisational fit	1	Fargason Jr. and Haddock (1992) [M; A]	"integrative solutions can reach high-quality decisions [...] more frequently" (p. 163)
S	Interaction		Vigilance	T	Salazar (2009) [G; B]	
S	Interaction		Vigilance training	T	Larson Jr. et al. (1998a) in McLeod (2013) [G; A; E196]	Or "reminders to follow vigilant interaction" (p. 632), citing Schultz et al. (1995).
S	Interaction		Vigilant interaction	T	McLeod (2013) [G; A; E196]	"discussion of task information, attention to other group members' information, discussion of positive and negative attributes of the alternatives, and systematic information processing" (p. 627). Especially in situations "where people as well as information are in different locations" (p. 629).
S	Interaction		Vigilant interaction	T	Oetzel (2017) [G; B]	"vigilant interaction theory argues that the quality of the group's interaction shapes the quality of the individual members' thinking which impacts on the quality of the decision-making of the group'" (p. 1)
S	Team	Communication	Communication	P	Ceschi et al. (2014) [B; A; E183]	
S	Team	Communication	Communication	2G	Hirokawa (1988) [G; A; E126]	Communication as a means to satisfy other conditions required for high-quality decision making.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Communication	Communication	1	Taylor et al. (2013) [M; R]	"Poor communication within the team […] can lead to disfunctional teamwork", "Communication with colleagues has been cited as a major source of stress in MDTs" (p. 82)
S	Team	Communication	Communication between team-members	1	Seretis et al. (2014) [M; A; O64]	
S	Team	Communication	Team communication	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Composition	Balance	1	Hamilton et al. (2017) [M; A]	"in decision experience, power, influence, emotions" (p. 57)
S	Team	Composition	Cohesiveness	2G	Mullen et al. (1994) [G; R17]	"the component of cohesiveness that appears to be critical for the emergence of groupthink is interpersonal attraction" (p. 189), as opposed to "commitment to task or group pride" (p. 189)
S	Team	Composition	Collaboration with top management	2G	Simons (1996) [B; A; S183]	
S	Team	Composition	Cross-functional teams	1	Fargason Jr. and Haddock (1992) [M; A]	Team decision making yields better results than single decision makers.
S	Team	Composition	Different perspectives	2G	Yaniv (2011) [G; A; E162]	"By assigning group members to different perspectives (framings of a problem), the susceptibility of groups to decision biases is reduced dramatically." (p. 48)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Composition	Dominance	2G	Bakay et al. (2014) [B; A; S115]	"when information is dominated by one or few members, the overall decision quality tends to be higher" (p. 347)
S	Team	Composition	Dominance	2T	Burris et al. (2009) [G; A; E204/E102]	"inner-circle members influence the groups' decisions more" (p. 1244)
S	Team	Composition	Dominance	1	Kee et al. (2004) [M; A; SIO]	E.g., lack of overly dominant team members.
S	Team	Composition	Domination	2G	Hirokawa and Pace (1983) [G; A; E150]	Dominant or influential group members can push their group towards a high-quality decision, or prevent this.
S	Team	Composition	Domination	1	Lanceley et al. (2008) [M; A; O53]	"MDM discussions are dominated by those with surgical, medical, or diagnostic expertise with limited contributions from those with a nursing, palliative, or psychosocial background." (p. 215)
S	Team	Composition	Group cohesiveness	T	Various, in Pavitt (2014) [G; R]	
S	Team	Composition	Group diversity	2G	Atas et al. (2017) [G; B; E256]	"the higher the diversity, the more information is exchange between group members" (p. 376), yielding higher quality decisions. Furthermore, higher diversity "can be regarded as a mechanism to counteract discussion biases" (p. 376).
S	Team	Composition	Group preference diversity	2G	Brodbeck et al. (2002) [G; A; E162]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Composition	Group size	2G	Lu et al. (2012) [G; R65]	"large group size helps groups with a high unique information ratio to outperform those with a low unique information ratio, whereas small group size has the opposite effect" (p. 70)
S	Team	Composition	Interest asymmetry	3	Edmondson et al. (2003) [G; A]	Leading to e.g. value-claiming behaviour, self-serving behaviour, interpersonal conflict (Amason, 1996; Jehn, 1995), etc.
S	Team	Composition	Involvement of different professional groups	1	Lamb et al. (2012) [M; A]	
S	Team	Composition	Multidisciplinary team influences	1	Bhugra et al. (2011) [M; A; I31]	
S	Team	Composition	Patient participation	1	Lamb et al. (2012) [M; A]	
S	Team	Composition	Postdiscussion preferences	T	Pavitt (2014) [G; R]	
S	Team	Composition	Prediscussion preference distribution	T	Various, in Pavitt (2014) [G; R]	
S	Team	Composition	Solution diversity	2G	Wanous and Youtz (1986) [G; A; E594]	"solution diversity seems to enhance decision quality, but may lower decision acceptance and group member satisfaction" (p. 156)
S	Team	Composition	Team cohesion	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Composition	Team composition	1	Lamb et al. (2011b) [M; R37]	"systematic input from nursing personnel would address some of the current shortcomings" (p. 2116)
S	Team	Composition	Team composition	1	Lamb et al. (2011a) [M; R]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Composition	Team composition	1	Lamb et al. (2013) [M; A]	"Higher quality of information and team contribution are themselves associated with [...] larger team size" (p. 719)
S	Team	Composition	Team composition	1	Malhotra et al. (2007) [E; A]	"Decision quality [...] depends upon the decision-makers level of expertise" (p. 182)
S	Team	Composition	Team composition	3	van Riel et al. (2011) [G; A; O251]	
S	Team	Composition	Team conflict / cohesion	1	Kidger et al. (2009) [M; A; I]	
S	Team	Composition	Team diversity	3	Chan and Ip (2010) [G; A]	"Individuals with different backgrounds, competencies, responsibilities, and interests speak different languages" (p. 973, citing Brereton and McGarry (2000)), yielding "conflicts and dissension" (p. 973).
S	Team	Composition	Team diversity	3	Mannix and Neale (2005) [G; R]	
S	Team	Composition	Team member competenties	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Composition	Team member personalities	1	Lamb et al. (2013) [M; A]	
S	Team	Conflict	Advocacy	3	Brodbeck et al. (2002) [G; A; E162] in Kerr and Tindale (2004) [G; R]	"for the alternative favored by unshared information" (p. 637).
S	Team	Conflict	Cognitive conflict	2G	Amason (1996) [G; A; SI] in Waddell et al. (2013) [B; A; E100]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Conflict	Competition	2T	Lin et al. (2017) [B; A; S264]	Competition within a team interferes with sense making, thereby reducing decision quality.
S	Team	Conflict	Competitiveness	2G	Gillet et al. (2009) [B; A; E]	"groups make qualitatively better decisions than individuals when there is no competition with other players in an inter-temporal common pool environment" (p. 794)
S	Team	Conflict	Conflict	2T	Lang et al. (2008) [G; R]	
S	Team	Conflict	Conflict	2G	van de Vliert and de Dreu (1994) [G; A]	"conflict stimulation enhances performance when conflict focuses on task issues, when tension level is low, and when disputants' goals are positively interdependent" (p. 211)
S	Team	Conflict	Decisional conflict	1	Hamilton et al. (2017) [M; A]	"e.g., uncertainty about the course of action" (p. 55)
S	Team	Conflict	Devil's advocacy	2T	Schwenk and Cosier (1993) [B; A; E152]	"devil's advocacy increased the commitment of high-consensus group members to the decisions their groups had reached" (p. 126)
S	Team	Conflict	Devil's advocacy	2G	Waddell et al. (2013) [B; A; E100]	"devil's advocacy groups achieved higher decision quality, [but] also had higher levels of affective conflict. As a result, while they selected the best solution, devil's advocacy […] may hinder the solution's implementation"
S	Team	Conflict	Devil's advocate	T	Salazar (2009) [G; B]	
S	Team	Conflict	External observation and challenging	T	Salazar (2009) [G; B]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Conflict	Intrateam task disagreement	2T	Chang and Yeh (2014) [G; A; S220]	"at a moderate level of intrateam task disagreement, the effectiveness of decision-making comprehensiveness will be highest" (p. 101)
S	Team	Conflict	Minority dissent	2G	Choi and Thompson (2005) [B; A; E66+E99], in Coyle et al. (2015) [E; P]	"a dissenting minority stimulates a majority to engage in a divergent thinking process which in turn results in better performance, decisions and creativity" (p. 123)
S	Team	Conflict	Minority dissent	2G	de Dreu et al. (2000) [G; A; S108]	
S	Team	Conflict	Minority dissent	2G	Nemeth and Rogers (1996) [G; A; E86]	"minority dissent stimulates a search for information" (p. 73)
S	Team	Conflict	Mutual interests	2G	House (1996) [G; A]	"When mutual interests among work unit members with respect to solving problems or making effective decisions exists or can be established, the group decision process will increase both decision quality and decision acceptance." (p. 342)
S	Team	Conflict	Pre-discussion dissent	2G	Schulz-Hardt et al. (2006) [G; A; E447]	Yields higher solution rates in hidden profile situations.
S	Team	Conflict	Pre-discussion dissent	1	Schulz-Hardt and Mojzisch (2012) [G; R]	
S	Team	Conflict	Reflexivity	3	Hammedi et al. (2011) [G; A; S126]	"develop a stop-and-think attitude among screening committee members" (p. 662), especially positive effect in early screening stages and under higher levels of complexity and uncertainty.

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Conflict	Relationship conflict	2T	Kotlyar et al. (2011) [B; A; E208]	
S	Team	Conflict	Task conflict	2T	Kotlyar et al. (2011) [B; A; E208]	
S	Team	Conflict	Team conflict	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Consensus	Ability to reach a decision	1	Lamb et al. (2012) [M; A]	
S	Team	Consensus	Agree on decision	1	Kidger et al. (2009) [M; A; I]	
S	Team	Consensus	Consensus	2T	Schwenk and Cosier (1993) [B; A; E152]	
S	Team	Consensus	Consensus on decisions	1	Lamb et al. (2011a) [M; R]	
S	Team	Consensus	Mechanisms for aggregating opinion	1	Lamb et al. (2013) [M; A]	
S	Team	Consensus	Opinion aggregation	1	Kee et al. (2004) [M; A; SIO]	
S	Team	Goals	Establishment of decision criteria and goals	T	McLeod (2013) [G; A; E196]	
S	Team	Goals	Establishment of goals and objectives	2G	Hirokawa and Scheerhorn (1986) [G; B] in Schultz et al. (1995)	
S	Team	Goals	Group goals	2G	Sassenberg et al. (2014) [G; A; E53]	
S	Team	Integration	Collective identification	P	Van Der Vegt and Bunderson (2005) [E; A; S] in Ceschi et al. (2014) [B; A; E183]	
S	Team	Integration	Group learning	P	Ceschi et al. (2014) [B; A; E183]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Integration	Knowledge integration	2T	Robert et al. (2008) [G; A; E172]	Knowledge integration is influenced by social capital ("structural, relational and cognitive" (p. 315))
S	Team	Integration	Team learning	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Integration	Transactive memory	P	Hammedi et al. (2013) [G; A; S136]	
S	Team	Integration	Transactive memory	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Integration	Transactive memory	3	Moreland (2006) in Edmondson et al. (2003) [G; A]	Reduces information asymmetry.
S	Team	Integration	Transactive memory	3	Wegner (1987) and Stewart and Stasser (1995) in Kerr and Tindale (2004) [G; R]	"Assigning group members to be responsible for certain categories of information and making sure that knowledge of who knows what is shared among the group" (p. 637), in hidden profile situations.
S	Team	Leadership	Leader	3	Larson Jr. et al. (1994) in Kerr and Tindale (2004) [G; R]	Can promote or aid in information sharing.
S	Team	Leadership	Leader information	2G	Henningsen et al. (2004) [G; A; E188]	"Overall, evidence is found indicating a leader's access to information and leader selection processes influence group discussions and decision quality" (p. 62)
S	Team	Leadership	Leader information	2G	Larson Jr. et al. (1998b) [G; A; E303]	"the information held by the leader prior to discussion interacted to influence group decision quality" (p. 482)
S	Team	Leadership	Leader style	T	Various, in Pavitt (2014) [G; R]	
S	Team	Leadership	Leadership	1	Shah et al. (2014) [M; A; O267]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Leadership	Leadership	2T	Burris et al. (2009) [G; A; E204/E102]	"leaders attended to and recalled suggestions from their inner circle more regardless of argument strength, suggesting heuristic information processing" (p. 1244)
S	Team	Leadership	Leadership	3	Hammedi et al. (2011) [G; A; S126]	Stimulating openness.
S	Team	Leadership	Leadership	2G	Kim et al. (1998) [B; P; E212]	"Objective decision quality […] was significantly better in groups with a leader" (p. 145)
S	Team	Leadership	Leadership	1	Lamb et al. (2011b) [M; R37]	
S	Team	Leadership	Leadership	1	Lamb et al. (2011a) [M; R]	
S	Team	Leadership	Leadership	1	Lamb et al. (2011d) [M; A; O112]	
S	Team	Leadership	Leadership	1	Lamb et al. (2013) [M; A]	
S	Team	Leadership	Leadership	2G	Mullen et al. (1994) [G; R17]	
S	Team	Leadership	Leadership	1	Taylor et al. (2013) [M; R]	
S	Team	Leadership	Leadership intervention	3	Larson Jr. et al. (1998b) in Edmondson et al. (2003) [G; A]	In hidden profile situations, to uncover unshared information.
S	Team	Leadership	Leadership micro-behaviour	2T	Meyer et al. (2016) [G; A; E165]	
S	Team	Leadership	Leadership style	2G	Chen et al. (1996) [G; A; E148]	"significantly lower quality decisions arose from groups with a directive rather than a participative leader" (p. 581)
S	Team	Leadership	Leadership style	1	Kee et al. (2004) [M; A; SIO]	
S	Team	Leadership	Leadership style	1	Kidger et al. (2009) [M; A; I]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Leadership	Leadership style	2G	Larson Jr. et al. (1998b) [G; A; E303]	"leadership style […] interacted to influence group decision quality" (p. 482)
S	Team	Participation	Group interaction	2G	Hirokawa and Rost (1992) [G; A; E]	"Specifically, […] group decision performance is directly related to a group's efforts to analyze and understand its task and objective(s) as well as identify the positive and negative qualities of alternative choices" (p. 267)
S	Team	Participation	Participation	2G	Bakay et al. (2014) [B; A; S115]	"the more participation in decision-making, the better group decision quality will be" (p. 347).
S	Team	Participation	Participation	2G	Clark et al. (2000) [G; A]	
S	Team	Participation	Participation	2G	House (1996) [G; A] in Bakay et al. (2014) [B; A; S115]	"appropriately balanced individual participation in [the] decision-making process is argued to be associated with the decision quality" (p. 337)
S	Team	Participation	Participation level	1	Kidger et al. (2009) [M; A; I]	
S	Team	Participation	Participation type	1	Kidger et al. (2009) [M; A; I]	
S	Team	Participation	Talkativeness	T	Various, in Pavitt (2014) [G; R]	
S	Team	Participation	Team attendance	1	Kee et al. (2004) [M; A; SIO]	
S	Team	Participation	Team attendance	1	Lamb et al. (2011b) [M; R37]	
S	Team	Participation	Team attendance	1	Lamb et al. (2011a) [M; R]	Lowered due to time commitments, scheduling conflicts or too little cases "to make attendance worthwhile" (p. 166)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team	Participation	Team attendance	1	Lamb et al. (2012) [M; A]	"presence of all core team members" (p. 1760)
S	Team	Participation	Team attendance	1	Lamb et al. (2013) [M; A]	
S	Team	Participation	Team attendance	1	Taylor et al. (2013) [M; R]	
S	Team	Participation	Team member contributions	1	Lamb et al. (2013) [M; A]	
S	Team	Structure	Role agreement / clarity	3	Mathieu et al. (2000) in Kerr and Tindale (2004) [G; R]	
S	Team	Structure	Roles clarity	1	Taylor et al. (2013) [M; R]	
S	Team	Structure	Team coordination	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Structure	Team regulation	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team	Structure	Team structure	1	Sullivan et al. (2016) [M; R]	"e.g., team members should be co-located, and the team should be small in size, occupationally diverse, have a leader, and be supported by the practice or organisation" (p. 454)
S	Team		Behavioural integration	2T	Carmeli and Schaubroeck (2006) [B; A; S116]	Behavioural integration includes "social integration […], frequency and quality of member exchange, and collaboration" (p. 442)
S	Team		Collective efficacy	T	Salazar (2009) [G; B]	
S	Team		Group atmosphere	T	Salazar (2009) [G; B]	
S	Team		Group confidence	2G	de Dreu and Beersma (2010) [G; A; E148]	Group confidence benefits (harms) decision quality when task ambiguity is low (high)

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team		Group member status	2G	Hollingshead (1996) [G; A; E159]	
S	Team		Quality of team process	1	Hahlweg et al. (2017) [M; A; O]	
S	Team		Status	T	Various, in Pavitt (2014) [G; R]	
S	Team		Team adaptation	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team affect, mood, and emotion	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team cooperation	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team culture	1	Sullivan et al. (2016) [M; R]	"dysfunctions of a team that build on each other in the following order: absence of trust, fear of conflict, lack of commitment, avoidance of accountability, and inattention to results" (p. 458-459)
S	Team		Team efficacy and group potency	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team mental models	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team performance dynamics	3	Kozlowski and Ilgen (2006) [G; R]	
S	Team		Team working	1	Lamb et al. (2011b) [M; R37]	
S	Team		Team working	1	Lamb et al. (2013) [M; A]	
S	Team		Team working skills	1	Kidger et al. (2009) [M; A; I]	
S	Team		Team working skills	1	Lamb et al. (2012) [M; A]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
S	Team		Unit and team climate	3	Kozlowski and Ilgen (2006) [G; R]	
S			Communication with patients and primary care	1	Lamb et al. (2011a) [M; R]	
S			Emotional behaviour	2G	Bakay et al. (2014) [B; A; S115]	"negative emotional behaviour is directly reducing the decision quality" (p. 347)
S			Evaluation	1	Chen et al. (2013) [G; A]	"Overall system thinking and rational decision-making evaluation" (p. 207)
S			Feedback	1	Chen et al. (2013) [G; A]	"Immediate and multi-frequency feedback rate in a decision-making process missile control model", which are "key factors of decision quality that influence the precision of the prediction" (p. 207)
S			Need for approval	T	Various, in Pavitt (2014) [G; R]	
S			Need for cognition	T	Various, in Pavitt (2014) [G; R]	
S			Psychological safety	3	Edmondson et al. (2003) [G; A]	Function of "interpersonal trust and mutual respect" (p. 306), yields feeling of safety to take risks (e.g., discuss possibly bad ideas)
S			Reminder function	2G	Schultz et al. (1995) [G; A; E262]	
S			Situational awareness	2T	Nowak and Pautasso (2013) [E; P; E]	
S			Trust in top management	2G	Simons (1996) [B; A; S183]	

Table B.1: Results of literature search into influences on decision quality (continued)

Group	Category	Sub-category	Factor	Search	Reference	Notes
I			Ability to implement a decision	1	Lamb et al. (2012) [M; A]	
I			Acceptance	P	Cross et al. (2009) [G; A]	"A 'good' or 'right' decisions is of little value if it is not accepted or acted on by employees or informal networks of employees." (p. 36)
I			Clarity of decision	1	Kidger et al. (2009) [M; A; I]	
I			Commitment	2T	Kotlyar et al. (2011) [B; A; E208]	"The highest quality decisions can be considered failures if their implementation never occurs due to lack of team commitment to enforcing their decisions" (p. 675)
I			Contribution	3	Various in Edmondson et al. (2003) [G; A]	Lack of contribution to a decision decreases commitment.
I			Implementation of MDT decision	1	Lamb et al. (2011a) [M; R]	
I			Recording of MDT decision	1	Lamb et al. (2011a) [M; R]	
I			Subordinate participation	3	Vroom and Yetton (1973) in Edmondson et al. (2003) [G; A]	Especially when they are required in the implementation phase.
I			Understanding decisions	2G	Jackson et al. (2014) [G; P; S]	e.g. satisfaction with decision-making process and clarity of argumentation
			Uncontrollable factors	1	Bhugra et al. (2011) [M; A; I31]	

Table B.2: Summarised results of literature search into influence on decision quality

Group	Category	Sub-category	Count
Contextual and supportive	Facilities		2
	Medium		2
	Procedures		16
	Resources		3
	Time		8
	Other		4
	Total		**35**
Technical	Information	Amount	2
		Availability	6
		Content	14
		Context	6
		Exchange	14
		Forecasting	8
		Format	2
		Multiple domains	2
		Processing	22
		Quality	4
		Other	9
	Total		**89**
Socio-psychological	Cognitive reasoning	Bias	8
		Framing	2
		Other	9
	Discussion	Format	2
		Openness	5
		Structure	2
		Other	7
	Experience		3
	Fit	Client	5
		Organisation	2
	Interaction		4
	Team	Communication	5
		Composition	31
		Conflict	20
		Consensus	6
		Goals	2

Table B.2: Summarised results of literature search into influence on decision quality (continued)

Group	Category	Sub-category	Count
		Integration	7
		Leadership	20
		Participation	14
		Structure	4
		Other	23
	Other		10
	Total		**191**
Implementation			8
Grand total			**323**

C

Uncertainty quantification and propagation toolkit

In order to quantify and propagate the uncertainties associated to numerical solution methods and aerodynamic flow models, the topic of Part I, a MATLAB toolkit was developed. Furthermore, the data visualisation program Tableau was used for analysis of the data. This appendix provides some details of the programming work conducted, with Appendix C.1 discussing how data was generated (using MATLAB) and Appendix C.2 treating how it was subsequently analysed (using MATLAB and Tableau).

C.1. Data generation (MATLAB)

Code listings can be accessed through GitLab. The repository is closed to the public, but access can be requested through https://gitlab.com/BramPeerlings/UQP_Toolkit. The repository includes a short user manual. Furthermore, the use of all scripts and functions is outlined in their header. A function for more rapidly moving files was obtained from the MathWorks File Exchange (The MathWorks / Jan, 2014).

The main method of interfacing with the toolkit is through a `RunSuite`-, `AnalysisSuite`- or `RunSuite_QP`-program, depending on the intended use. Both scripts use a consistently defined data structure, indicating which results to generate or analyse. These consists of the following fields:

- `solver`: solver(s)
- `airfoil`: geometry and representation(s) (spacing and number of coordinate points)
- `alpha`: angle(s) of attack
- `Re`: Reynolds number(s)
- `Mach`: Mach number(s)

In the `RunSuite_QP`-script, this structure is extended with fields which determine the coupling with 2D-results (`solver2D`), which aircraft or wing is analysed (`aircraft`) and at what Mach number AVL is run (`Mach_AVL`). This can be differed from the main Mach number to disable the three-dimensional Prandtl-Glauert correction.

In all cases, (partially solver-specific) structures control (run) settings and (analysis) output.

C.1.1. File overview

Besides the main *suites*, the toolkit consists of a set of other functions and programs, listed below. As the overview shows, some are responsible for interfacing with external solvers, whereas others are used to perform simple data manipulation tasks.

Geometry

- `CompareNACA0012.m`: script to compare NACA0012 geometries. Creates and saves plots.
- `CompareRAE2822.m`: script to compare RAE2822 geometries. Creates and saves plots.
- `FindCircumSpacing.m`: function to find circumferential spacing (distance between adjacent coordinate points) of airfoils.
- `FindCircumSpacingBatch.m`: script to use `FindCircumSpacing.m` in batch.
- `NACA0012.m`: function to generate NACA0012 geometry files, formatted according to specification required by the specified solver. Geometries are generated using the mathematical difference of the airfoil or based on hard-coded data (such as experimental measurements).
- `RAE2822.m`: function to generate NACA0012 geometry files, formatted according to specification required by the specified solver. Geometries are generated from hard-coded data, either a design specification or set of experimental measurements.
- `nonLinspace.m`: function to create a non-linear spacing, used by `NACA0012.m`.

CST-representation

- `EvaluateCST.m`: function to generate y-coordinates of a geometry defined by CST-coefficients.
- `EvaluateCSTError.m`: function to compare the result of `EvaluateCST.m` with a reference geometry and find the (mean) error.
- `OptimiseCST.m`: function to find CST-coefficients for a given geometry, by minimising the result of `EvaluateCSTError.m`.

Solvers

Each solver has their own wrapper:

- `AVL_par_seeker.m`: AVL-wrapper
- `MSES_par_seeker.m`: MSES-wrapper
- `VGK_par_seeker.m`: VGK-wrapper
- `XFOIL_par_seeker.m`: XFOIL-wrapper

The keyword `par` in the filename indicates that the wrapper (partly) executes in parallel. The keyword seeker in the filename indicates the wrapper tries minor angle-of-attack adjustments (defined in `settings.seeker`, in `RunSuite.m`) in case a value does not converge. For AVL, the seeker-bit is only used when running in coupled-2D-mode, where AVL does some seeking to determine the lift slope curve, if there are no converged 2D-results available at the specified angle of attack (and associated differencing bounds).

Furthermore, there are helper-scripts and -functions specifically related to a solver:

- `ApplyCompressibilityCorrection.m`: script to apply a compressibility correction (Prandtl-Glauert, Karman-Tsien or Laitone) to uncorrected data (from `UndoCompressibilityCorrection.m`). Also updates `cl`, `cpmin` and `x_cpmin`.
- `UndoCompressibilityCorrection.m`: script to compute the 'original'/uncorrected pressure coefficient distribution from a (Karman-Tsien) corrected distribution. Also updates `cl`, `cpmin` and `x_cpmin`.
- `AVL_UpdateStructs.m`: script to perform updates to the data-structs of AVL.

- `MSES_PlotGrid.m`: script to plot the streamlines of the computational grid of an MSES-run.
- `VGK_ShockAnalysis.m`: script to analyse shocks in terms of `dcp_dx`, shock strength and shock length, in order to help tune (or check) the parameters in `FindShock.m`.
- `VGK_ShockFix.m`: script to apply a bugfix regarding the shock location and strength determination to previously generated results.
- `VGK_PlotGrid.m`: script to plot the computational grid of a VGK-run.
- `XFOIL_cl.m`: function to compute `cl` from `cp` using the method employed in the XFOIL-code. Used by both `...CompressibilityCorrection`-scripts.
- `XFOIL_cm.m`: function to compute `cl` from `cp` using the method employed in the XFOIL-code. Used by both `...CompressibilityCorrection`-scripts.

_Shared

Analysis

- `AnalyseBrief.m`: function to read brief data, plot it and save these plots to file. It allows for comparison of up to two variables and is able to compute and plot the (absolute and relative) difference between two datasets.
- `AnalyseConsistency.m`: function to read brief data of multiple (identical) runs and compare the values of specified parameters for consistency. It allows to determine whether there is some form of variability in solver output.
- `AnalyseFull.m`: function to read full data, plot it and save these plots to file. It allows for comparison of up to two variables and is able to compute and plot the (absolute and relative) difference between two datasets.
- `AnalyseShock.m`: script to analyse shocks in terms of `dcp_dx`, shock strength and shock length, in order to help tune (or check) the parameters in `FindShock.m`. [Not completed / tested.]
- `ExportData.m`: script to read brief data and store the result in a database-like TXT and/or XLSX-file, for later analysis using Tableau or similar.
- `ExportData_UP.m`: script to read uncertainty propagation data and store the result in a database-like TXT and/or XLSX-file, for later analysis using Tableau or similar.
- `ExportData_UPbatch.m`: batch-version of `ExportData_UP.m`, useful for exporting data from a number of solvers.
- `ExportRefData.m`: script to read brief data (from a `.mat`-struct), compute/determine reference values from that brief data and store the result in a database-like TXT and/or XLSX-file, for later analysis using Tableau or similar.
- `FindShock.m`: script to find the position and strength of a shock wave. [Not completed / tested.]

(Experimental) data manipulation

- `CompareExperimental.m`: script that compares various variables (in the `brief`-struct) of NACA0012 experimental data.
- `CompareInterpolation.m`: script that compares the results of various interpolation methods applied to specified variables (`cd` and `cm`, currently) of NACA0012 experimental data. Outputs differences to screen.
- `ConvertAxisBase.m`: script to convert values expressed in one x-axis (e.g. `cd_cn`) to values expressed in another x-axis (e.g. `cd_alpha`), using a table lookup relation between the two axes (`cn_alpha`).
- `ConvertCnCl.m`: script to convert normal force coefficient `cn` to lift force coefficient `cl`.
- `InterpolateDragMoment`: script to interpolate `cd_a` and `cm_a`-values. Results of various interpolation methods can be compared with `CompareInterpolation.m`.
- `SetExperimentalAlpha.m`: script to to update angle-of-attack values of experimental datasets (NACA0012, Harris 1981) in `full`-structs in bulk, e.g. to round `alpha_in` to a particular value used in a comparison set.

- `SetMax.m`: script to save the maximums of particular vector-fields in the `brief`-struct in a dedicated field in that struct. Also saves the index at which that maximum occurs.
- `SetMaxLocalMach.m`: script to save (the maximum) local Mach number in to the `brief`- and `full`-structs.

Data saving, plot export, graphics settings

- `ComparisonName.m`: script to combine comparison data in a text string, e.g. to be used as filename by `StorePlots.m`.
- `FileRename.m` and `FileRename.mex`: (MEX-)script to move and rename files. Much faster than `movefile`.
- `PlotData.m`: script to generate plots based on manually defined data, using the same format as the output by e.g. `AnalyseBrief`. Suitable for e.g. convergence plots and aerodynamic polars.
- `PlotData_Full.m`: script to generate plots based on manually defined data, using the same format as the output by e.g. `AnalyseBrief`. Suitable for pressure distributions.
- `PlotDifference.m`: function to create and store (absolute and relative) difference plots of data in the `brief`- and `full`-structs.
- `PlotSettings.m`: script to initialise plot-settings, such as colors and linetypes.
- `StorePlots`: script to store PDF- and PNG-versions of plots to the location specified in settings.loc.analysis.
- `StoreRunData`: script to store metadata of a solver run in a sub-directory of the location specified in settings.loc.out, as well as ordered forms of the `brief`- and `full`-structs.

File structuring and clean-up

- `CleanDataDirs.m`: script that cleans specified files from the data-directories, i.e. the solver-specific directories in `settings.loc.out`.
- `CleanGeomDir.m`: script that cleans specified files (such as geometry output `.dat`-files or PDF-plots) the geometry-directory, i.e. the directory specified in `settings.loc.geom`.
- `CleanWorkingDirs.m`: script that cleans specified files from the solver working directories, i.e. the solver-specific directories in `settings.loc.solver`.
- `EmptyDataDirs.m`: script that empties the solver-specific directories in `settings.loc.out`. Use with caution.
- `FolderControl.m`: script that adds the relevant folders (`control`, `general`, `shared`, `geom`, `solver`, `out` and `analysis` in `settings.loc`) to the MATLAB-path.
- `ListFilesFolders.m`: function that lists files and/or folders, possibly limited to a particular extension.
- `ReplaceFolderSubstr.m`: function that replaces substrings in the names of sub-folders of a specified directory. Used for removing and re-adding the datetimetimestamp.

Other

- `FindNearest.m`: script to find the value (and its index) in a vector (haystack) nearest to a specified value (needle). Proceed with caution in case of multiple-valued vectors (e.g. a cl-a-curve that has a cl-value at an a both before and after stall).
- `FindValueIndex.m`: script to find the (first) index of a particular value (needle) in a vector (haystack). CAUTION: Sometimes shows unpredictable performance.
- `GenerateRunNames.m`: script to generate a list of run names, in order to make it easier to check whether all runs have completed.
- `IsEqualDiff.m`: script to determine whether the difference between all elements of a vector is equal (whether the vector has a consistent step-size).
- `SetupRun.m`: script that performs initial tasks at the start of a solver run, such as copying the geometry to the solver working directory and creating the output folder.

- `StructDefLim`: script to set default values and (lower and upper limits) to struct-fields. Used for setting default values for solver-specific settings, at the start of the wrapper-files.

C.1.2. Data structures

Data generated in the various solvers is stored in two data structures. `brief` contains the results per test case (per angle of attack), `full` stores more detailed results per angle of attack and chordwise position. In order to simplify data comparison between solvers, the field names are largely consistent between (two-dimensional) solvers.

For `brief` and `full`, Table C.1 and Table C.2 show the field names, definition, data type and applicability to the solver for the two-dimensional cases. Table C.3 and Table C.4 provide the same information for the three-dimensional case. The fields are listed in the order as they appear.

`brief` - two-dimensional

Table C.1: Field overview in two-dimensional `brief` data structure

Field name	Definition	Data type	XFOIL	VGK	MSES
`name`	Name (input)	string	✓	✓	✓
`name_out`	Name (output)	string	✓	✓	✓
`shortname`	Short name	string (1D array)		✓	
`airfoil`	Geometry	string	✓	✓	✓
`spacing`	Spacing	string	✓	✓	✓
`panels`	Number of coordinate points	integer	✓	✓	✓
`solver`	Solver	string	✓	✓	✓
`Re`	Reynolds number	float	✓	✓	✓
`Mach`	Mach number	float	✓	✓	✓
`xtr`	Trip location	struct	✓	✓	✓
`Ncrit`	Critical e^N	integer	✓		✓
`conv`	Convergence flag	boolean	✓	✓	✓
`error`	Error flag	boolean	✓	✓	✓
`runtime`	Runtime	float (1D array)	✓	✓	✓
`alpha_in`	Angle of attack (input)	float (1D array)	✓	✓	✓
`alpha`	Angle of attack (analysed, i.e. including seeker-modifications)	float (1D array)	✓	✓	✓
`cl`	Lift coefficient	float (1D array)	✓	✓	✓
`cl_max`	Maximum lift coefficient	float	✓	✓	✓
`i_cl_max`	Index of maximum lift coefficient	integer	✓	✓	✓
`a_cl_max`	Angle of attack of maximum lift coefficient	float	✓	✓	✓
`cm`	Pitching moment coefficient	float (1D array)	✓	✓	✓

Table C.1: Field overview in two-dimensional `brief` data structure

Field name	Definition	Data type	XFOIL	VGK	MSES
`cd`	Drag coefficient	float (1D array)	✓	✓	✓
`cdf`	Friction drag coefficient	float (1D array)	✓	✓	✓
`cdp`	Pressure drag coefficient	float (1D array)	✓	✓	✓
`cdv`	Viscous drag coefficient	float (1D array)			✓
`cdw`	Wave drag coefficient	float (1D array)			✓
`cdw1`	Wave drag coefficient, first-order method	float (1D array)		✓	
`cdw2`	Wave drag coefficient, second-order method	float (1D array)		✓	
`cl_cd`	Lift-to-drag ratio	float (1D array)	✓	✓	✓
`cl_cd_max`	Maximum lift-to-drag ratio	float	✓	✓	✓
`i_cl_cd_max`	Index of maximum lift-to-drag ratio	integer	✓	✓	✓
`a_cl_cd_max`	Angle of attack of maximum lift-to-drag-ratio	float	✓	✓	✓
`cpmin`	Minimum pressure coefficient	float (1D array)	✓	✓	✓
`x_cpmin`	Chordwise location of minimum pressure point	float (1D array)	✓	✓	✓
`top_xtr`	Transition location, upper surface	float (1D array)	✓	✓	✓
`bot_xtr`	Transition location, bottom surface	float (1D array)	✓	✓	✓
`M_max`	Maximum local Mach number	float (1D array)	✓	✓	✓
`shock_up_auto_loc`	Automatically determined shock location(s), upper surface	float (2D array)		✓	✓
`shock_lo_auto_loc`	Automatically determined shock location(s), lower surface	float (2D array)		✓	✓
`shock_up_man_loc`	Manually determined shock location(s), upper surface	float (2D array)		✓	✓
`shock_lo_man_loc`	Manually determined shock location(s), lower surface	float (2D array)		✓	✓
`shock_up_auto_st`	Automatically determined shock strength(s), upper surface	float (2D array)		✓	✓
`shock_lo_auto_st`	Automatically determined shock strength(s), lower surface	float (2D array)		✓	✓
`shock_up_man_st`	Manually determined shock strength(s), upper surface	float (2D array)		✓	✓

Table C.1: Field overview in two-dimensional `brief` data structure

Field name	Definition	Data type	XFOIL	VGK	MSES
`shock_lo_man_st`	Manually determined shock strength(s), lower surface	float (2D array)		✓	✓

`full` - two-dimensional

Table C.2: Field overview in two-dimensional `full` data structure

Field name	Definition	Data type	XFOIL	VGK	MSES
`name`	Name (input)	string	✓	✓	✓
`name_out`	Name (output)	string	✓	✓	✓
`shortname`	Short name	string (1D array)		✓	
`airfoil`	Geometry	string	✓	✓	✓
`spacing`	Spacing	string	✓	✓	✓
`panels`	Number of coordinate points	integer	✓	✓	✓
`solver`	Solver	string	✓	✓	✓
`Re`	Reynolds number	float	✓	✓	✓
`Mach`	Mach number	float	✓	✓	✓
`s`	Angular coordinate	float (2D array)	✓	✓	✓
`x`	x-coordinate	float (2D array)	✓	✓	✓
`y`	y-coordinate	float (2D array)	✓	✓	✓
`cp`	Pressure coefficient	float (2D array)	✓	✓	✓
`p_p0`	Local static pressure / freestream stagnation pressure	float (2D array)		✓	
`UeVinf`	Velocity ratio	float (2D array)	✓		✓
`Dstar`	Boundary layer displacement thickness	float (2D array)	✓		✓
`Theta`	Boundary layer momentum thickness	float (2D array)	✓		✓
`Cf`	Skin-friction coefficient	float (2D array)	✓		✓
`H`	Boundary layer shape parameter	float (2D array)	✓	✓	✓
`Mach_l`	Local (boundary layer edge) Mach number	float (2D array)	✓	✓	✓

`brief` - three-dimensional

Table C.3: Field overview in three-dimensional `brief` data structure

Field name	Definition	Data type
`name`	Name (input)	string

Table C.3: Field overview in three-dimensional `brief` data structure (continued)

Field name	Definition	Data type
`name_out`	Name (output)	string
`wing`	Wing name	string
`airfoil`	Geometry	string
`spacing`	Spacing	string
`panels`	Number of coordinate points	integer
`solver`	Solver	string
`solver_2D`	Coupled two-dimensional solver	string
`Re`	Reynolds number	float
`Mach`	Mach number	float
`Mach_AVL`	Mach number, used by AVL ($= 0$ when P-G correction disabled)	float
`conv`	Convergence flag	boolean
`error`	Error flag	boolean
`runtime`	Runtime	float (1D array)
`alpha_in`	Angle of attack (input)	float (1D array)
`alpha`	Angle of attack (analysed, i.e. including seeker-modifications)	float (1D array)
`i_low`	Index of lower α-bound used to determine local lift slope	float (1D array)
`i_high`	Index of upper α-bound used to determine local lift slope	float (1D array)
`claf`	Lift slope scaling factor	float (1D array)
`dcl_da`	Lift slope	float (1D array)
`CX`	Total force coefficient in x-direction	float (1D array)
`CY`	Total force coefficient in y-direction	float (1D array)
`CZ`	Total force coefficient in z-direction	float (1D array)
`CL`	Lift coefficient	float (1D array)
`CL_max`	Maximum lift coefficient	float (1D array)
`i_CL_max`	Index of maximum lift coefficient	float (1D array)
`a_CL_max`	Angle of attack of maximum coefficient	float (1D array)
`CD`	Total drag coefficient	float (1D array)
`CDv`	Viscous drag coefficient	float (1D array)
`CDi`	Induced drag coefficient	float (1D array)
`Cl`	Rolling moment coefficient	float (1D array)
`Cl_p`	Rolling moment derivative	float (1D array)
`Cm`	Pitching moment coefficient	float (1D array)

Table C.3: Field overview in three-dimensional `brief` data structure (continued)

Field name	Definition	Data type
`Cn`	Yawing moment coefficient	float (1D array)
`Cn_p`	Yawing moment derivative	float (1D array)
`CL_CD`	Lift-to-drag ratio	float (1D array)
`CL_CD_max`	Maximum lift-to-drag ratio	float
`i_CL_CD_max`	Index of maximum lift-to-drag ratio	integer
`a_CL_CD_max`	Angle of attack of maximum lift-to-drag-ratio	float
`CLff`	Lift coefficient from far-field computation	float (1D array)
`CDff`	Drag coefficient from far-field computation	float (1D array)
`CYff`	Force coefficient in y-direction from far-field computation	float (1D array)
`e`	Oswald factor	float (1D array)

`full` - three-dimensional

Table C.4: Field overview in three-dimensional `full` data structure

Field name	Definition	Data type
`name`	Name (input)	string
`name_out`	Name (output)	string
`wing`	Wing name	string
`airfoil`	Geometry	string
`spacing`	Spacing	string
`panels`	Number of coordinate points	integer
`solver`	Solver	string
`solver_2D`	Coupled two-dimensional solver	string
`Re`	Reynolds number	float
`Mach`	Mach number	float
`Mach_AVL`	Mach number, used by AVL ($= 0$ when P-G correction disabled)	float
`alpha_in`	Angle of attack (input)	float (1D array)
`alpha`	Angle of attack (analysed, i.e. including seeker-modifications)	float (1D array)
`i_low`	Index of lower α-bound used to determine local lift slope	float (1D array)
`i_high`	Index of upper α-bound used to determine local lift slope	float (1D array)
`claf`	Lift slope scaling factor	float (1D array)
`dcl_da`	Lift slope	float (1D array)
`j`	Strip number	float (2D array)

Table C.4: Field overview in three-dimensional `full` data structure (continued)

Field name	Definition	Data type
`YLE`	y-coordinate of leading edge	float (2D array)
`c`	Chord length	float (2D array)
`s`	Surface area	float (2D array)
`c_cl`	Chord length × local lift coefficient	float (2D array)
`a_inc`	Incidence angle	float (2D array)
`cl_norm`	Normalised lift coefficient	float (2D array)
`cl`	Strip lift coefficient	float (2D array)
`cd`	Strip total drag coefficient	float (2D array)
`cdv`	Strip viscous drag coefficient	float (2D array)
`cm_c4`	Quarter-chord pitching moment coefficient	float (2D array)
`cm_LE`	Leading-edge pitching moment coefficient	float (2D array)
`cp_xc`	Location of centre of pressure	float (2D array)

C.2. Data analysis (Tableau)

Different Tableau workbooks have been used for the comparison of data in the uncertainty quantification and uncertainty propagation stages of this research, as well as during the grid generation study preceding those two phases. Besides generating the visualisations, Tableau was used to perform differencing and normalisation computations. The remainder of this section provides the most important details for each (set of) workbook(s).

C.2.1. Grid refinement study

The workbook `GridRefinement_2D` was used for the grid refinement study. As input, it takes two Excel-sheets: one with all solver results that were used to determine the reference data (i.e., all solutions corresponding to the data points in Figure 6.5), and another with the computed reference values (using MATLAB, `ExportRefData.m`). These are combined using a left join on airfoil, Mach number, angle of attack and solver.

C.2.2. Uncertainty quantification

The workbook `UncertaintyQuantification_XU-XPG-XKT-X-XL-V-MSES+REF` was used for comparing the results of the two-dimensional solvers. Two versions were used: one using the data from VGK (partially conservative), another using the data from VGK (non-conservative). With the exception of the input file that is loaded, the files are identical.

The workbook takes a two input files (Excel-sheets) per solver: one with the results of individual runs (i.e., `brief`-data), another with the reference data. The reference data worksheets are matched to their `brief`-counterparts using a left join on airfoil, Reynolds number, Mach number, angle of attack and solver. The `brief`-files of the different solvers included are combined using a left join on name (combining geometry type and representation, Reynolds number and Mach number) and angle of attack.

Numerous computations are performed in the Tableau-workbook. In order to enable batch updates to these computations (*calculated fields*, in Tableau-jargon), their names (`Calculation_`, followed by a number) were manually standardised according to a schematic including the type of calculation, the solver(s) involved and the quantity of interest. Using a 12- to 13-digit format structured as `A00B00C00D000`, the coding scheme is explained below.

For `A` equal to 2, 3 or 4, the computation shows:

2. Difference between result and reference value: $X_i - X_r$
3. Difference between result and reference value, normalised to reference: $(X_i - X_r)/X_r$
4. Difference between result and reference value, normalised to result: $(X_i - X_r)/X_i$

In this case, `B` represents the solver and `C` defines the quantity of interest. `D` is always equal to 2.

For `A` equal to 5, 7, 9, 11, 12 or 13 the computation shows:

5. Difference between results of two solvers: $X_{i,1} - X_{i,2}$
7. Difference between results of two solvers, normalised to solver 2: $(X_{i,1} - X_{i,2})/X_{i,2}$
9. Difference between results of two solvers, normalised to solver 1: $(X_{i,1} - X_{i,2})/X_{i,1}$
11. Difference between reference values of two solvers: $X_{r,1} - X_{r,2}$
12. Difference between reference values of two solvers, normalised to reference 2: $(X_{r,1} - X_{r,2})/X_{r,2}$
13. Difference between reference values of two solvers, normalised to reference 1: $(X_{r,1} - X_{r,2})/X_{r,1}$

In this case, `B` indicates solver 2, `C` represents the quantity of interest and `D` shows solver 1.

For `A` equal to 6 or 8, the computation shows:

6. Difference between reference value and lower bound: $X_r - X_l$
8. Difference between reference value and upper bound: $X_r - X_u$

In this case, `B` represents the solver, `C` indicates the quantity of interest and `D` discerns between the lower (4) or upper (6) bound.

The solvers (used as `B` and/or `D`) are numbered as shown in the following list. The names and abbreviations (between parentheses) are used as written identifiers in the files, for example in the form of references to input files or in aliases of the calculated fields.

1. MSES (M)
2. VGK (V) (with partially- or non-conservative scheme, depending on which input file is used)
3. XFOIL (X): XFOIL, as output by the solver
4. XFOIL-KT (XKT): uncorrected XFOIL, plus Karman-Tsien compressibility correction
5. XFOIL-PG (XPG): uncorrected XFOIL, plus Prandtl-Glauert compressibility correction
6. XFOIL-L (XL): uncorrected XFOIL, plus Laitone compressibility correction
7. XFOIL-U (XU): uncorrected XFOIL

The quantities of interest (used as `C`) follow the numbering below. The field names correspond to the definitions presented in Table C.1. These field names are also used as aliases of the calculated fields.

1. `cl`
2. `cm`
3. `cd`
4. `cdf`
5. `cdp`
6. `cdv`
7. `cdw`
8. `cdw1`
9. `cdw2`

10. `cpmin`
11. `x_cpmin`
12. `top_xtr`
13. `bot_xtr`

C.2.3. Uncertainty propagation

The workbook `UncertaintyPropagation` was used for comparing the results of the wing-level uncertainty propagation effort using AVL. It takes as input one Excel-sheet per solver, including two[1] for the cases in which AVL was run independently of a set of two-dimensional results. The various input files are combined using a left join on wing, airfoil, spacing, panels (number of coordinate points), Reynolds number, Mach number and angle of attack.

Much alike the workbook used for the uncertainty quantification phase, the current workbook computes differences between various results and saves these in schematically named calculated fields. Using a 12-digit format structured as before (`A00B00C00D000`), `A` indicates the type of comparison, `B` defines solver 2, `C` shows the quantity of interest and `D` identifies solver 1. The numbering scheme is mostly identical to the code used for the uncertainty quantification part.

5. Difference between results of two solvers: $X_{i,1} - X_{i,2}$
7. Difference between results of two solvers, normalised to solver 2: $(X_{i,1} - X_{i,2})/X_{i,2}$
9. Difference between results of two solvers, normalised to solver 1: $(X_{i,1} - X_{i,2})/X_{i,1}$

The names and abbreviations (between parentheses) of solvers, incorporated into the field name as `B` and `D`, are used as written identifiers in the files, for example in the form of references to input files or in aliases of the calculated fields.

1. MSES (M): AVL + MSES
2. VGK (V): AVL + VGK, with partially-conservative scheme
3. XFOIL (X): AVL + XFOIL, as output by the solver
4. XFOIL-KT (XKT): AVL + uncorrected XFOIL, plus Karman-Tsien compressibility correction
5. XFOIL-PG (XPG): AVL + uncorrected XFOIL, plus Prandtl-Glauert compressibility correction
6. XFOIL-L (XL): AVL + uncorrected XFOIL, plus Laitone compressibility correction
7. XFOIL-U (XU): AVL + uncorrected XFOIL
8. decoupled (D): AVL, without coupling to a two-dimensional solver, with three-dimensional Prandtl-Glauert compressibility correction
9. decoupled-U (D-U): AVL, without coupling to a two-dimensional solver, without three-dimensional Prandtl-Glauert compressibility correction
10. VGK-NC (VNC): AVL + VGK, with partially-conservative scheme

The field names of quantities of interest `C` correspond to the definitions presented in Table C.3. These field names are also used as aliases of the calculated fields.

1. `CL`
2. `Cm`
3. `CD`
4. `CDv`
5. `CDi`
6. `CL_CD`
7. `dcl_da`

[1] One with and one without Prandtl-Glauert compressibility correction.

D

Numerical integration of pressure distributions

As detailed in Section 6.2.7, pressure distributions (either with or without a compressibility correction) obtained from XFOIL were numerically integrated with MATLAB to find the lift and pitching moment coefficient. Appendix D.1 shows the algorithms used, Appendix D.2 shows a comparison between the data as output by XFOIL versus the data numerically integrated using MATLAB.

D.1. Algorithms

Algorithm 1 was used to integrate the pressure distribution to lift coefficient, whereas Algorithm 2 was used to find the pitching moment coefficient. Both are implementations of the original XFOIL code (Drela and Youngren, 2013), more specifically subroutine `CLCALC` in `xfoil.f`, lines 1030 – 1110.

Algorithm 1 Numerical integration of pressure distribution to lift coefficient

$c_l = 0$

for $i = 1$ to $N - 1$ **do**
$d_x = x_{i+1} - x_i$
$d_y = y_{i+1} - y_i$
$D_X = d_x \cos(\alpha) + d_y \sin(\alpha)$

$C_{p,avg} = \left(C_{p,i+1} + C_{p,i}\right)/2$

$c_l = c_l + D_X \cdot C_{p,avg}$
end for

Algorithm 2 Numerical integration of pressure distribution to pitching moment coefficient

$x_{ref} = 0.25$
$y_{ref} = 0$

$c_m = 0$

for $i = 1$ to $N - 1$ **do**
$dx = x_{i+1} - x_i$
$dy = y_{i+1} - y_i$
$D_X = d_x \cos(\alpha) + d_y \sin(\alpha)$
$D_Y = d_y \cos(\alpha) - d_x \sin(\alpha)$

$a_x = \left[0.5\,(x_{i+1} - x_i) - x_{ref}\right]\cos(\alpha) + \left[0.5\,(y_{i+1} - y_i] - y_{ref}\right)\sin(\alpha)$
$a_x = \left[0.5\,(y_{i+1} - y_i) - y_{ref}\right]\cos(\alpha) + \left[0.5\,(x_{i+1} - x_i] - x_{ref}\right)\sin(\alpha)$

$C_{p,diff} = C_{p,i+1} - C_{p,i}$
$C_{p,avg} = \left(C_{p,i+1} + C_{p,i}\right)/2$

$c_m = c_m - D_X\left(C_{p,avg}a_x + C_{P,diff}D_X/12\right) - D_Y\left(C_{p,avg}a_y + C_{P,diff}D_Y/12\right)$
end for

D.2. Results

Figures D.1, D.2, D.5 and D.6 show the difference between the XFOIL results and the results obtained from MATLAB, using the algorithms shown in Appendix D.1. Figures D.3, D.4, D.7 and D.8 show these results normalised to the XFOIL results. In the normalised figures, angles of attack at or close to the zero-lift angle of attack ($\alpha = 0°$ for the NACA0012; $-2.25° \geq \alpha \geq -2°$ for the RAE2822) have been excluded, as relative differences would be unjustly magnified due to the low nominal value in the denominator. Furthermore, the angle of attack is limited to $-6° \geq \alpha \geq 6°$: as is suggested by the figures, the difference at $\alpha > 6°$ is too small to warrant graphical representation.

D.2.1. Lift coefficient

Difference

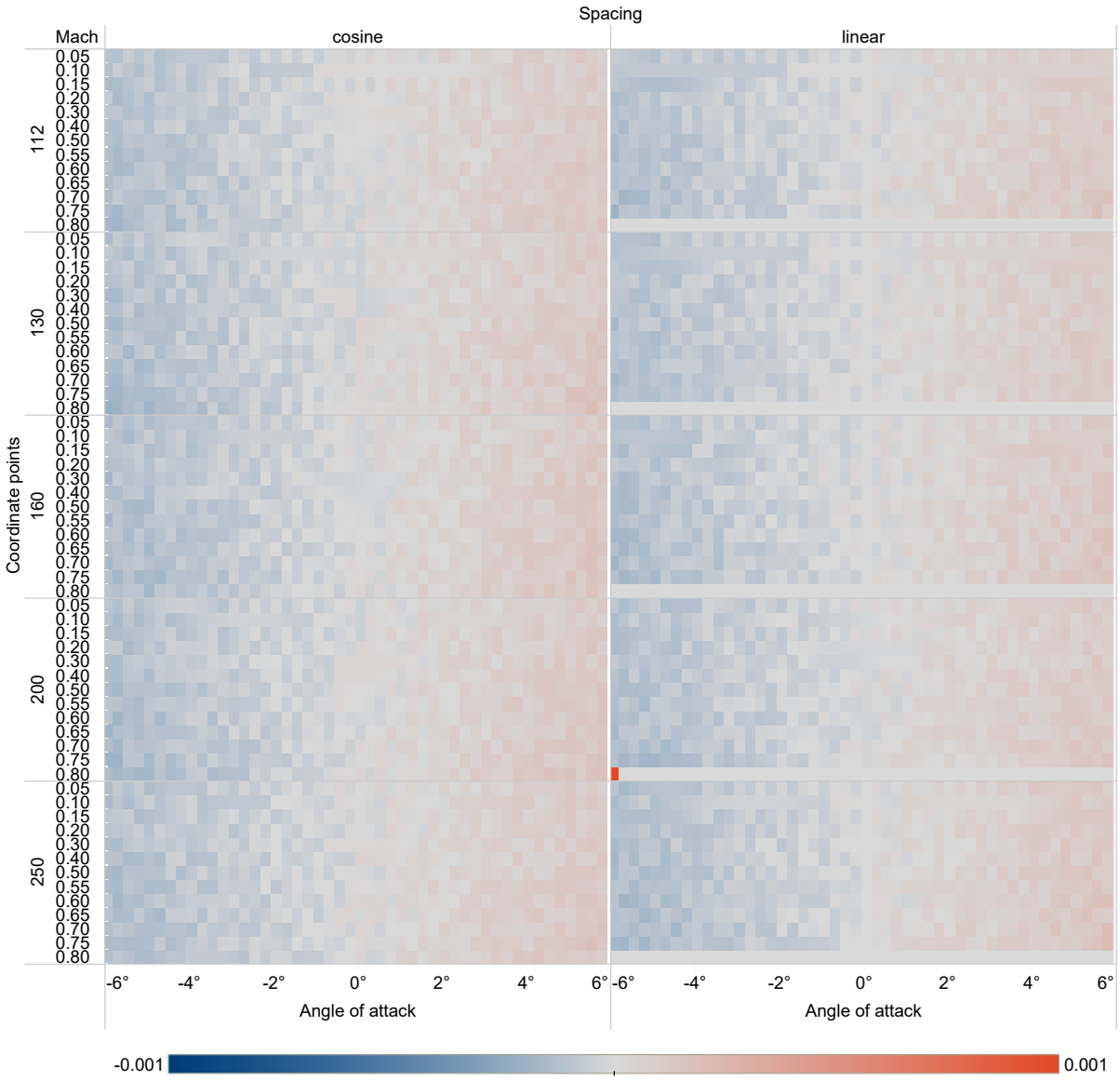


Figure D.1: Difference in lift coefficient between XFOIL results and manually integrated XFOIL results for NACA0012

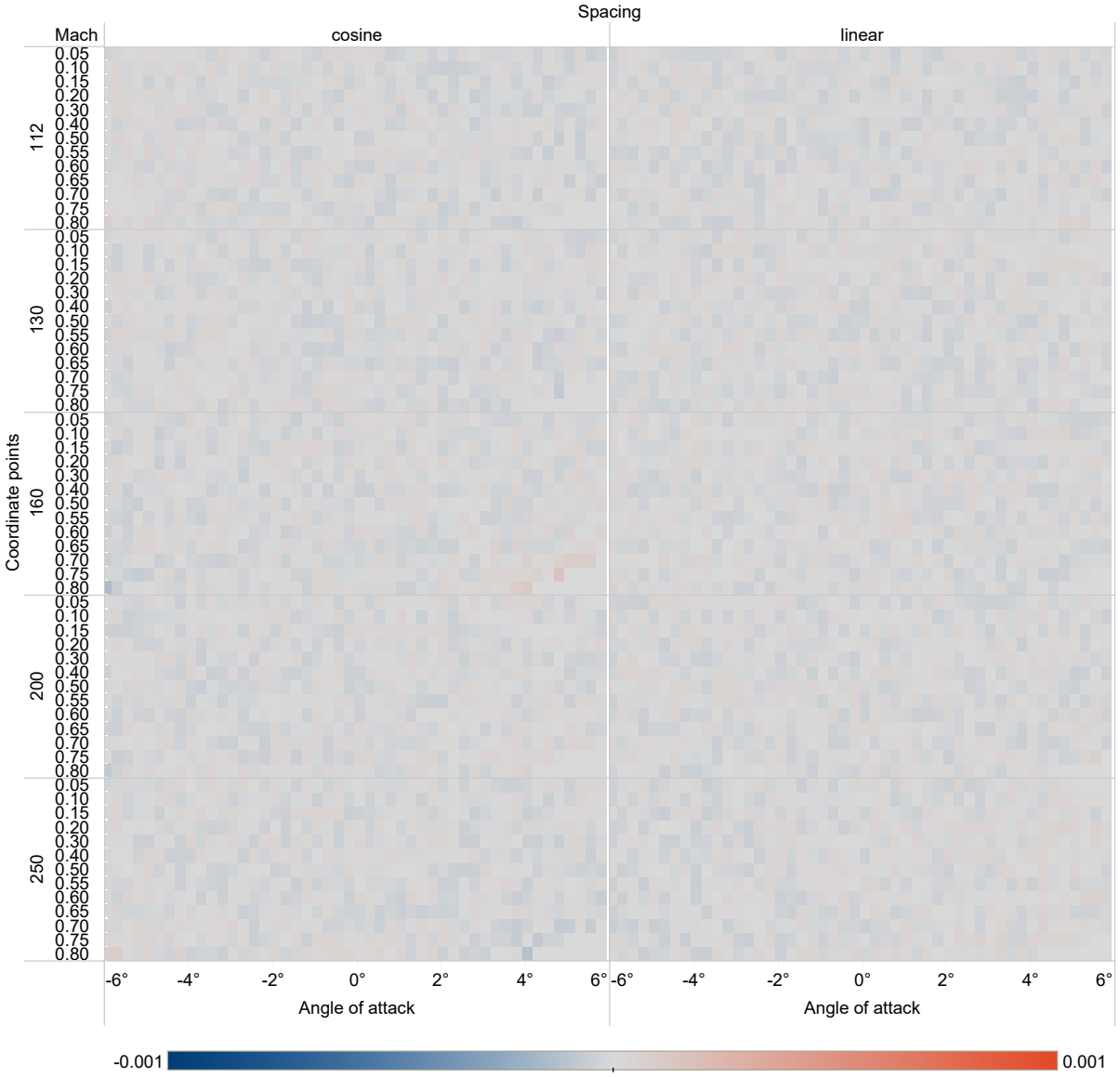


Figure D.2: Difference in lift coefficient between XFOIL results and manually integrated XFOIL results for RAE2822

Normalised difference

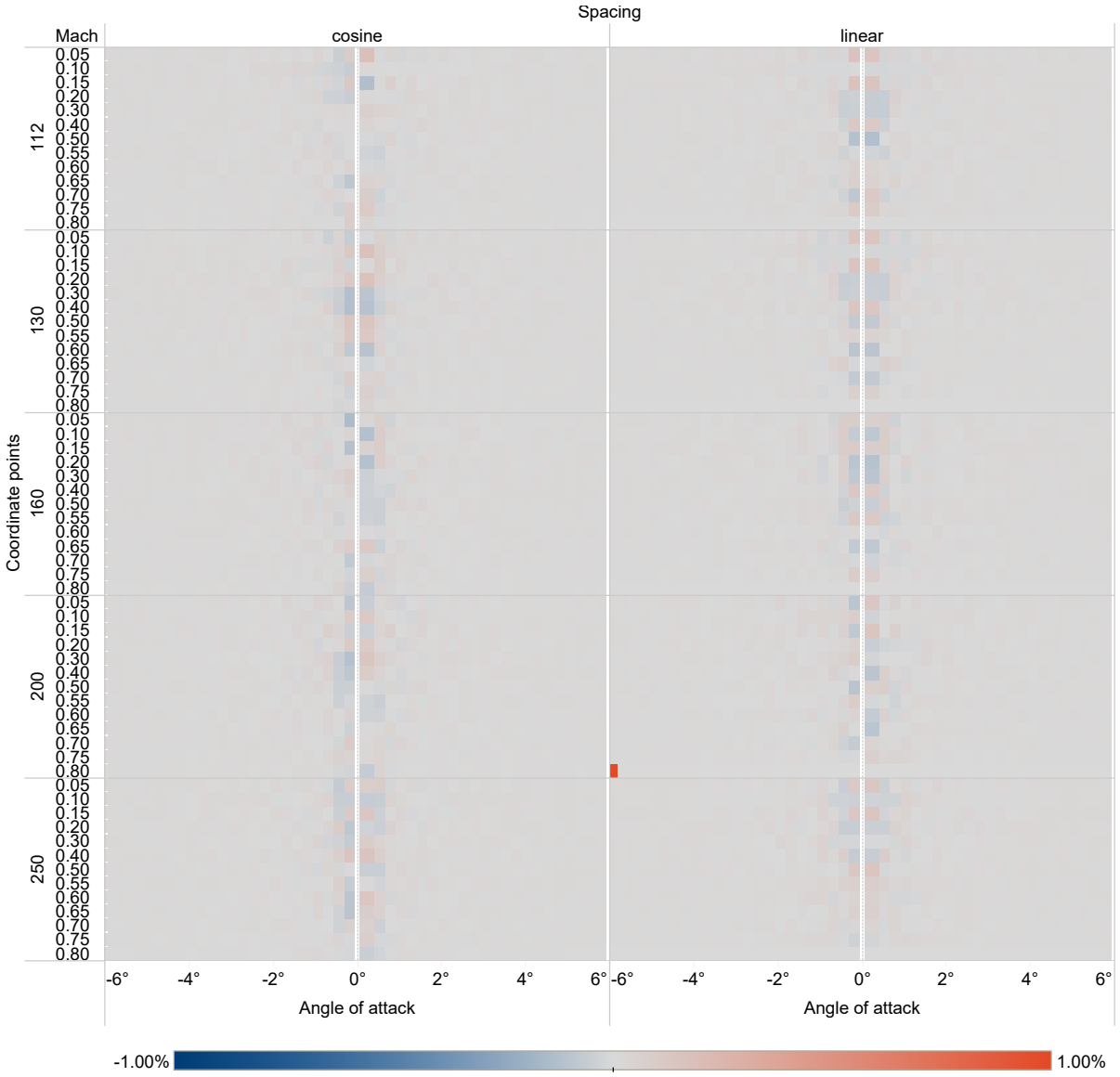


Figure D.3: Difference in lift coefficient between XFOIL results and manually integrated XFOIL results, normalised with respect to XFOIL results, for NACA0012

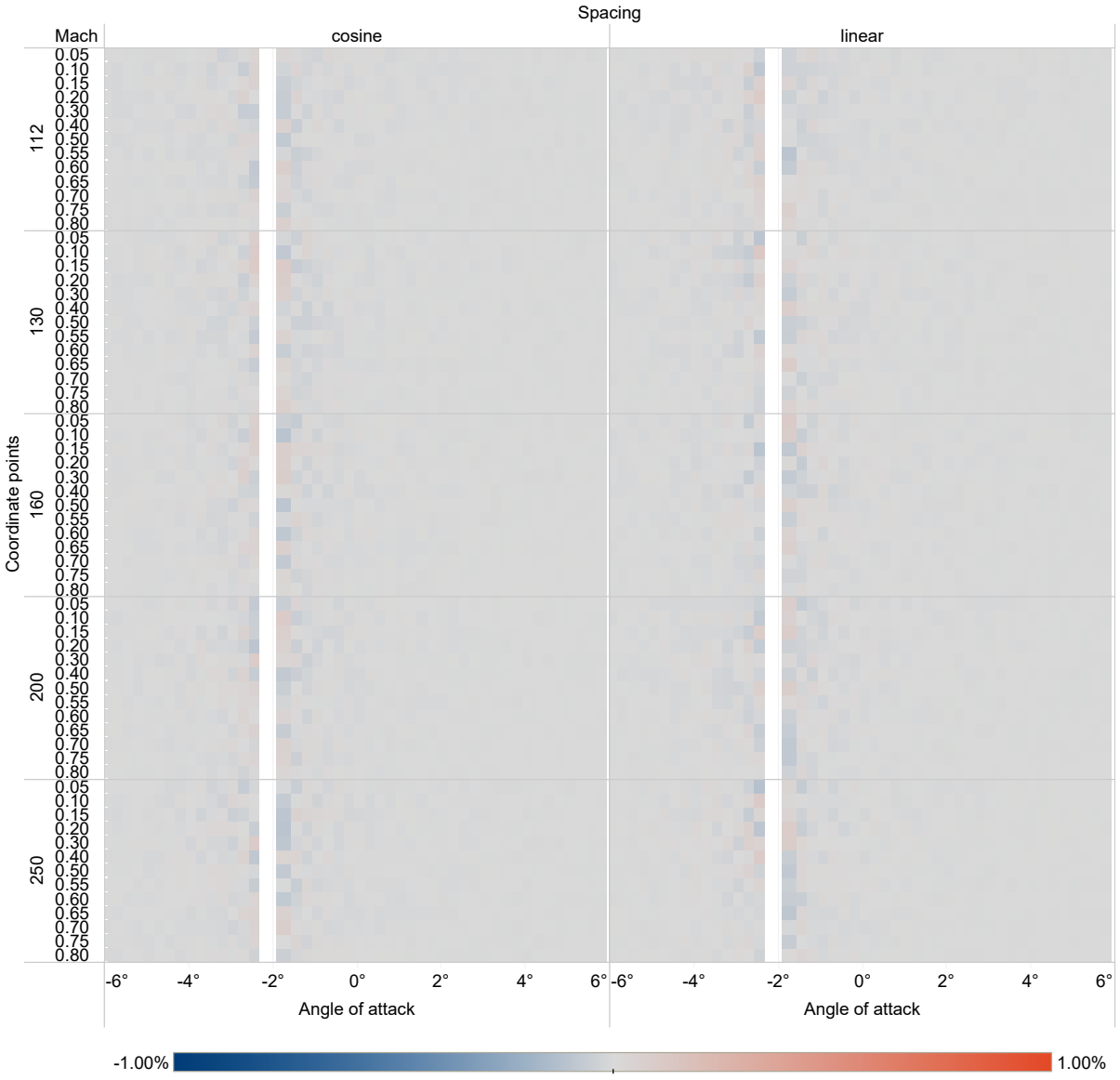


Figure D.4: Difference in lift coefficient between XFOIL results and manually integrated XFOIL results, normalised with respect to XFOIL results, for RAE2822

D.2.2. Pitching moment coefficient

Difference

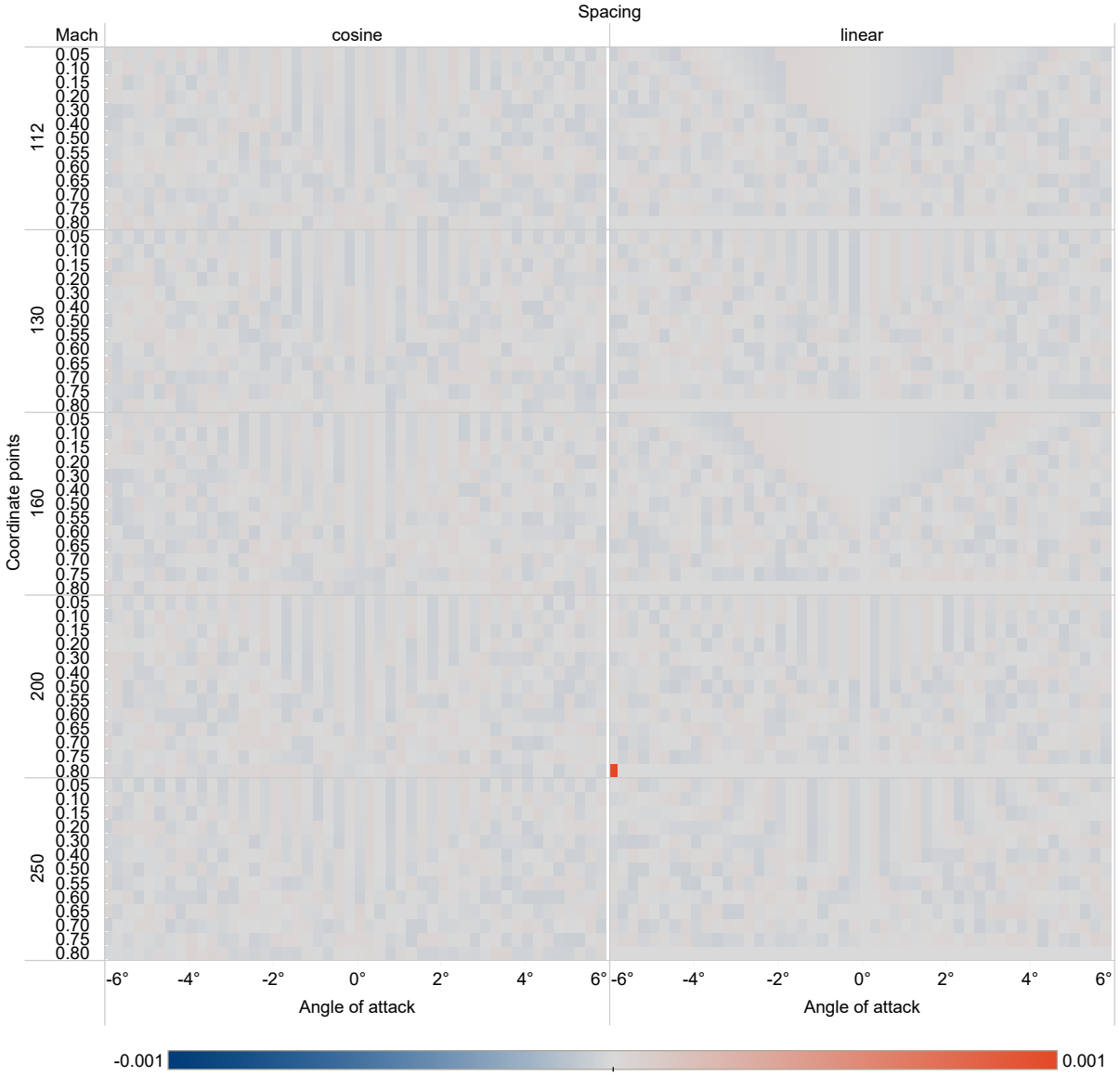


Figure D.5: Difference in pitching moment coefficient between XFOIL results and manually integrated XFOIL results for NACA0012

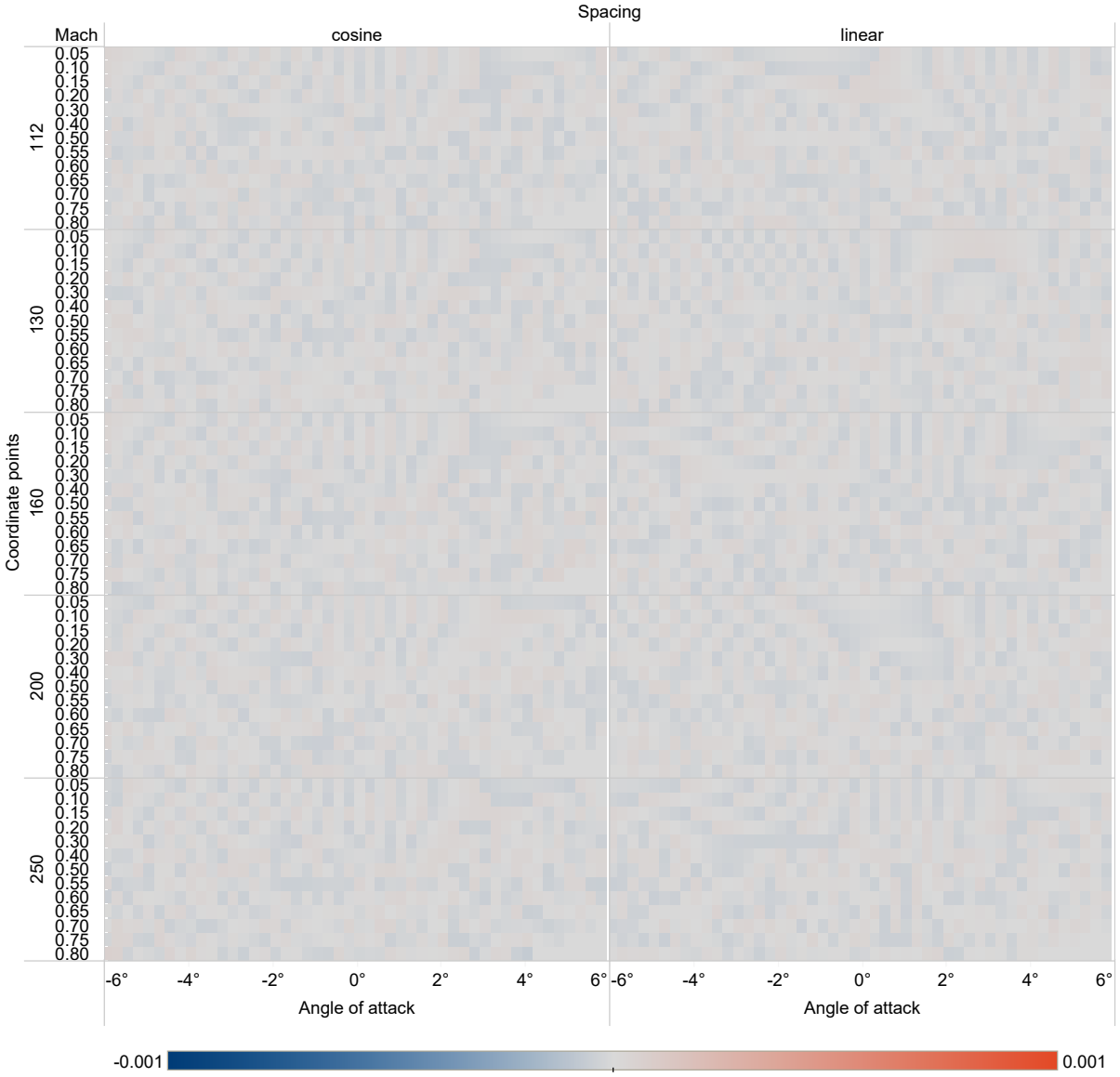


Figure D.6: Difference in pitching moment coefficient between XFOIL results and manually integrated XFOIL results for RAE2822

Normalised difference

As the pitching moment coefficient of the NACA0012 is very small, the normalised differences grow large – even beyond the scale.

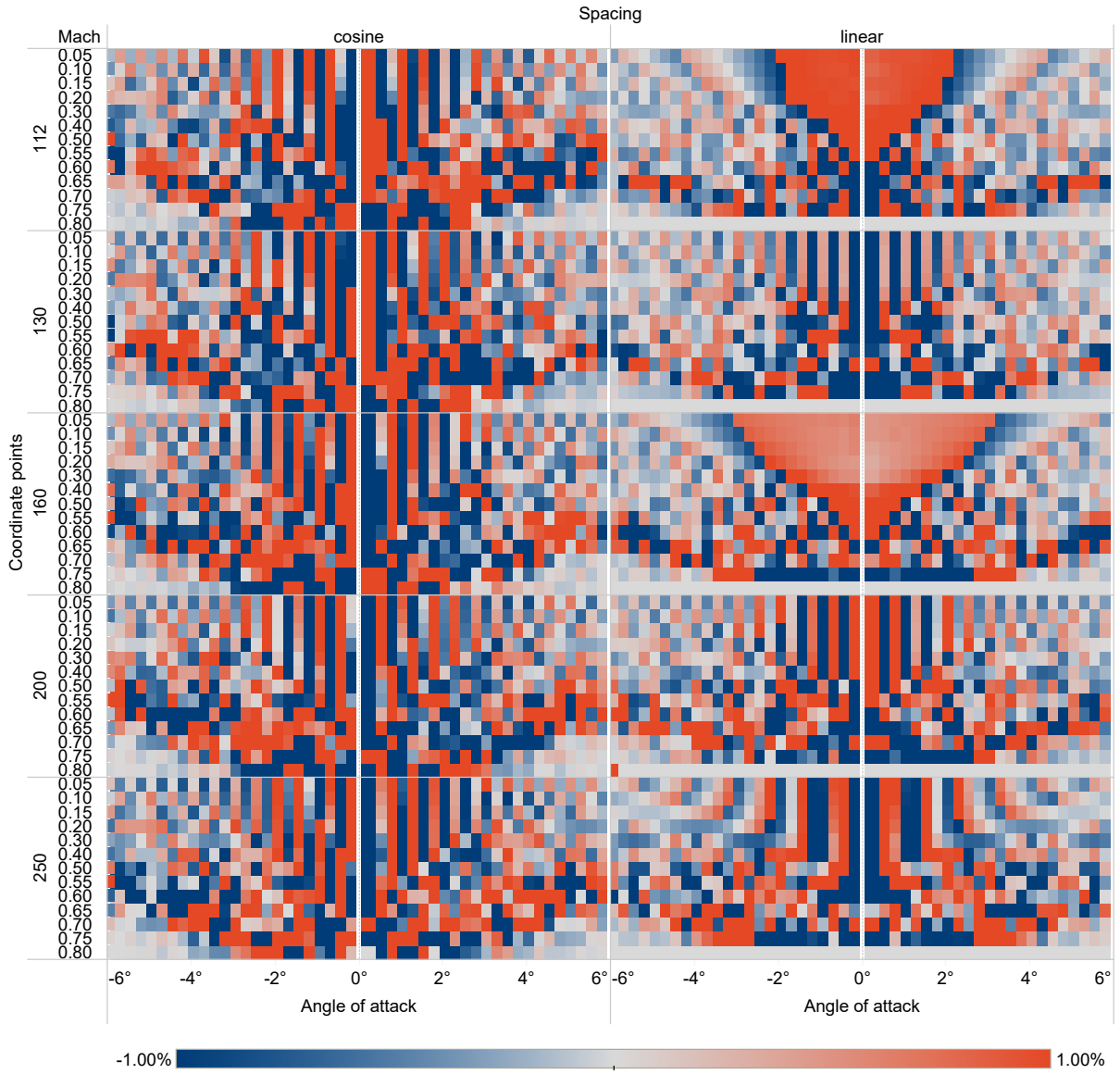


Figure D.7: Difference in pitching moment coefficient between XFOIL results and manually integrated XFOIL results, normalised with respect to XFOIL results, for NACA0012

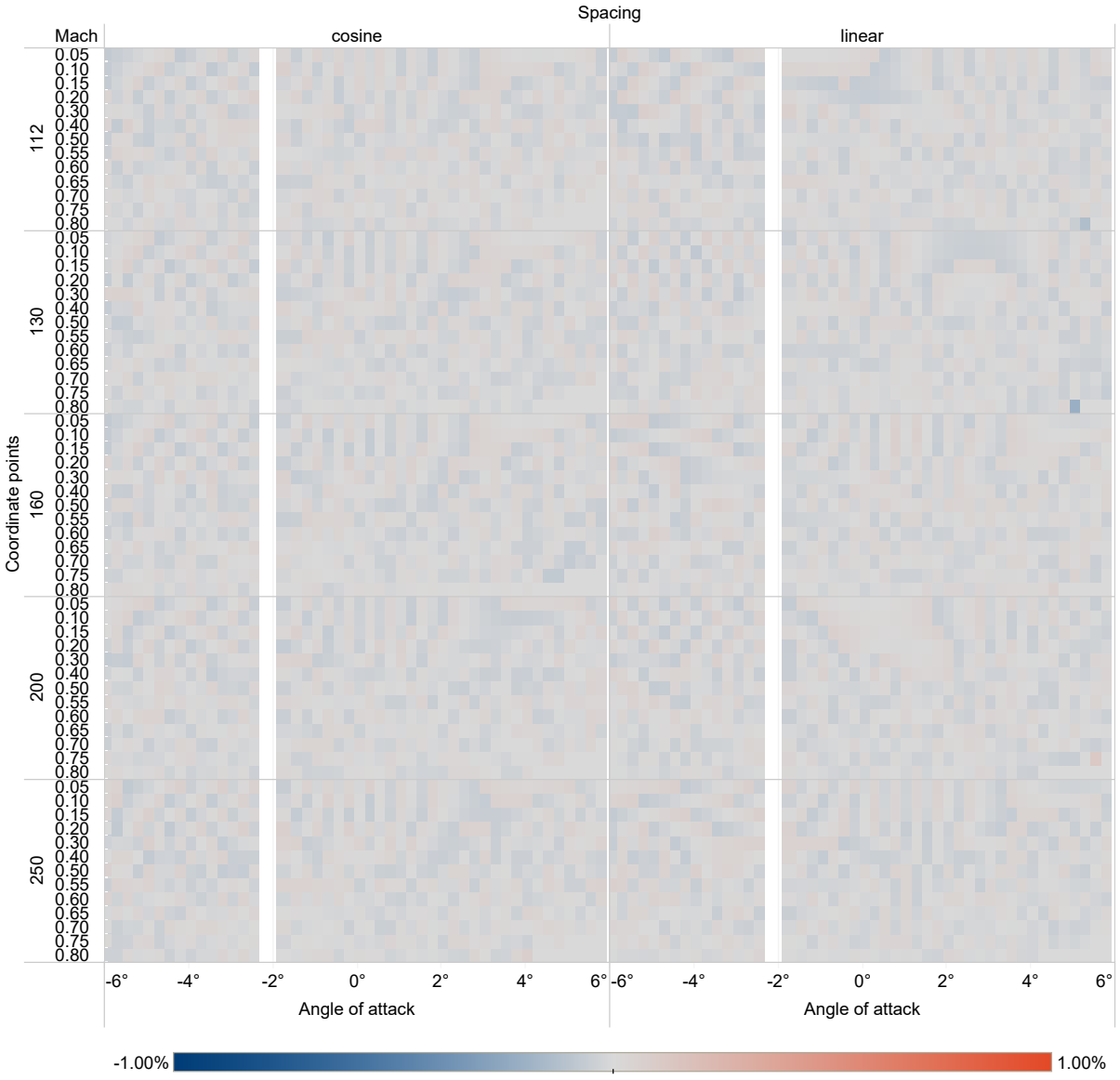


Figure D.8: Difference in pitching moment coefficient between XFOIL results and manually integrated XFOIL results, normalised with respect to XFOIL results, for RAE2822

E

Investigation of MSES anomaly

As briefly mentioned in Section 6.3.3, an abrupt change in lift slope at relatively modest angles of attack was observed in the results obtained from MSES. As this could not be logically attributed to any physical phenomenon, it was decided to exclude these results in the assessment of the irrotational flow assumption. This appendix presents the analysis underlying that decision in greater detail, by tracing the results from lift polar (Appendix E.1) to pressure distribution (Appendix E.2) to flowfield (Appendix E.3).

E.1. Lift polar

Figure E.1 shows lift polars for the NACA0012 and RAE2822, both represented using 130 coordinate points following a cosine spacing, at $M_\infty = 0.15$, as computed by VGK and MSES. Especially in case of the NACA0012 (solid line), the step change in lift slope can be clearly observed around $\alpha \approx 5°$. For the RAE2822, the discrepancy is seen at approximately $\alpha \approx 3°$.

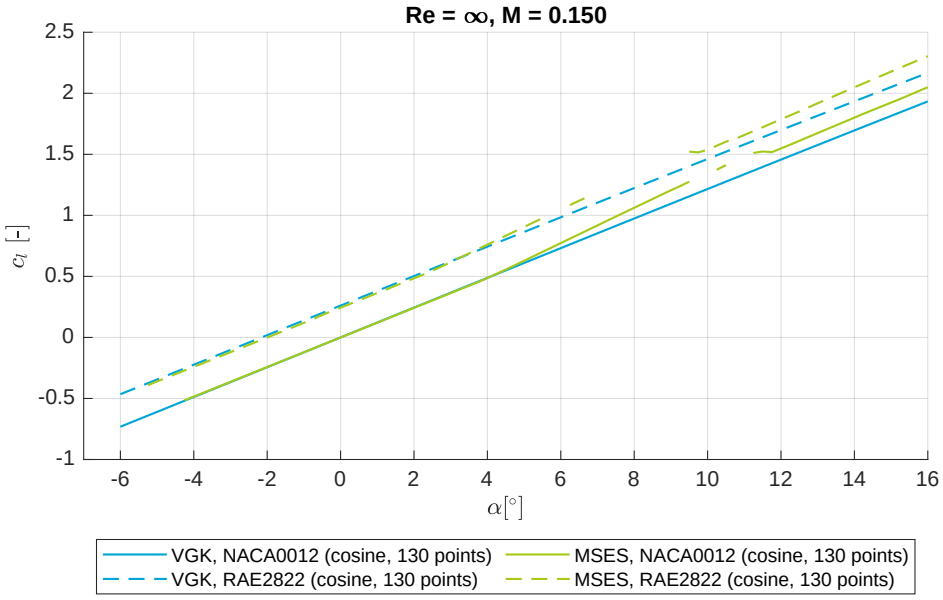
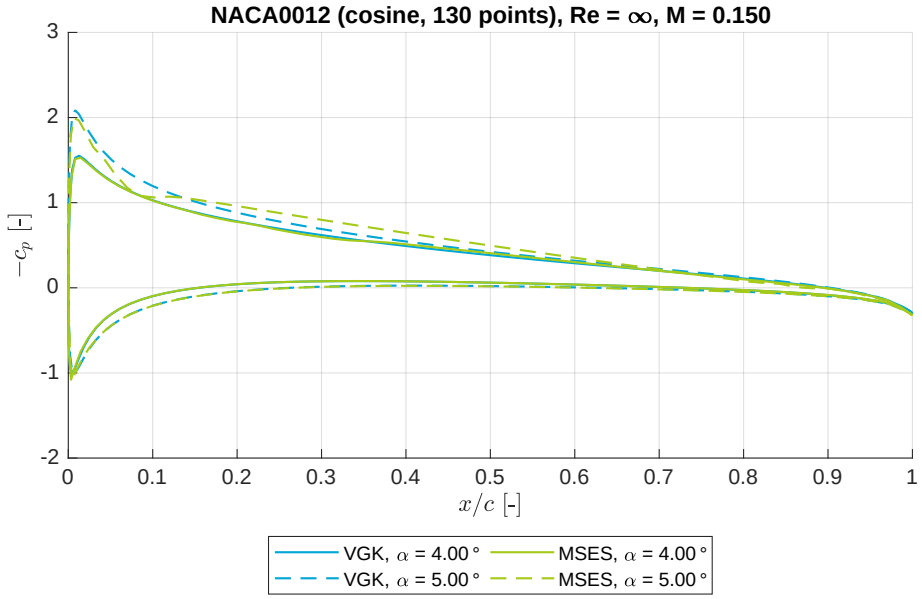


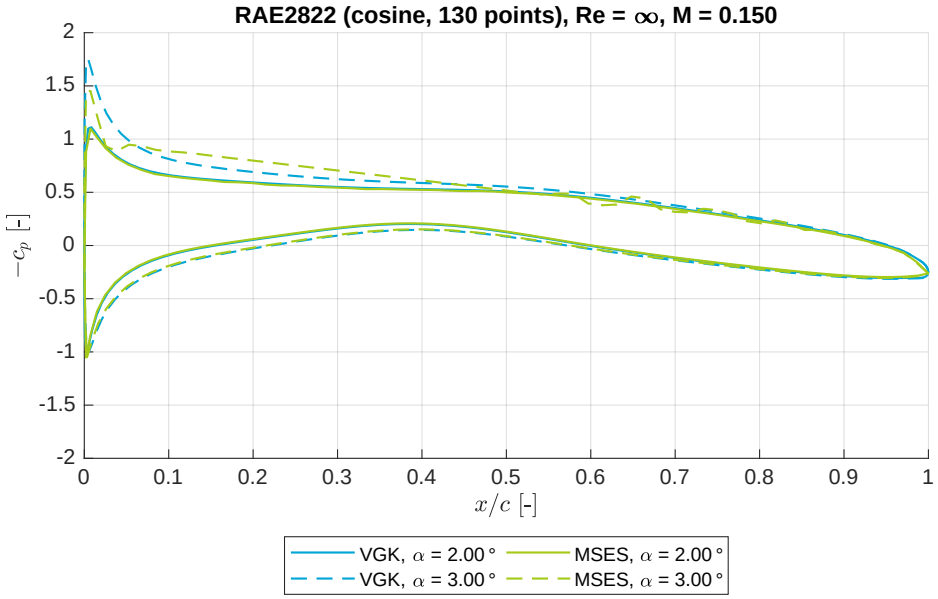
Figure E.1: Lift coefficient NACA0012 and RAE2822 airfoils, represented using 130 cosine-spaced coordinate points, computed by VGK and MSES at $Re = \infty$ and $M_\infty = 0.15$

E.2. Pressure distribution

Figure E.2 shows the pressure distributions corresponding to the airfoil analyses shown above. Figure E.2a shows the NACA0012 profile, with $\alpha = [4°, 5°$, and Figure E.2b corresponds to the RAE2822 geometry, with $\alpha = [2°, 3°]$. Again, the problem is best observed in the figure corresponding to the symmetrical profile. At $x/c \approx 0.08$, the green line representing the pressure coefficient at $\alpha = 5°$ is seen to level off, before decreasing (in magnitude) at $x/c = \approx 0.14$. Similarly, there is another plateau – although barely visible – at $x/c \approx 0.88$. The shape of the pressure distribution seems to indicate separated flow, but as the computations are inviscid, this cannot be.



(a) NACA0012

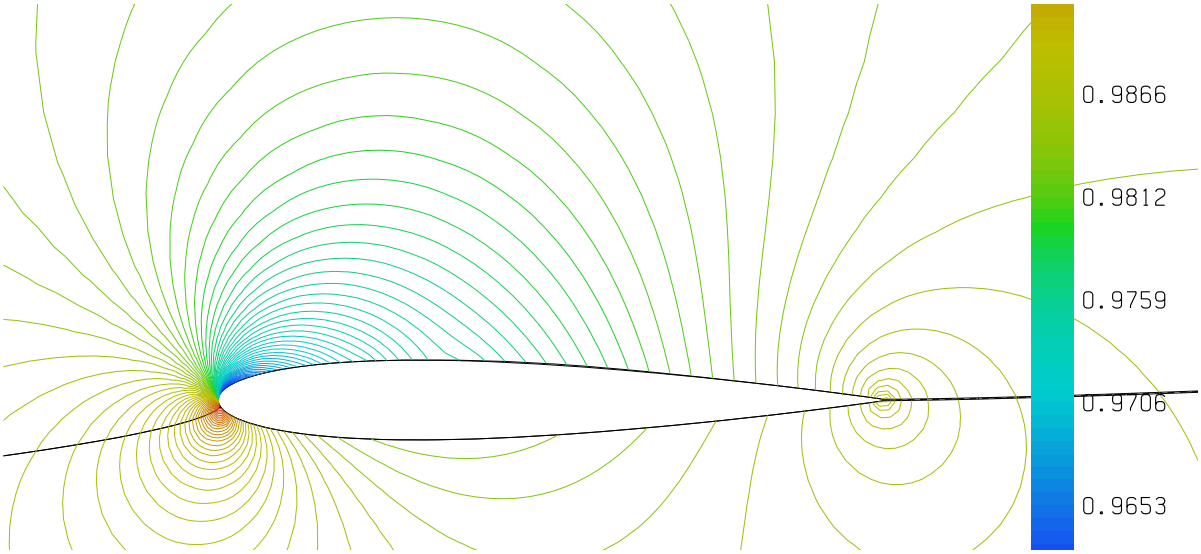


(b) RAE2822

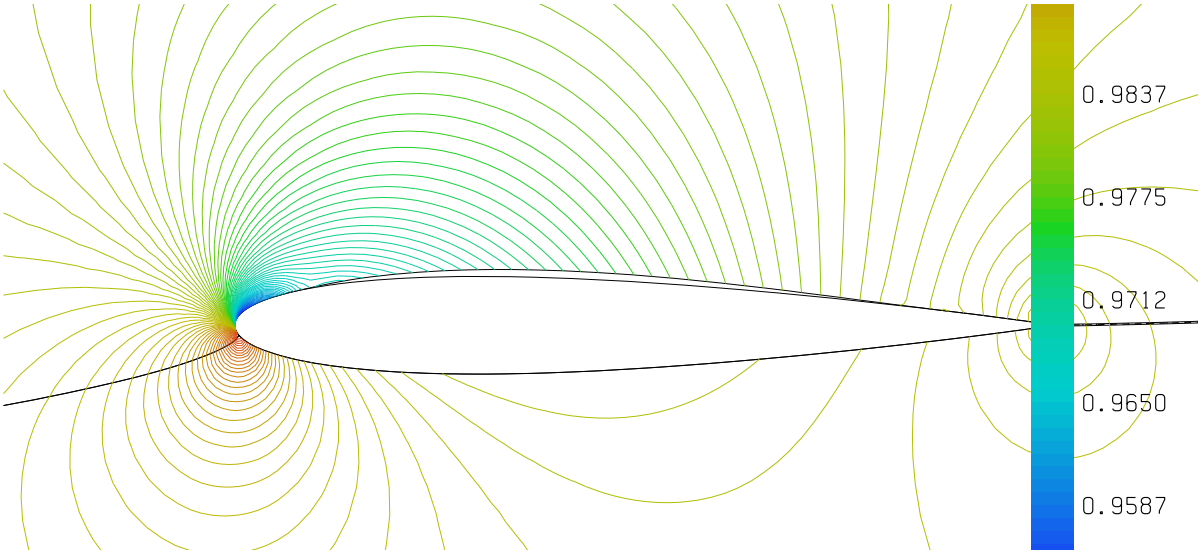
Figure E.2: Pressure distributions of NACA0012 and RAE2822 airfoils, represented using 130 cosine-spaced coordinate points, computed by VGK and MSES at $Re = \infty$, $M_\infty = 0.15$ and various angles of attack

E.3. Flowfield

The pressure ratio p/p_0 in the flowfield, depicted in Figure E.3, however is consistent with that hypothesis. Comparing Figure E.3a and Figure E.3b (NACA0012), and Figure E.3c and Figure E.3d (RAE2822), the inner streamline on the upper surfaces of the airfoil can be seen to detach from the geometry. This yields an abrupt increase in thickness, which explains the plateau in the pressure distribution as well as the change in lift slope.

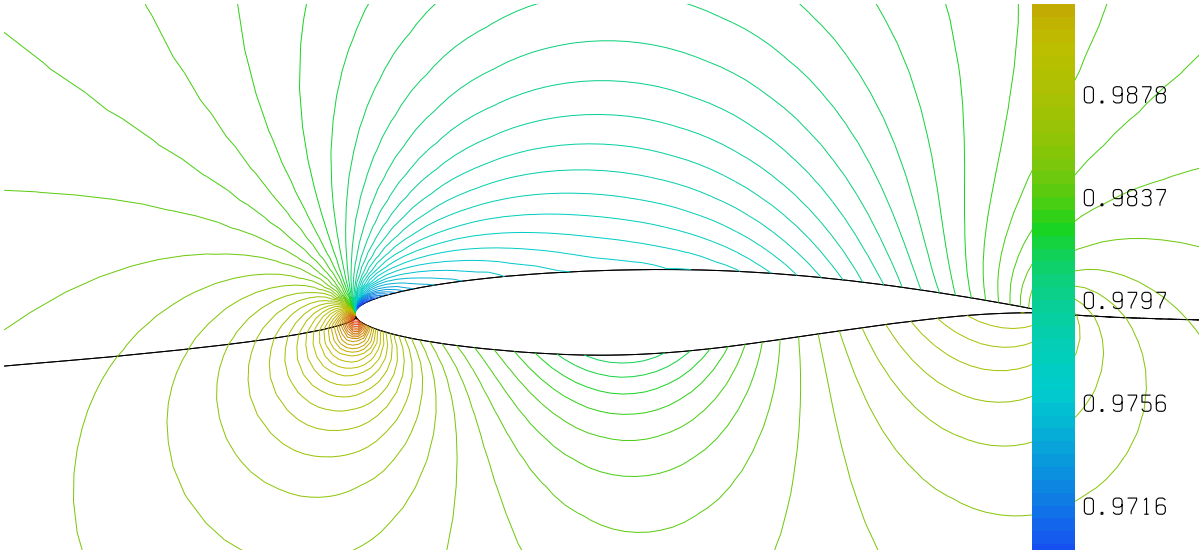


(a) NACA0012, $\alpha = 4°$

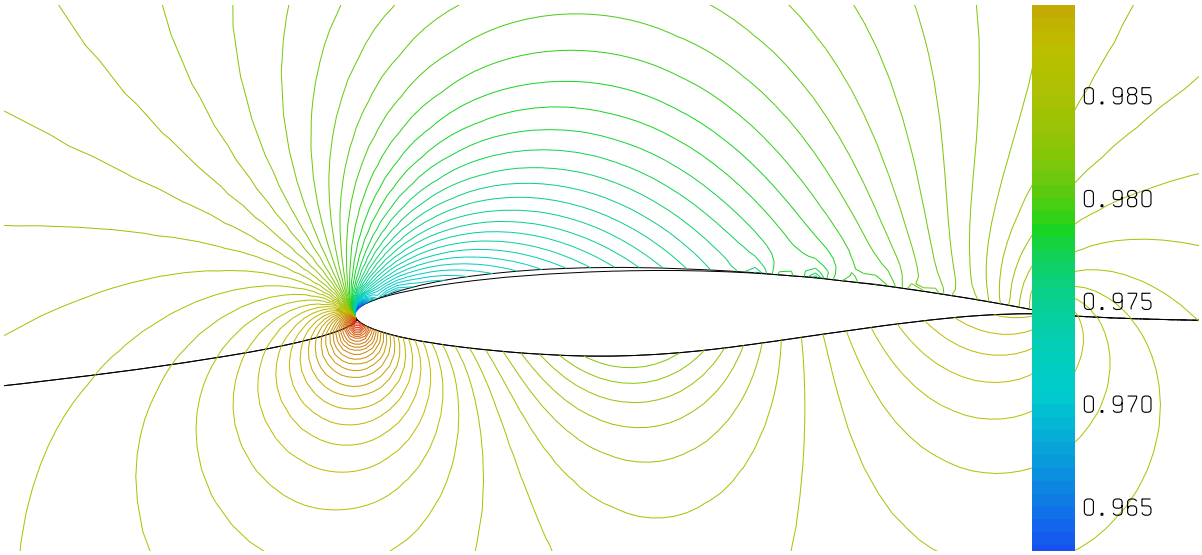


(b) NACA0012, $\alpha = 5°$

Figure E.3: Flowfield around the NACA0012 and RAE2822 airfoils, computed by MSES at $Re = \infty$, $M_\infty = 0.15$ and various angles of attack



(c) RAE2822, $\alpha = 2°$



(d) RAE2822, $\alpha = 3°$

Figure E.3: Flowfield around the NACA0012 and RAE2822 airfoils, computed by MSES at $Re = \infty$, $M_\infty = 0.15$ and various angles of attack (continued)

As this anomaly could not be corrected nor explained, it was decided to exclude MSES results at higher angles of attack from the analysis in Chapter 6.

F

Additional results

This appendix shows additional results gathered in the uncertainty quantification and propagation research efforts as documented in Chapters 6 and 7. It is split up into two sections: Appendix F.1 provides uncertainty quantification results (including grid refinement, the influence of solution method and the influence of flow model) and Appendix F.2 presents the results for the uncertainty propagation.

In order to simplify the comparison between the various cases analysed, some of the figures contained in the body of this report have been repeated here.

F.1. Uncertainty quantification

This section shows the full set of results regarding uncertainty quantification, presented in Chapter 6. Appendix F.1.1 is concerned with the grid refinement study, Appendix F.1.2 provides further information on the influence of the solution method and Appendices F.1.3 and F.1.4 are about the effect of flow model.

Although most figures included here have only briefly been discussed (and not shown) in Chapter 6, a number of figures is repeated here to simplify comparisons.

F.1.1. Grid refinement

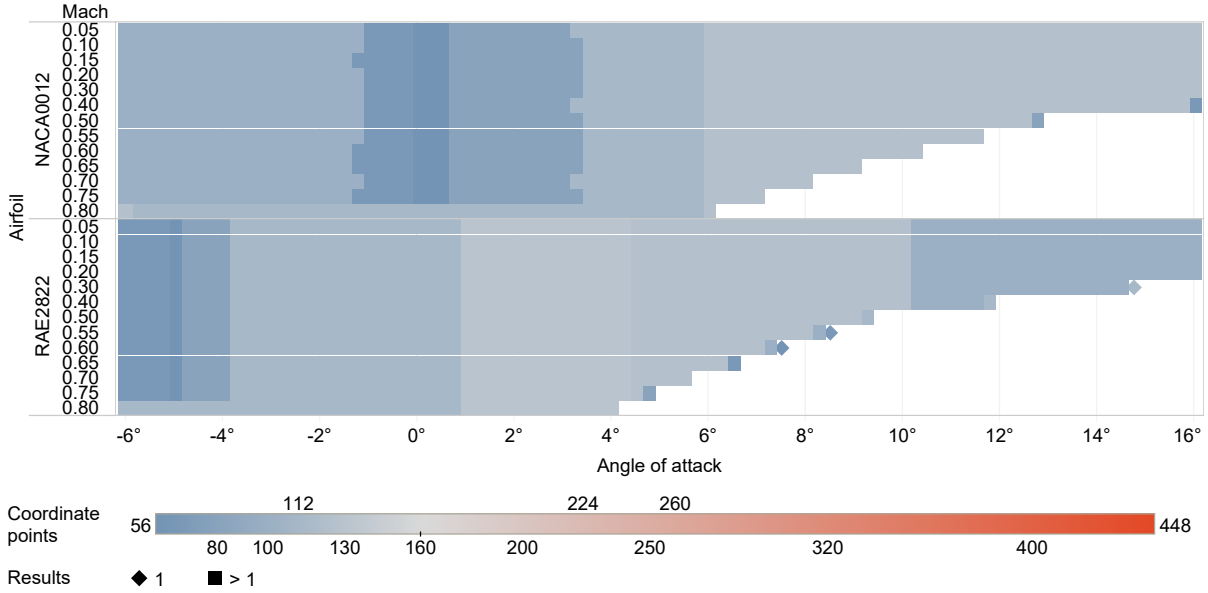


Figure F.1: Number of coordinate points required for convergence of lift coefficient (XFOIL-U, cosine spacing)

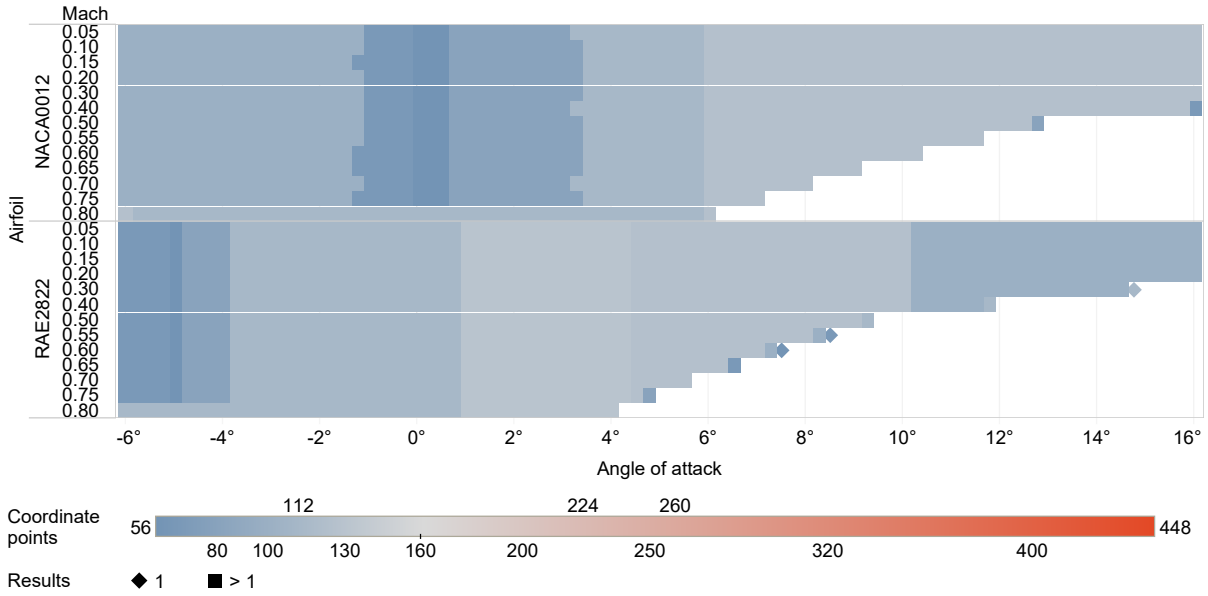


Figure F.2: Number of coordinate points required for convergence of lift coefficient (XFOIL-PG, cosine spacing)

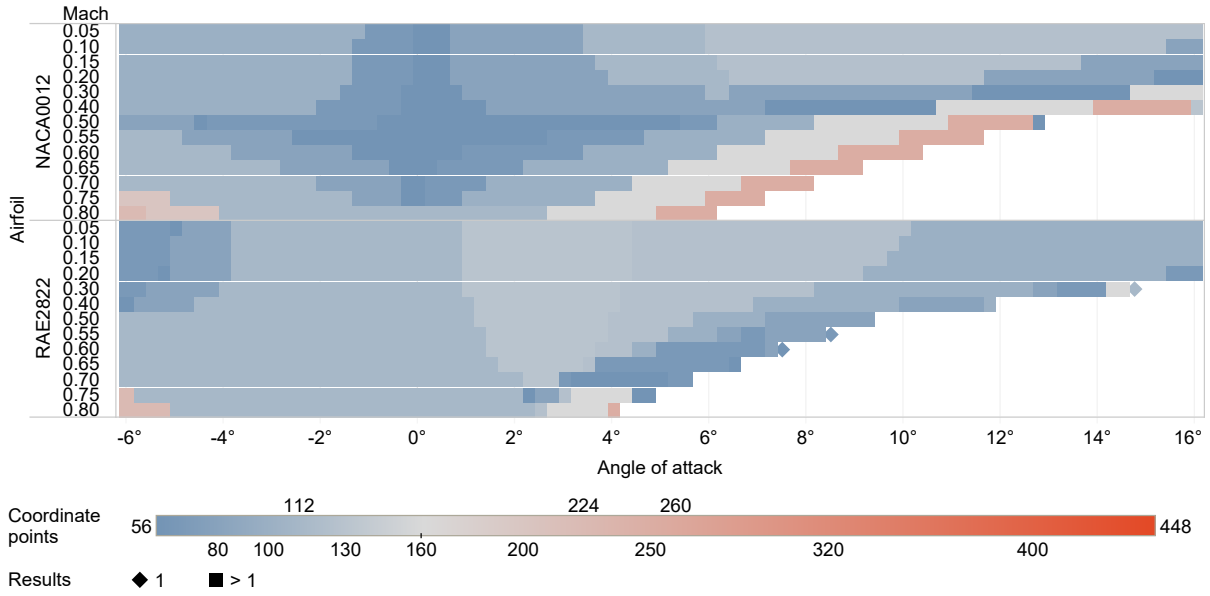


Figure F.3: Number of coordinate points required for convergence of lift coefficient (XFOIL-KT, cosine spacing)

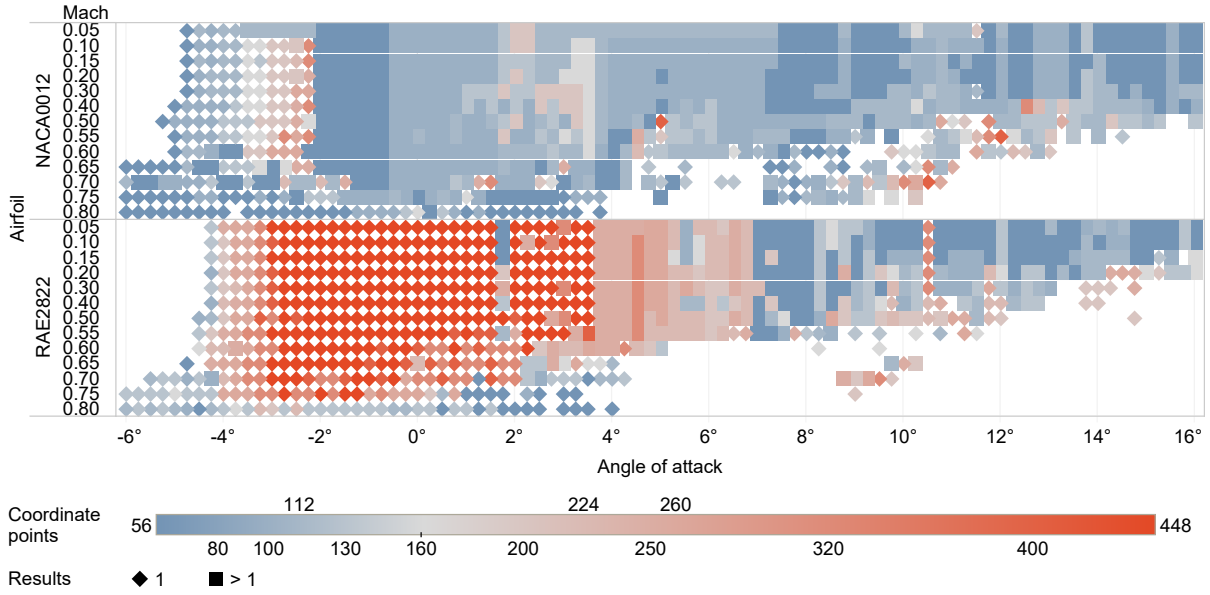


Figure F.4: Number of coordinate points required for convergence of lift coefficient (MSES, linear spacing)

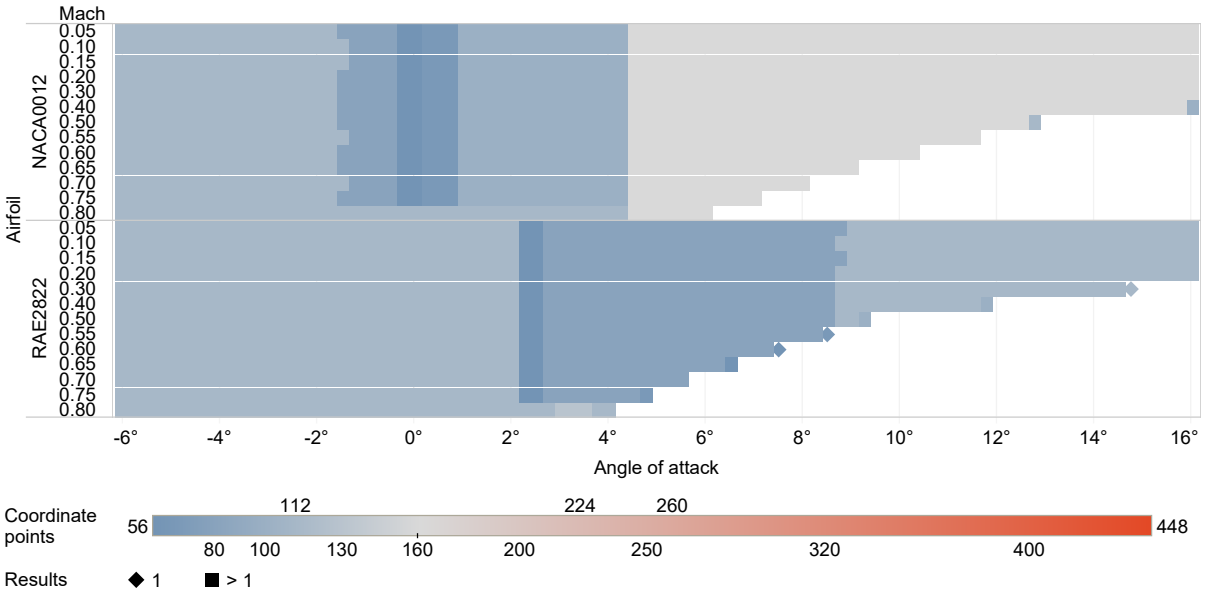


Figure F.5: Number of coordinate points required for convergence of pitching moment coefficient (XFOIL-U, cosine spacing)

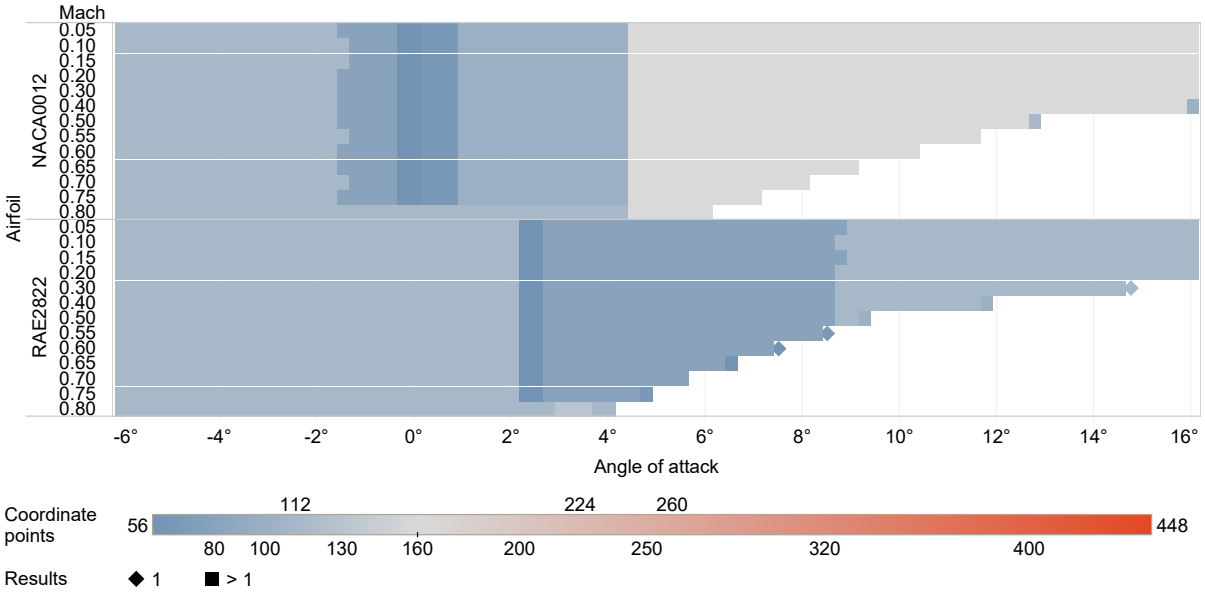


Figure F.6: Number of coordinate points required for convergence of pitching moment coefficient (XFOIL-PG, cosine spacing)

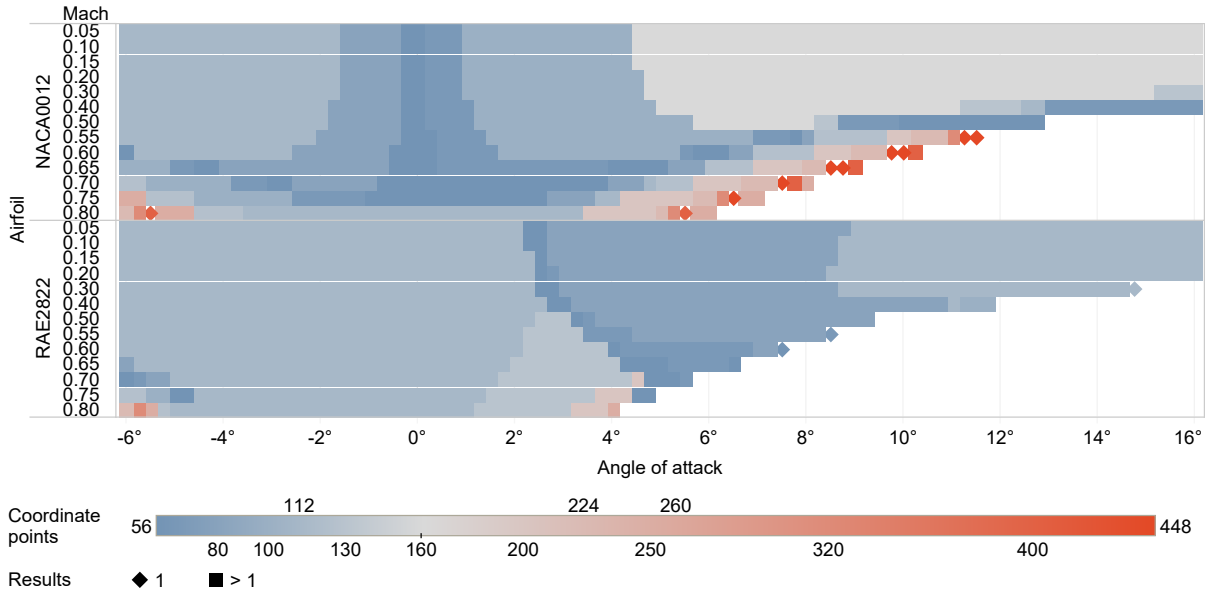


Figure F.7: Number of coordinate points required for convergence of pitching moment coefficient (XFOIL-KT, cosine spacing)

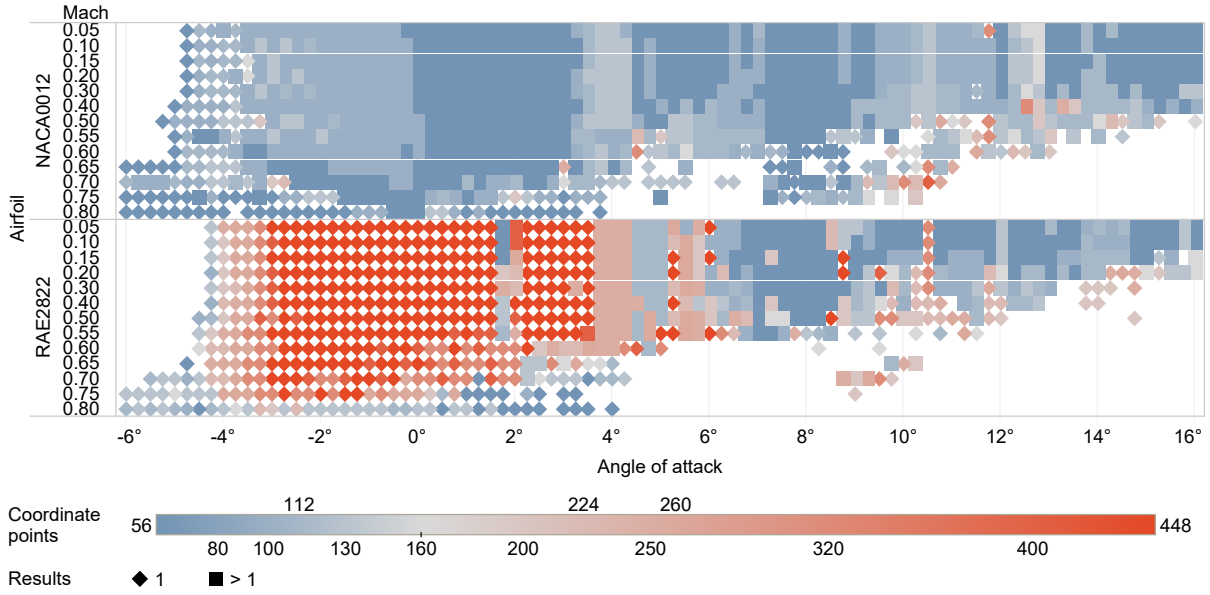
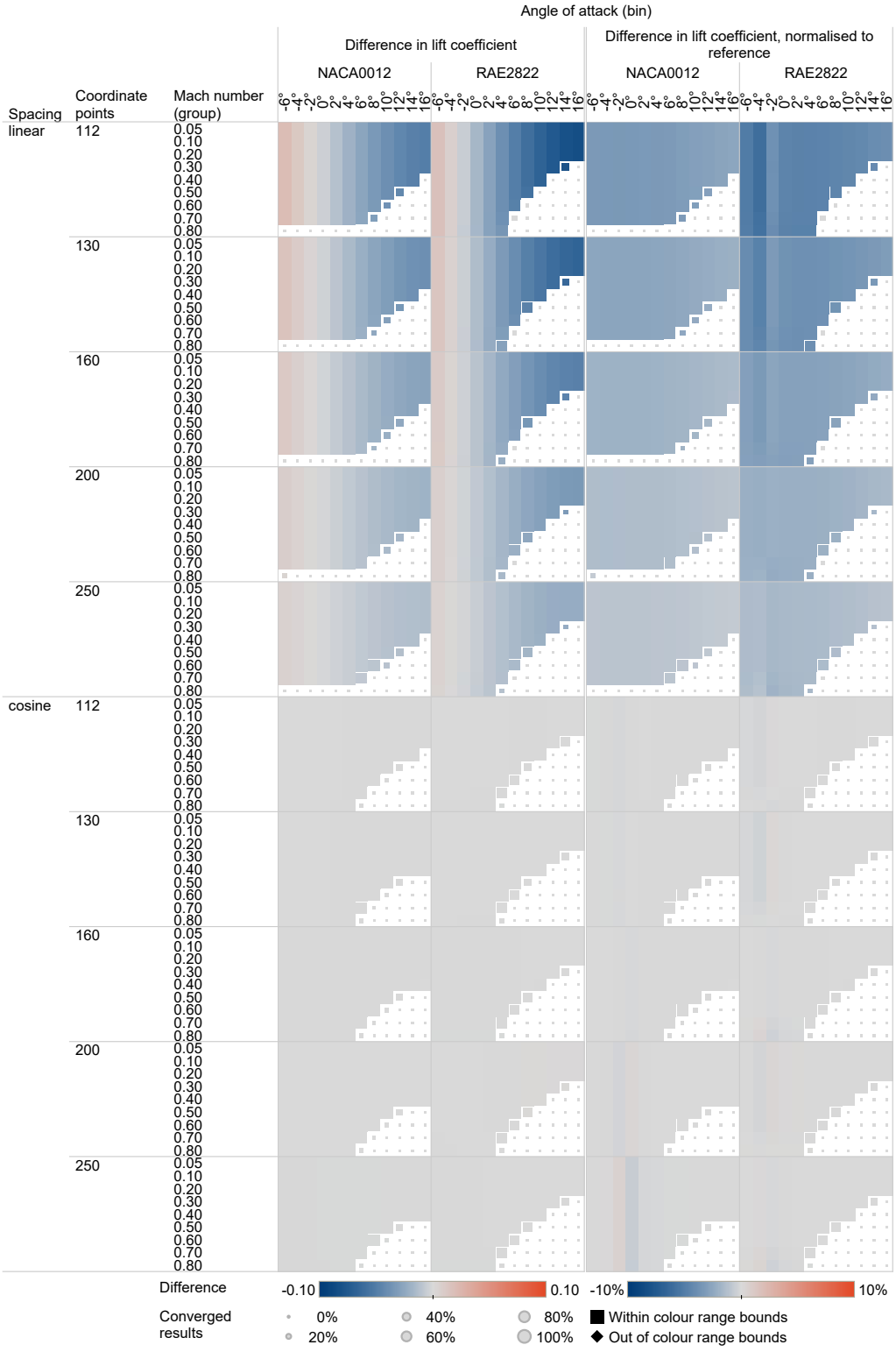


Figure F.8: Number of coordinate points required for convergence of pitching moment coefficient (MSES, linear spacing)

F.1.2. Influence of solution method

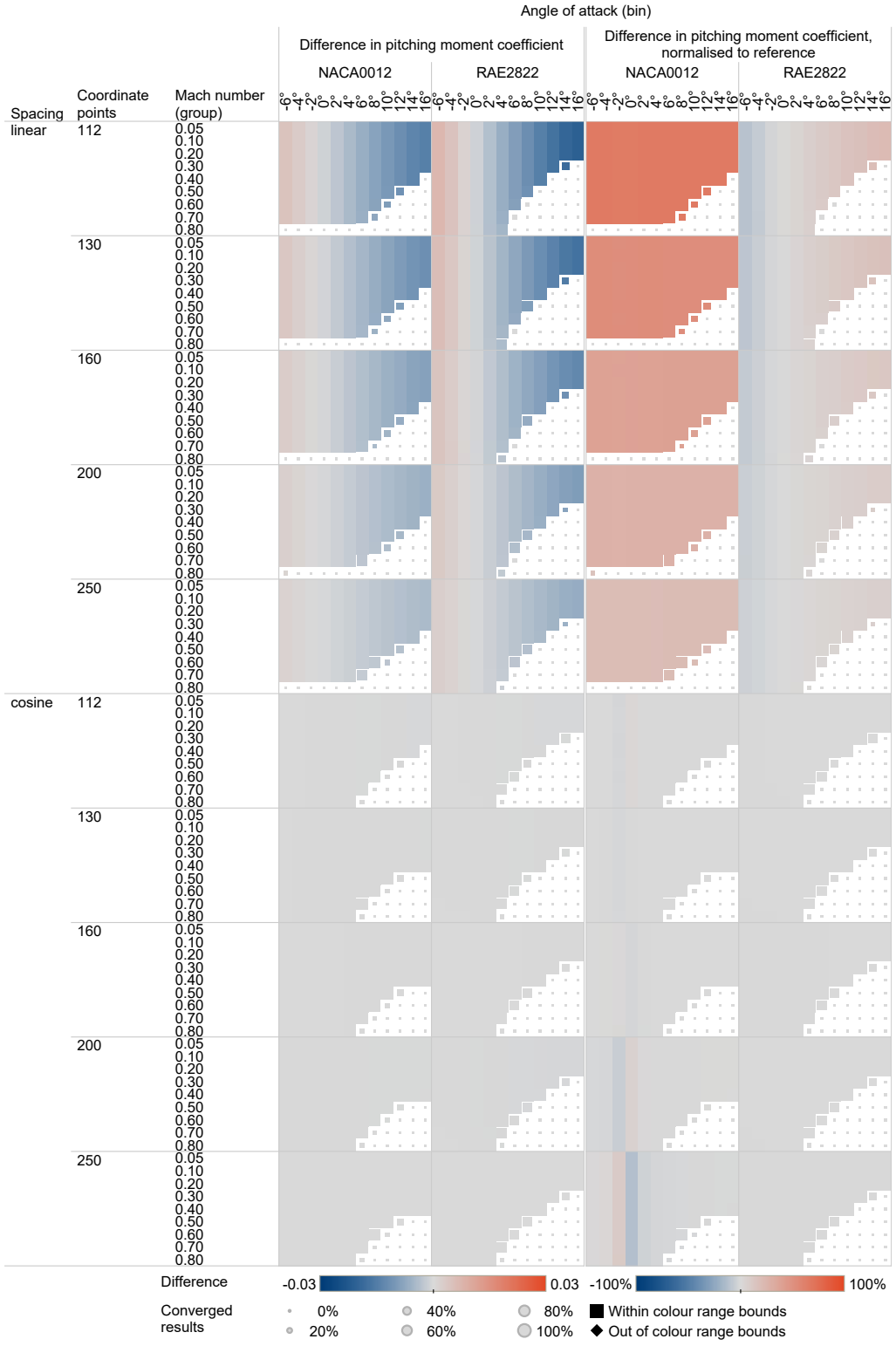
This section contains additional results showing the influence of solution method on lift coefficient, pitching moment coefficient, minimum pressure coefficient and the chordwise location at which the minimum pressure coefficient is found, represented using the heat maps used in Section 6.3.2. First, the results as shown in Section 6.3.2, normalised to the reference value, are presented. Second, differences are shown normalised to the result (i.e., a particular geometry representation), rather than the reference. As such, these results take the form of a correction factor that can be applied to the results from an imperfect representation. Last, the variation per quantity of interest is shown using line graphs. These include both the true difference, as well the two normalised differences.

Normalised to reference



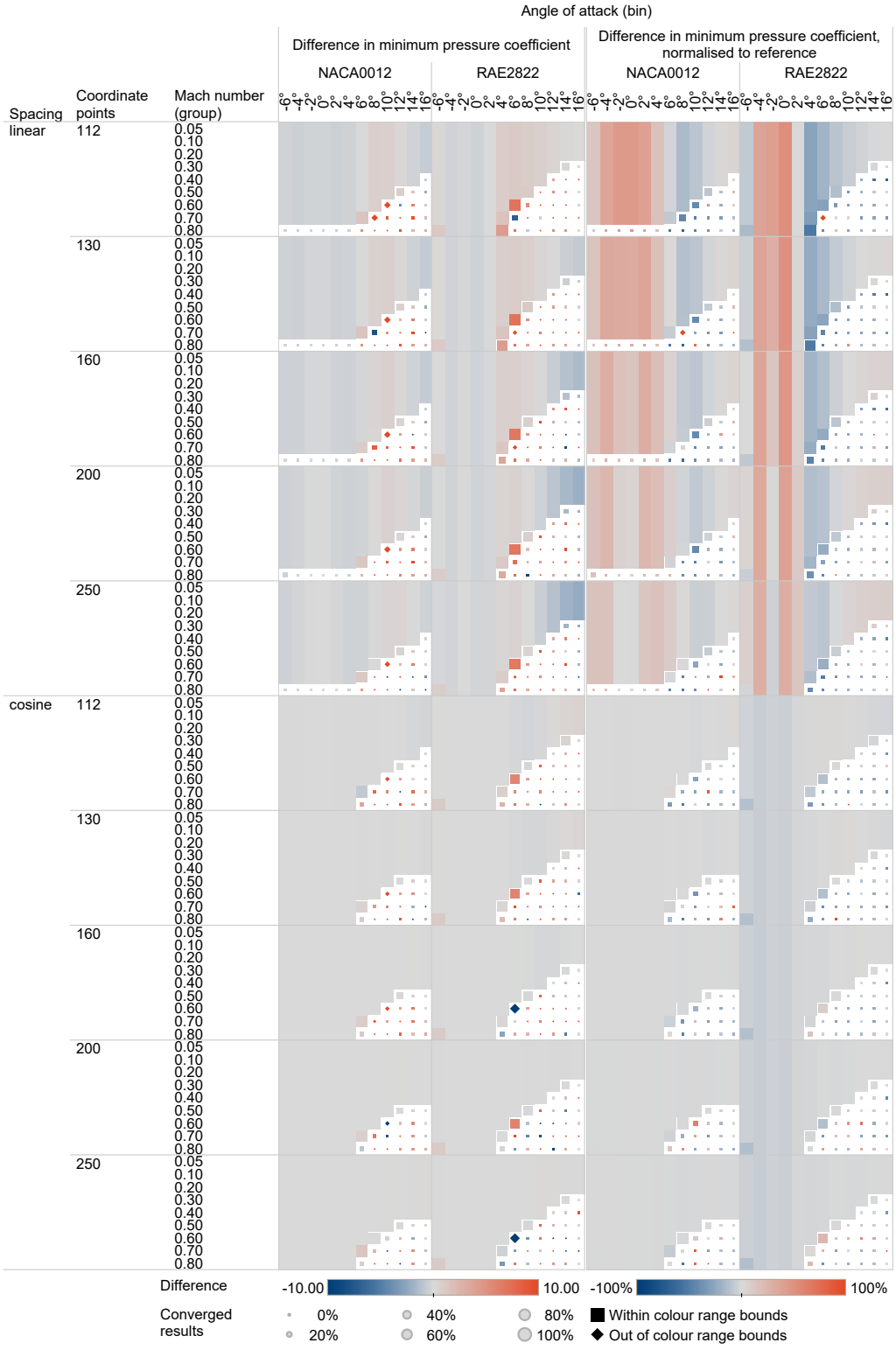
(a) Lift coefficient

Figure F.9: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack



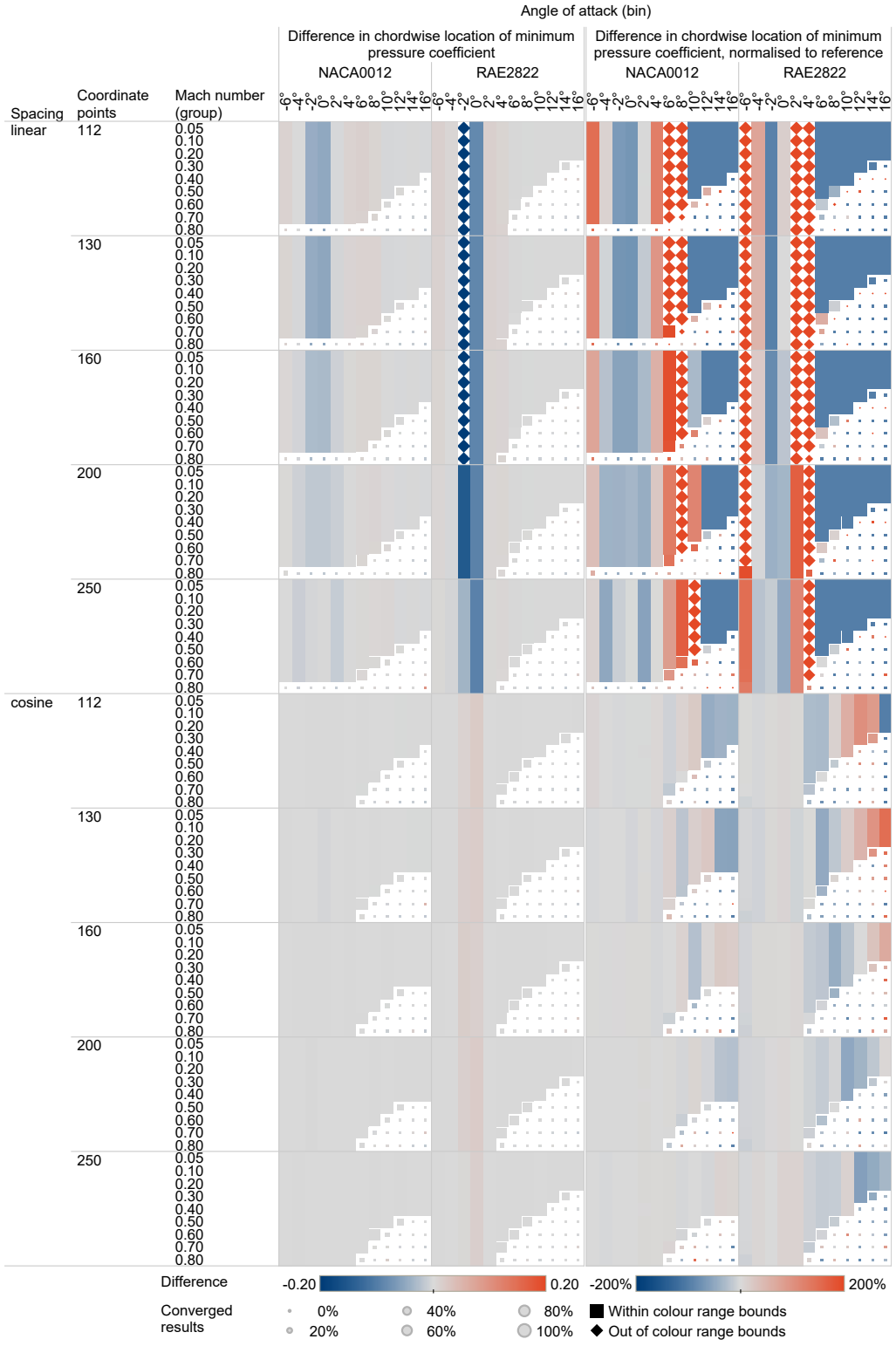
(b) Pitching moment coefficient

Figure F.9: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



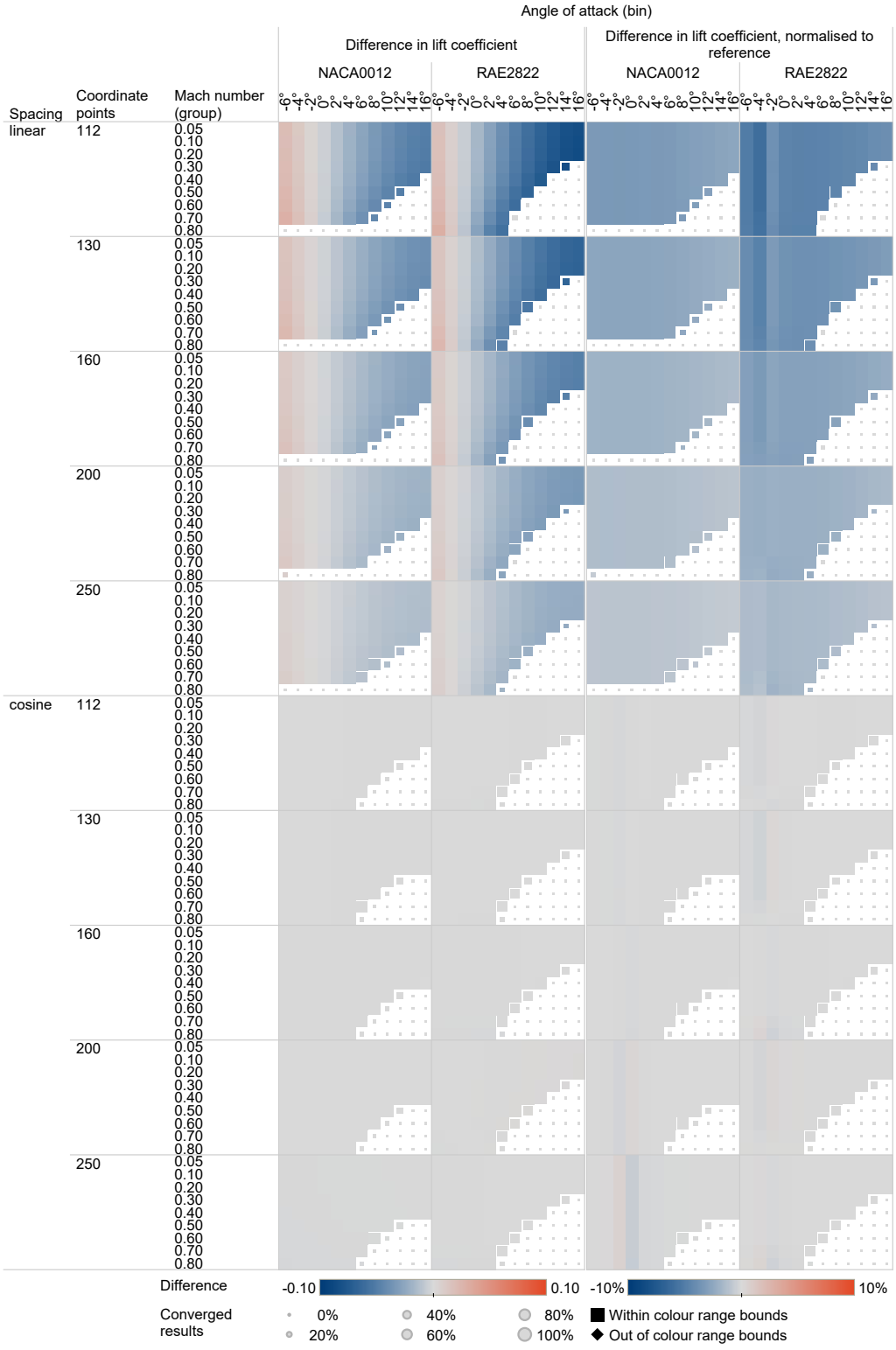
(c) Minimum pressure coefficient

Figure F.9: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



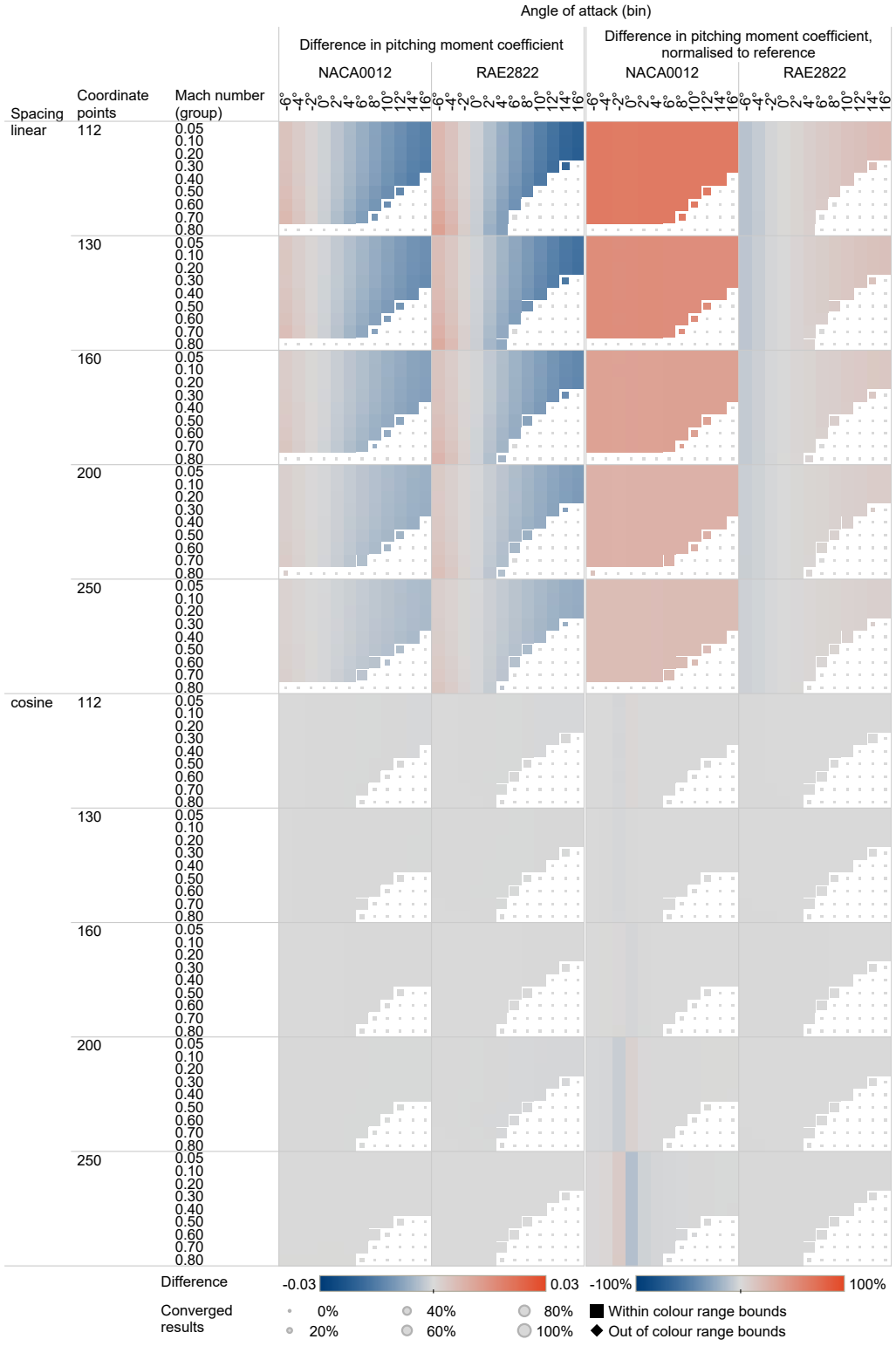
(d) Chordwise location of minimum pressure coefficient

Figure F.9: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



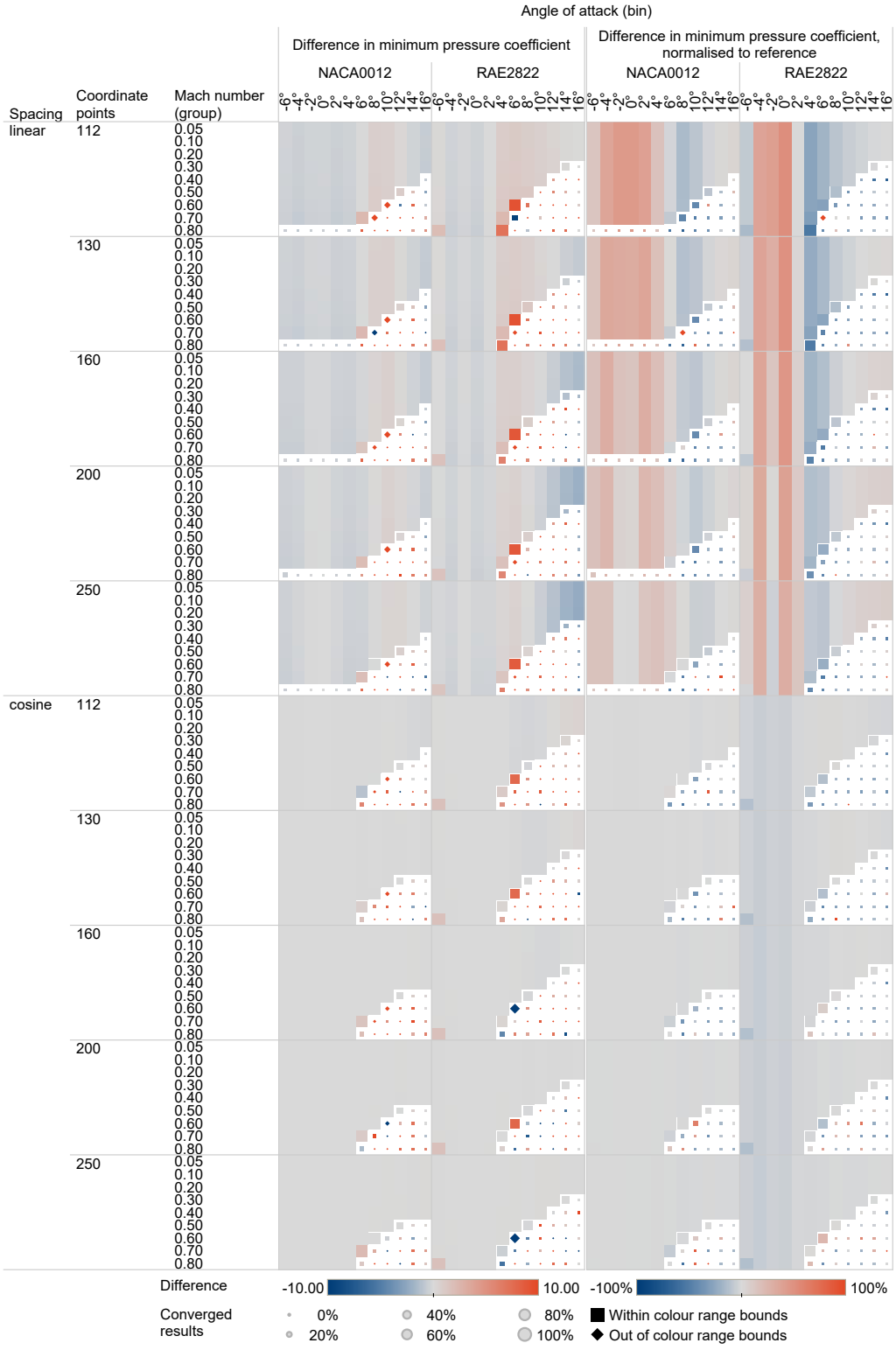
(a) Lift coefficient

Figure F.10: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack



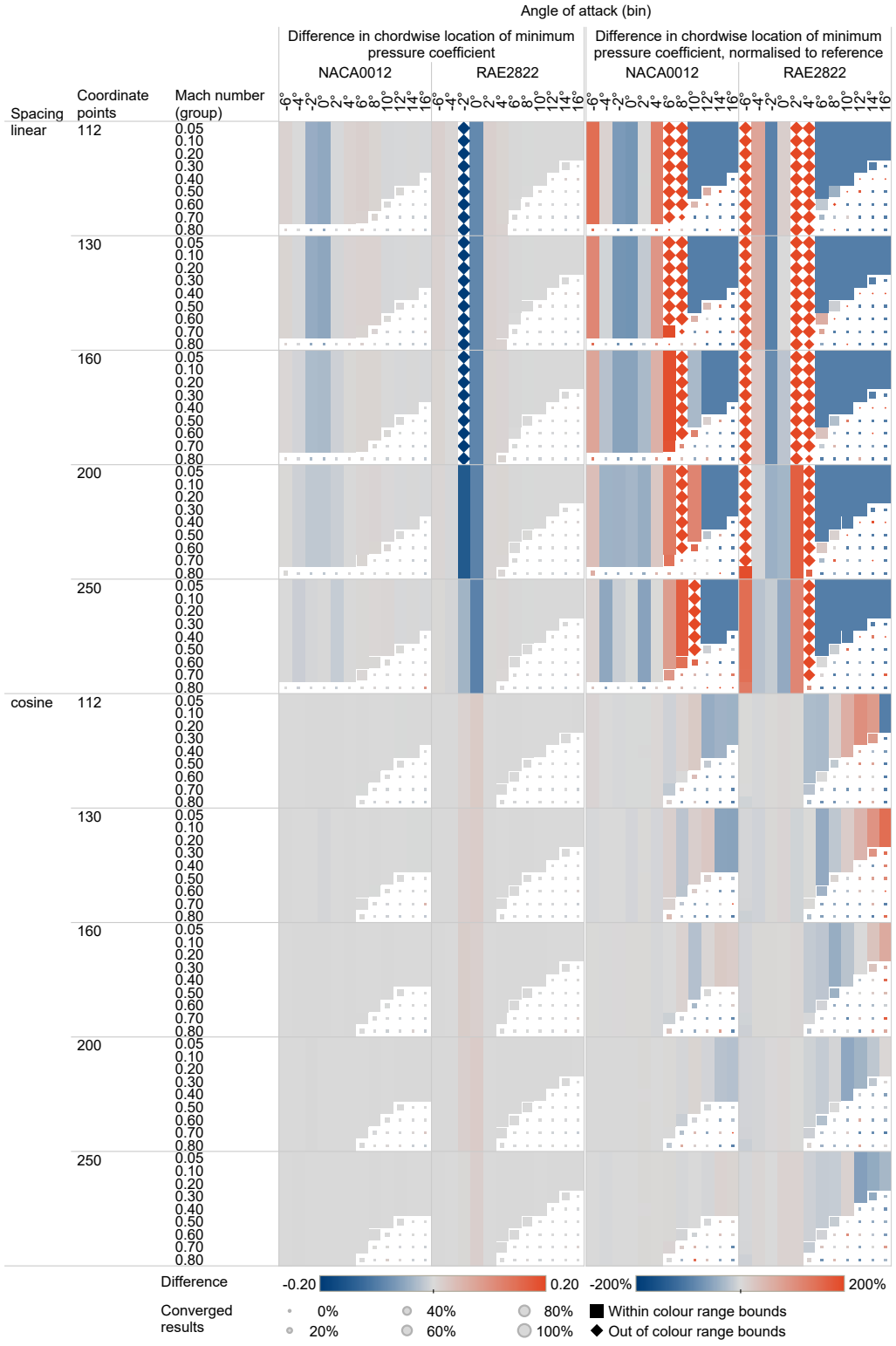
(b) Pitching moment coefficient

Figure F.10: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



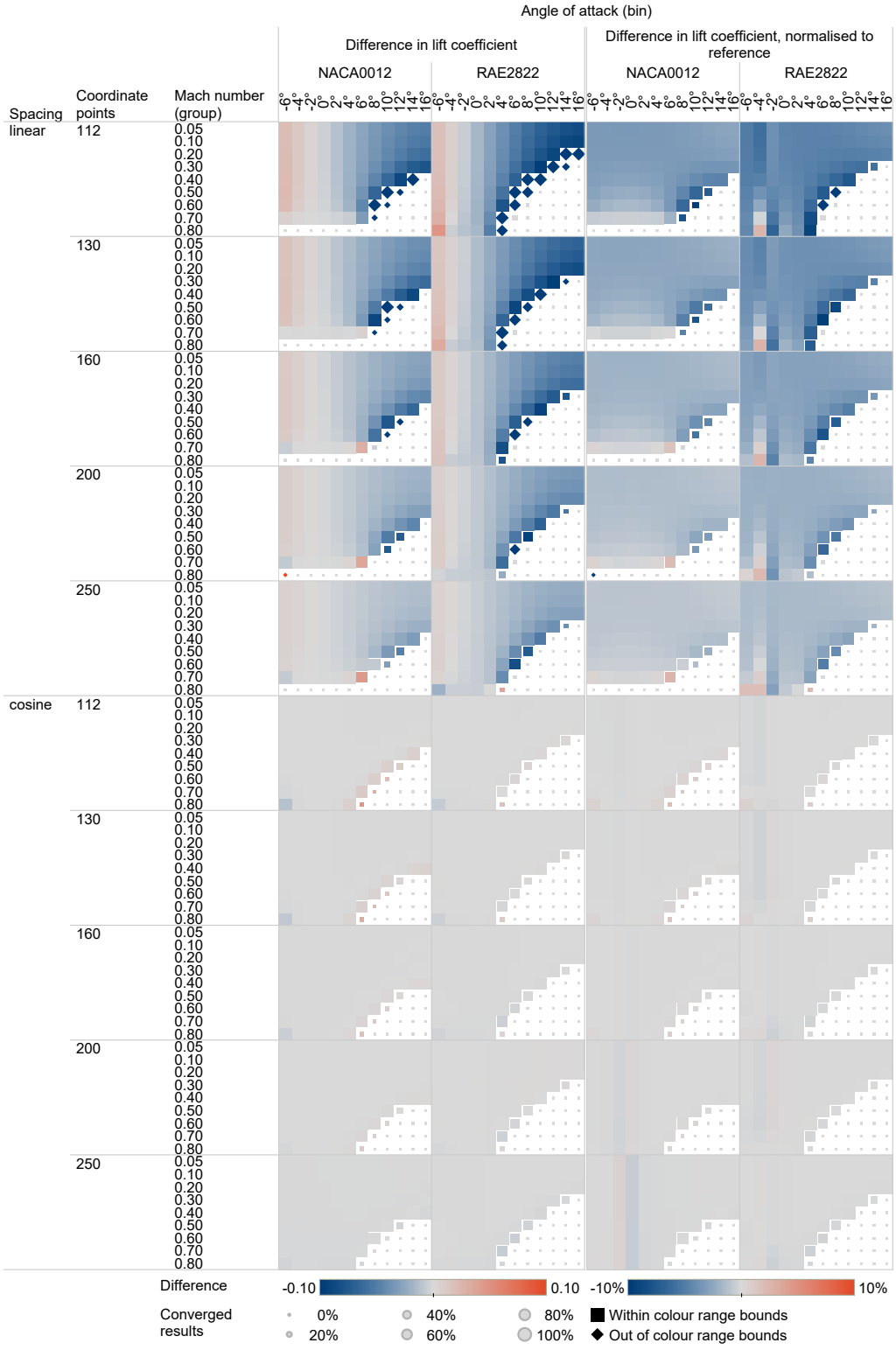
(c) Minimum pressure coefficient

Figure F.10: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



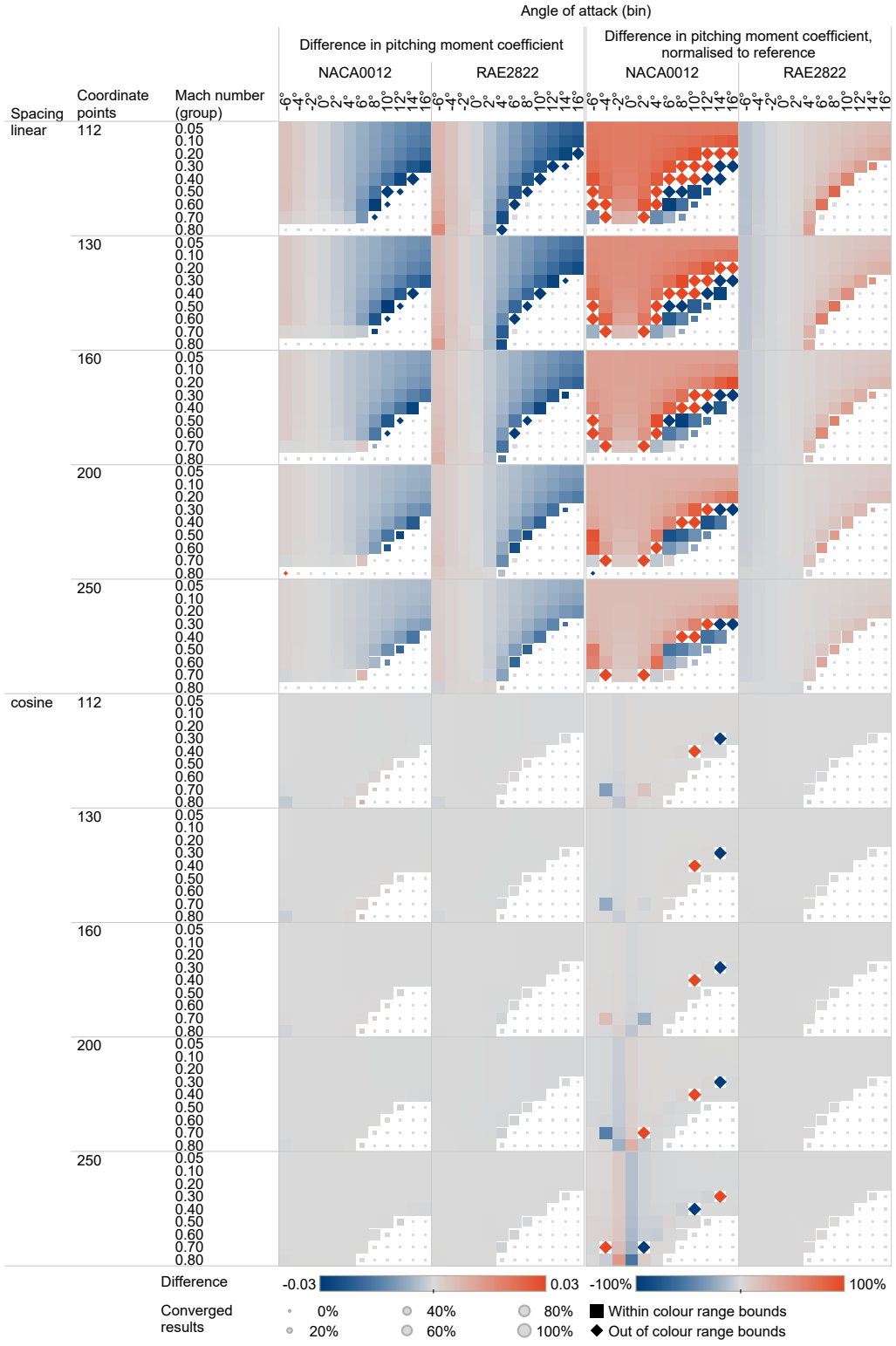
(d) Chordwise location of minimum pressure coefficient

Figure F.10: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



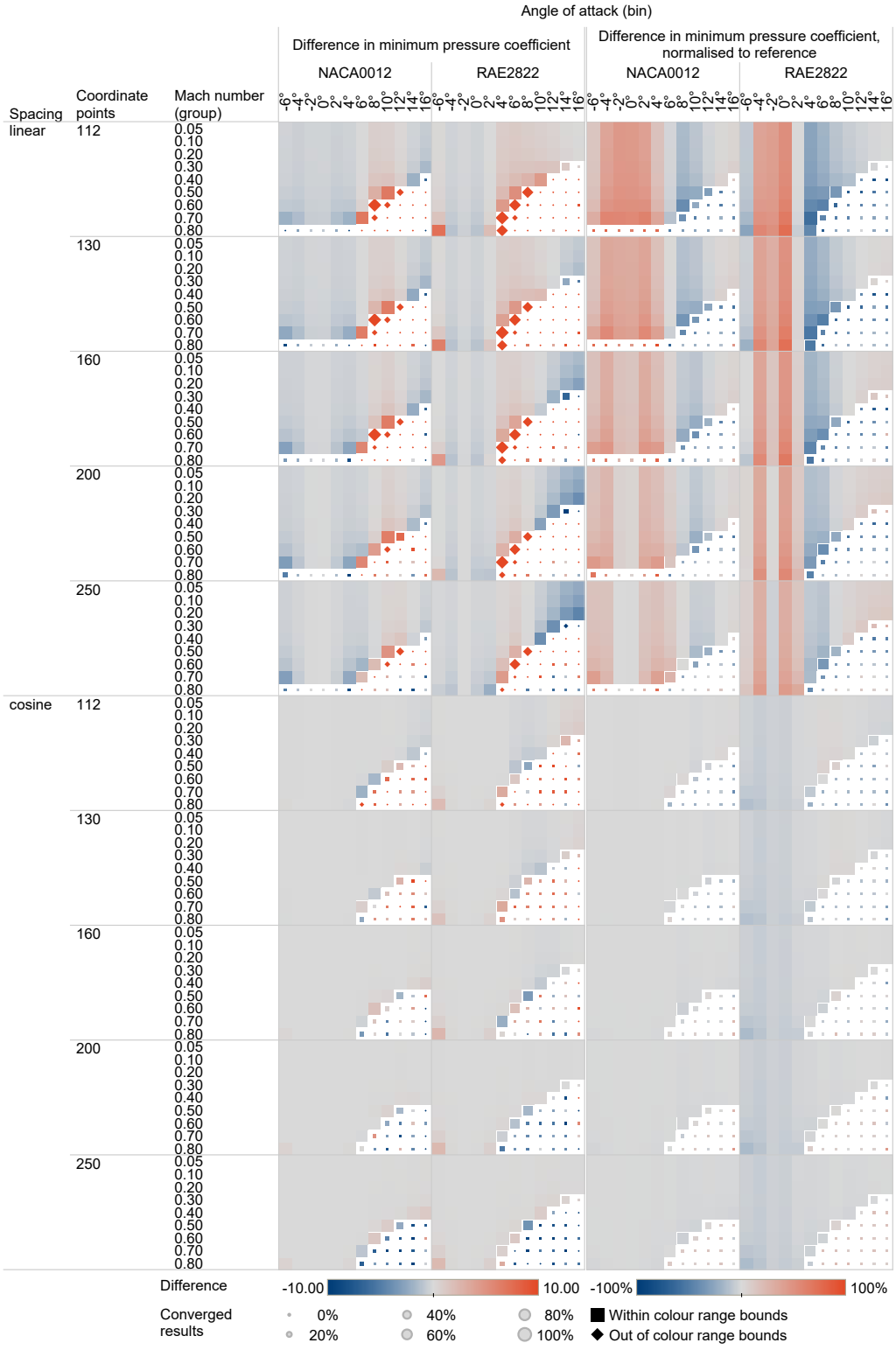
(a) Lift coefficient

Figure F.11: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack



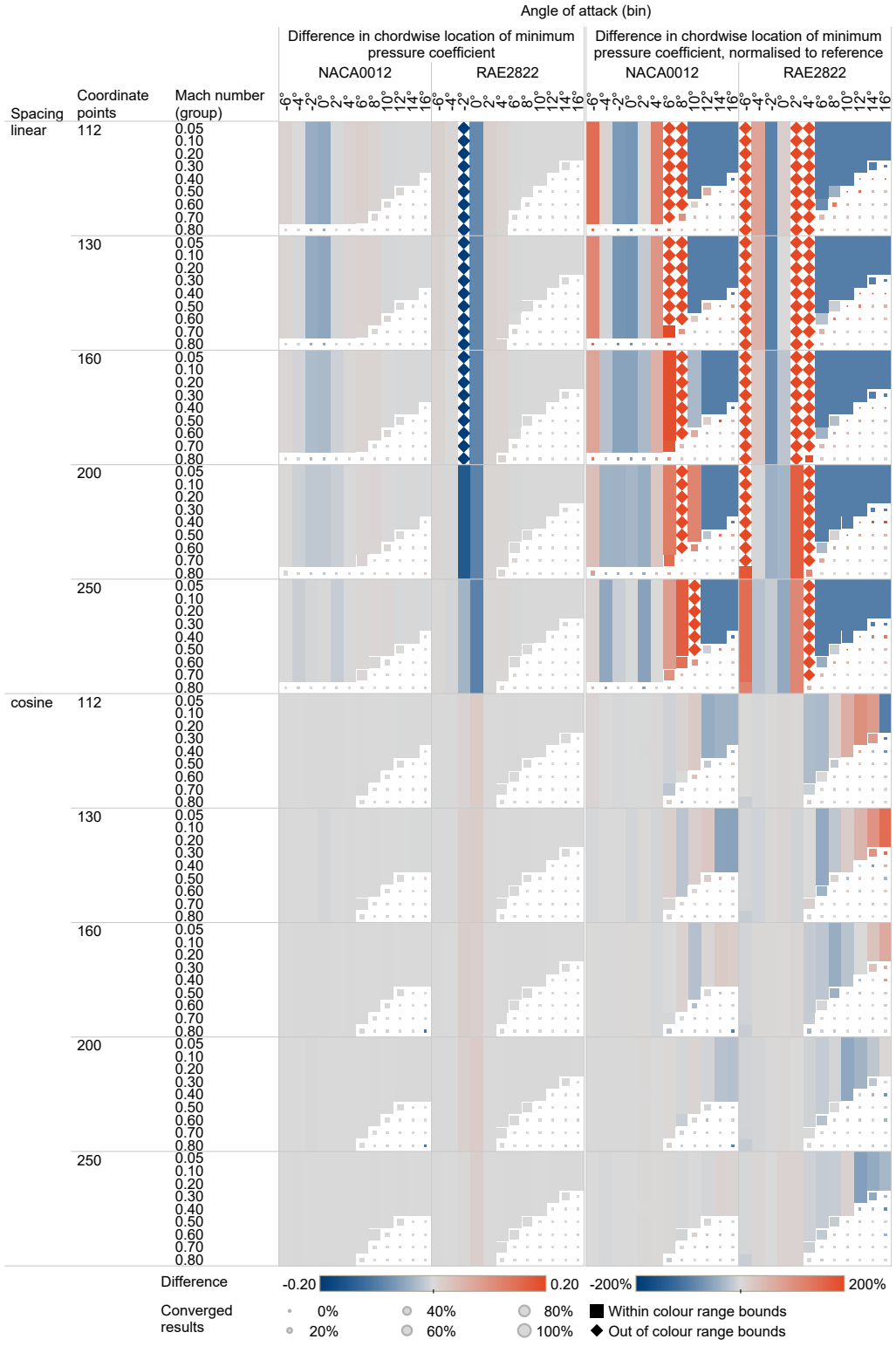
(b) Pitching moment coefficient

Figure F.11: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



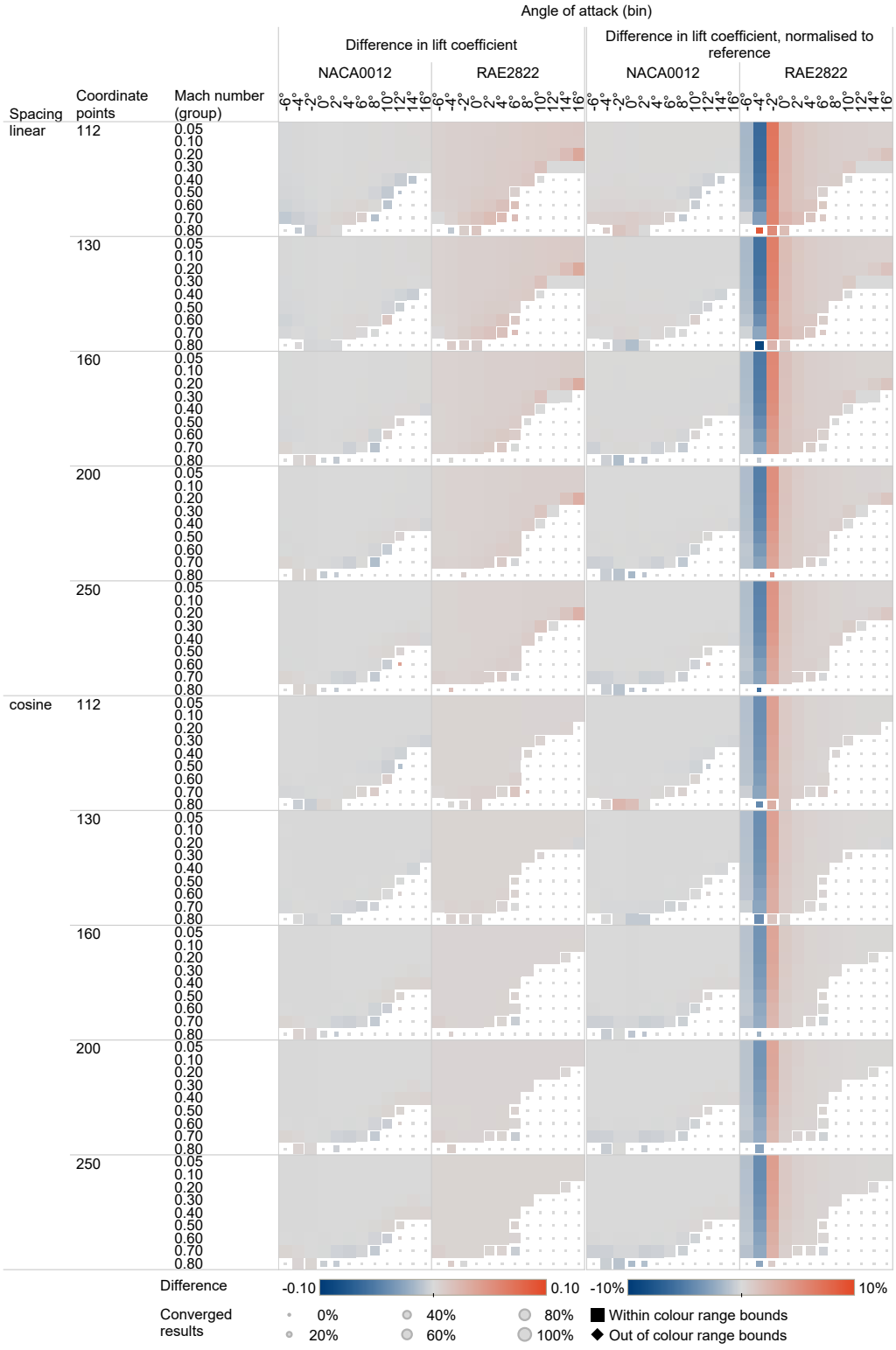
(c) Minimum pressure coefficient

Figure F.11: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



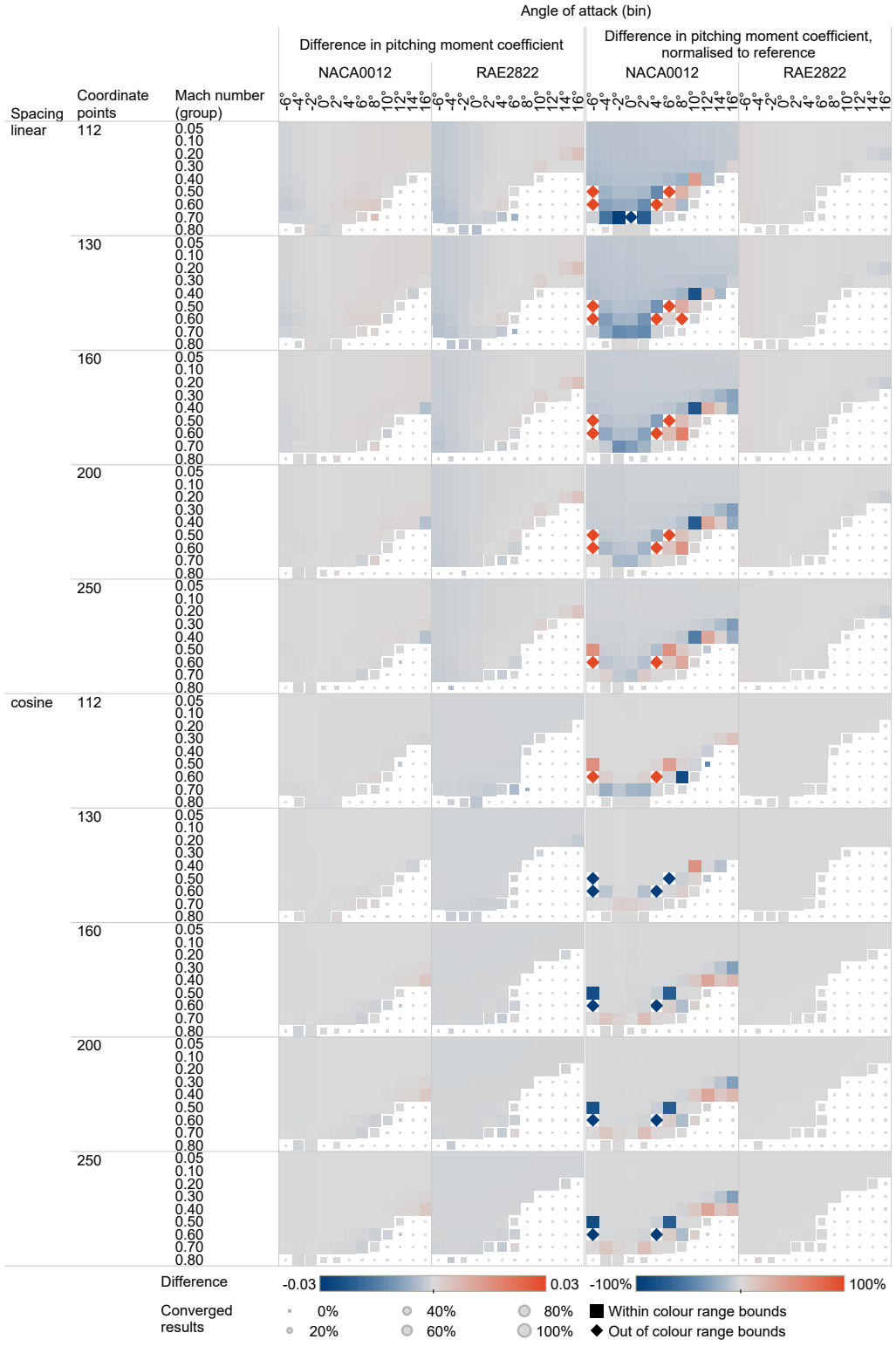
(d) Chordwise location of minimum pressure coefficient

Figure F.11: Difference in quantities of interest (true and normalised w.r.t. reference) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



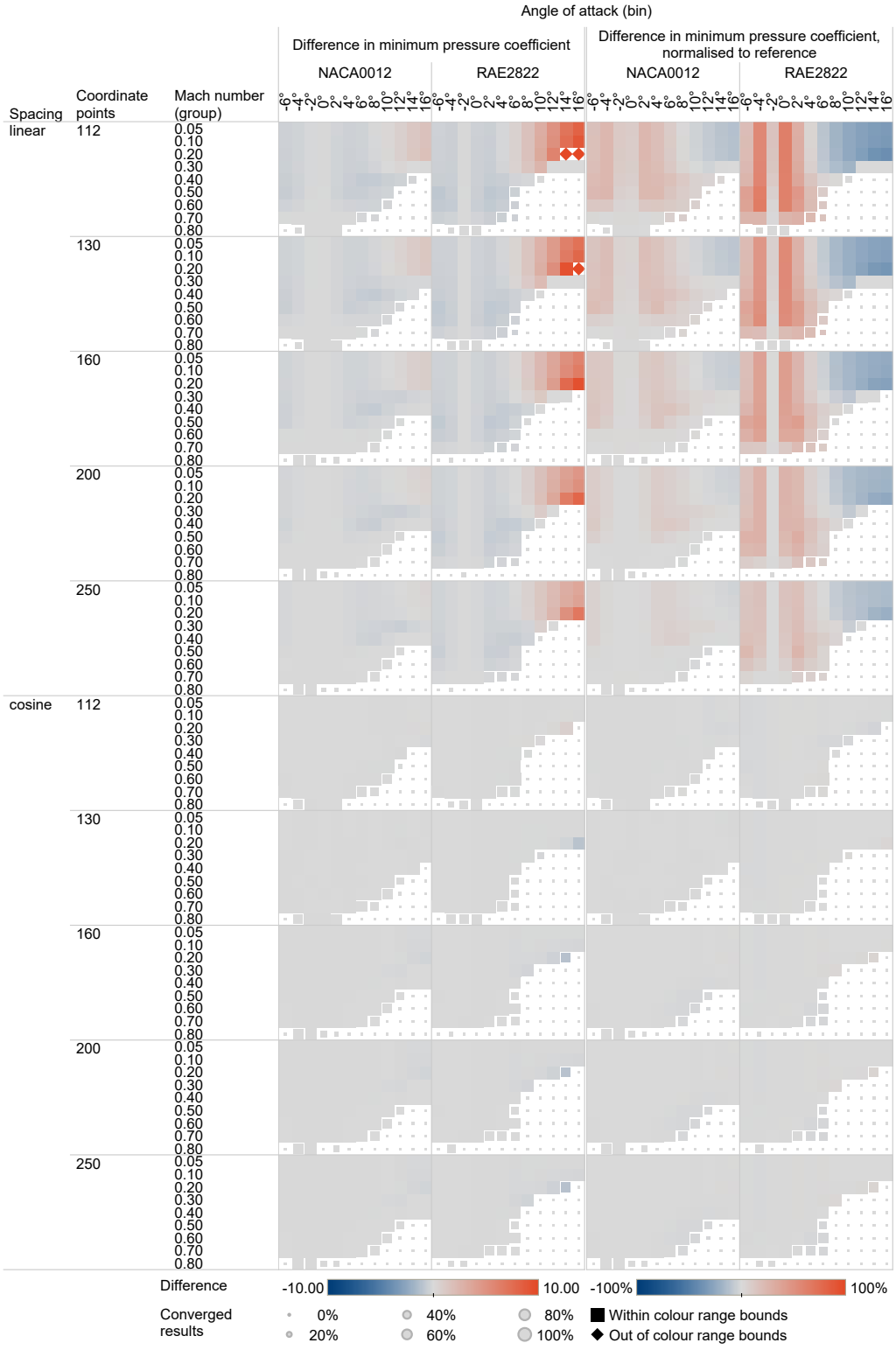
(a) Lift coefficient

Figure F.12: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack



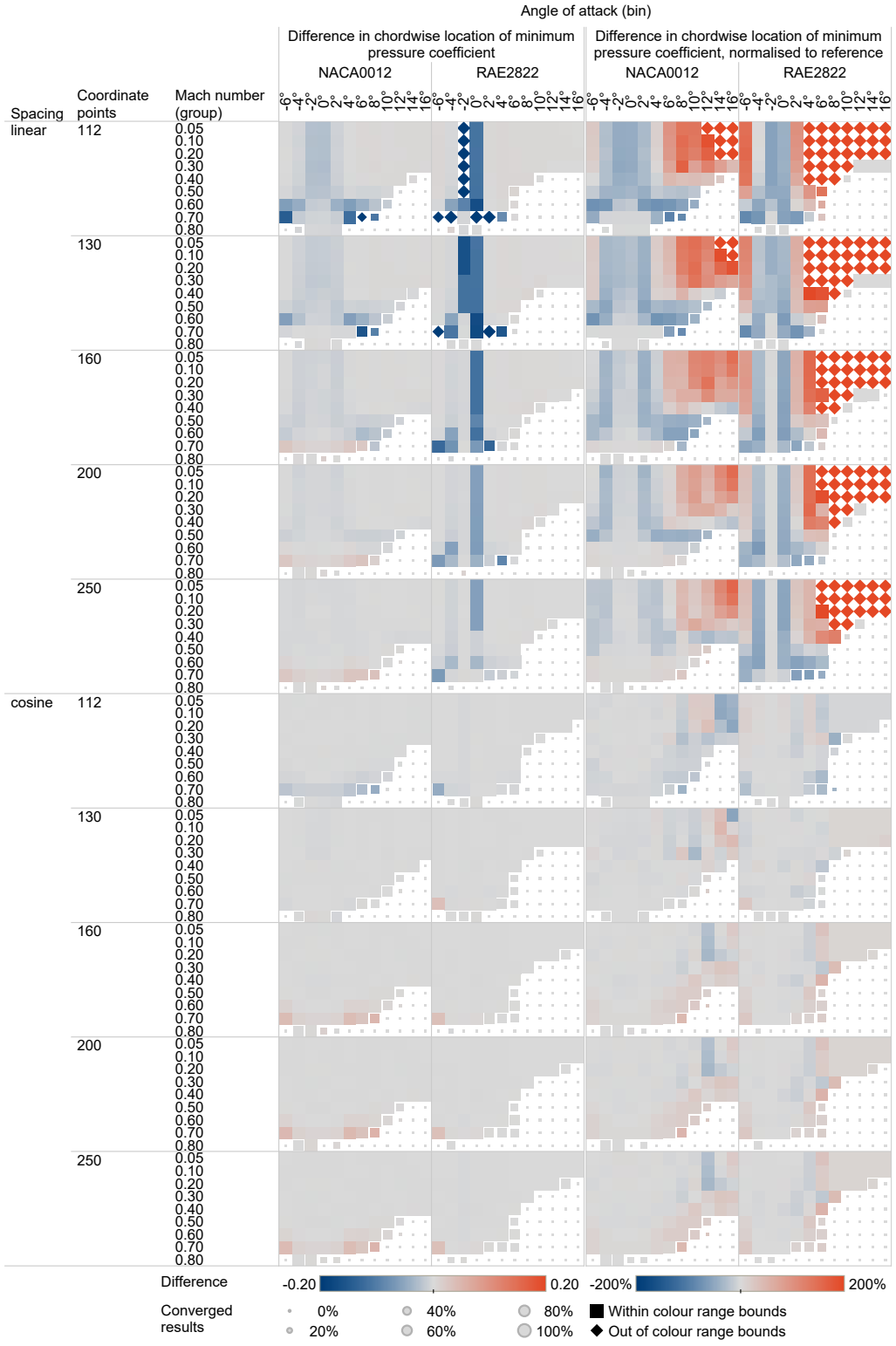
(b) Pitching moment coefficient

Figure F.12: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



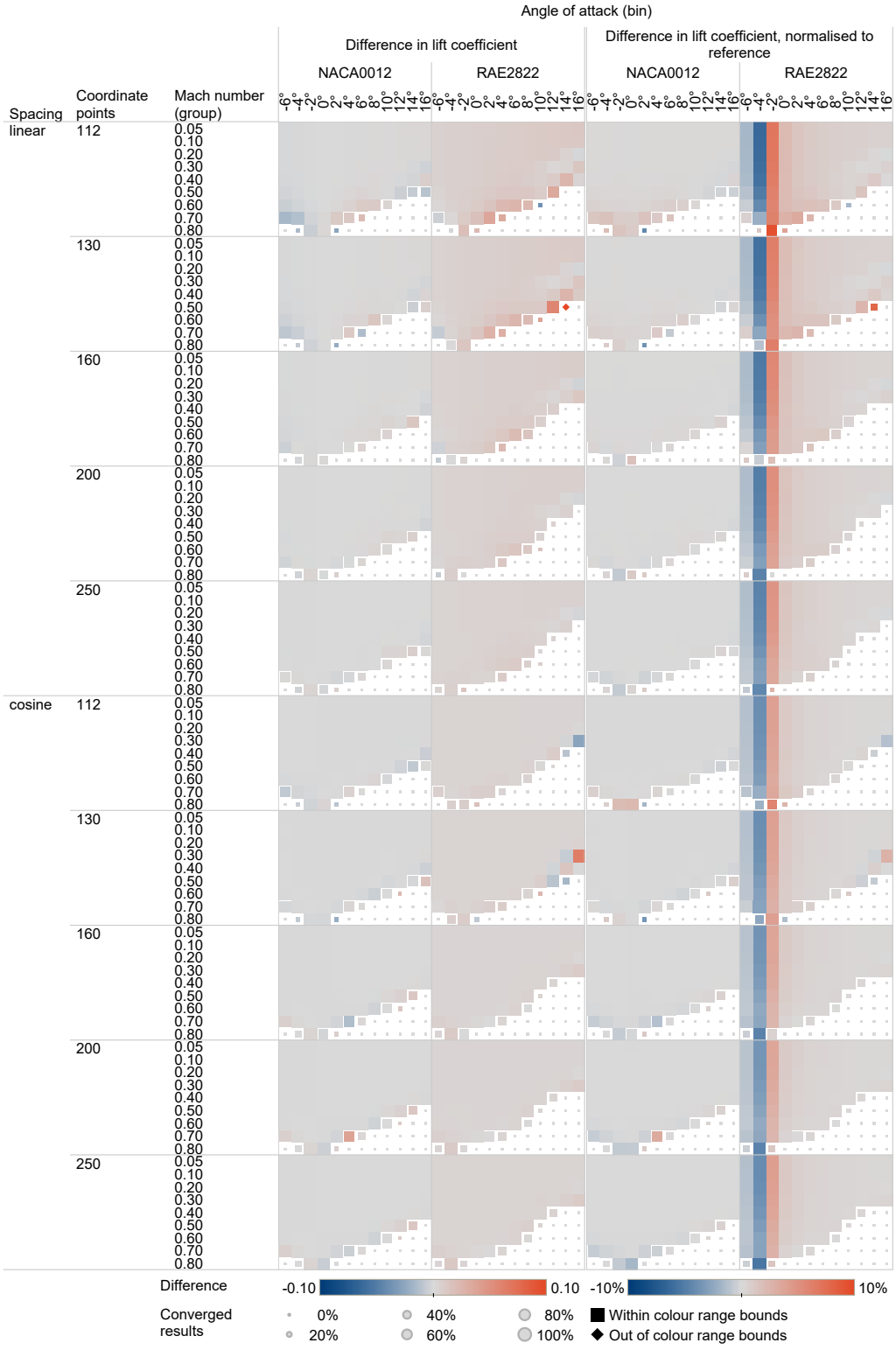
(c) Minimum pressure coefficient

Figure F.12: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



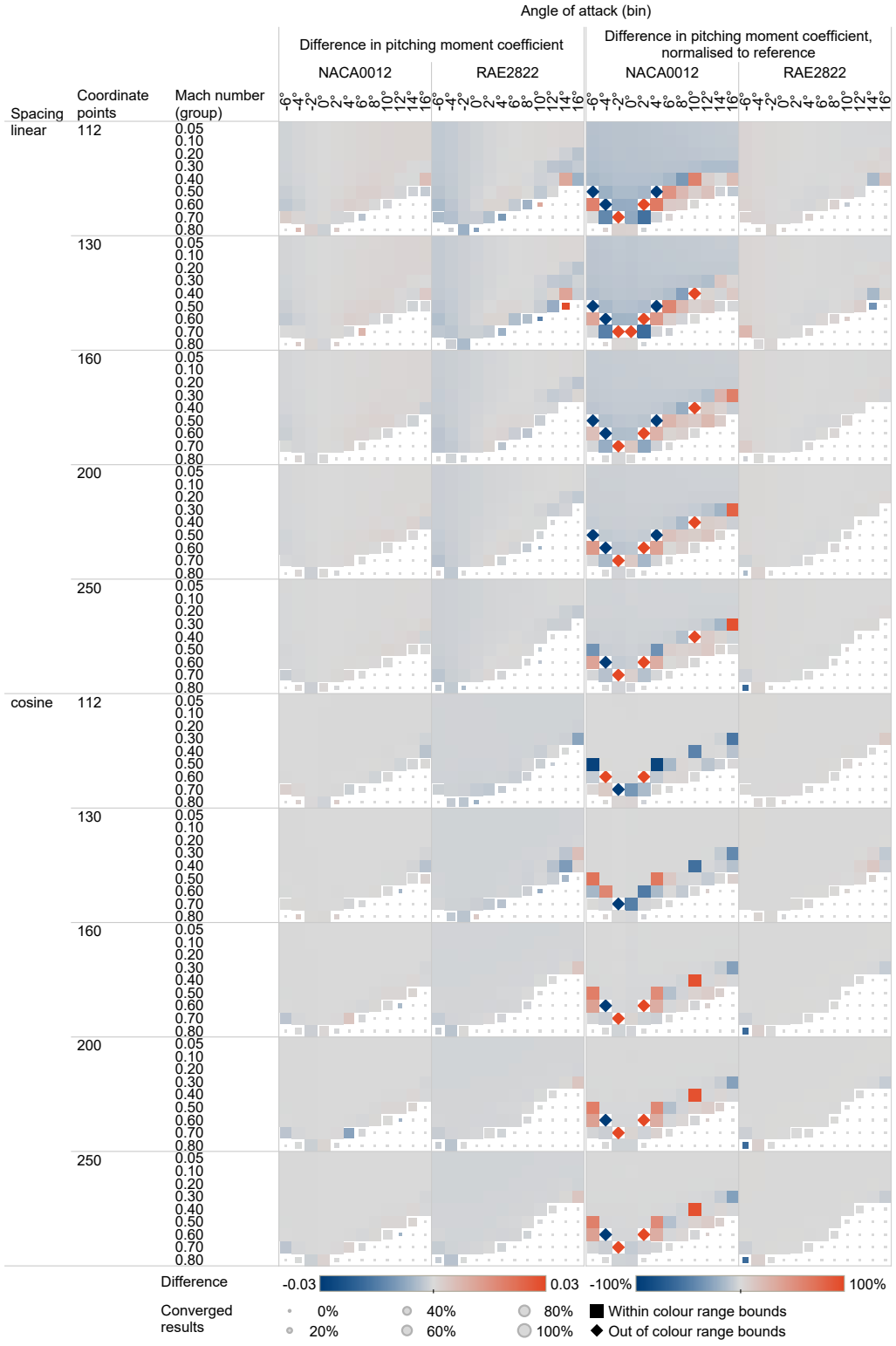
(d) Chordwise location of minimum pressure coefficient

Figure F.12: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



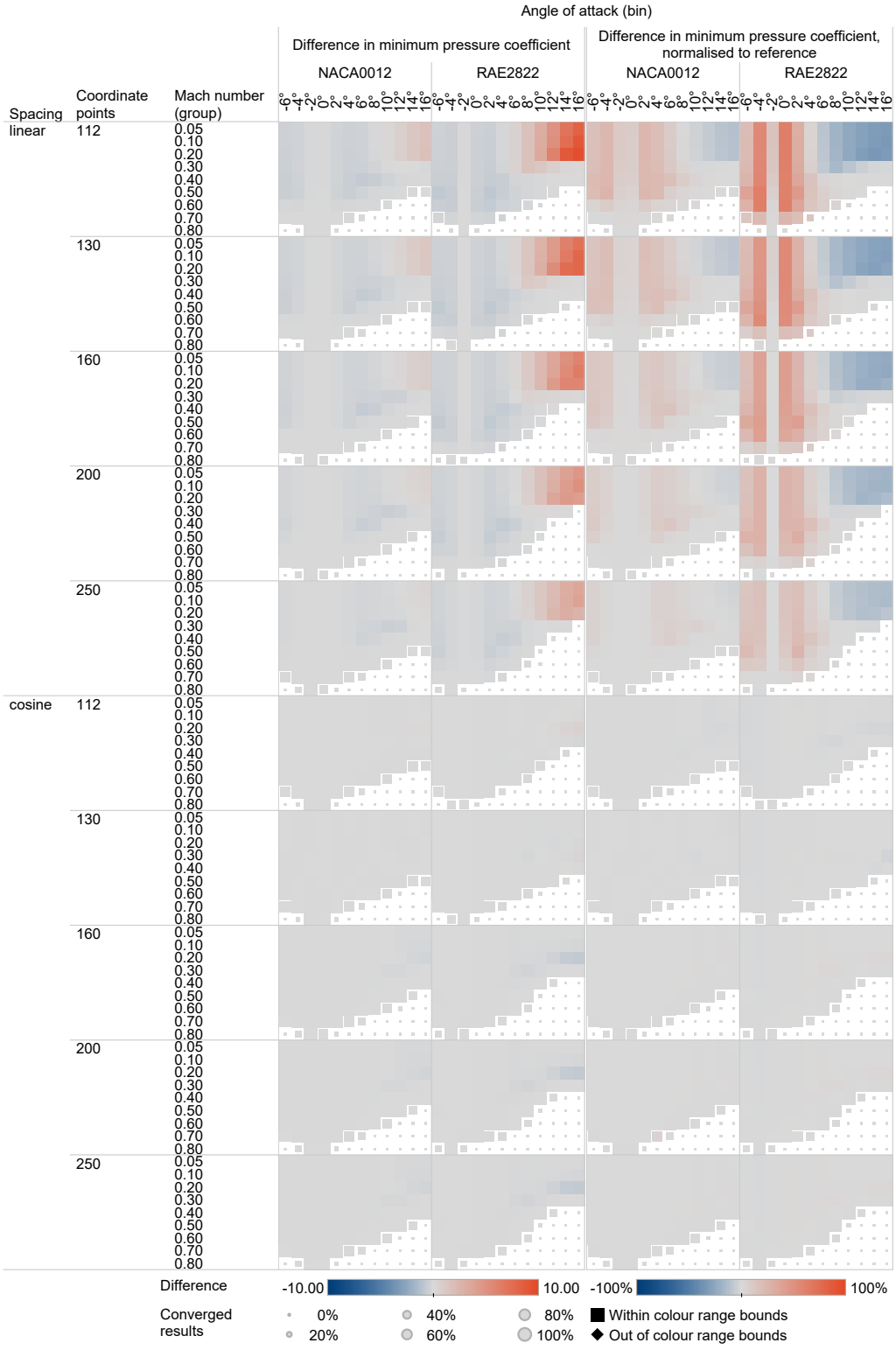
(a) Lift coefficient

Figure F.13: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack



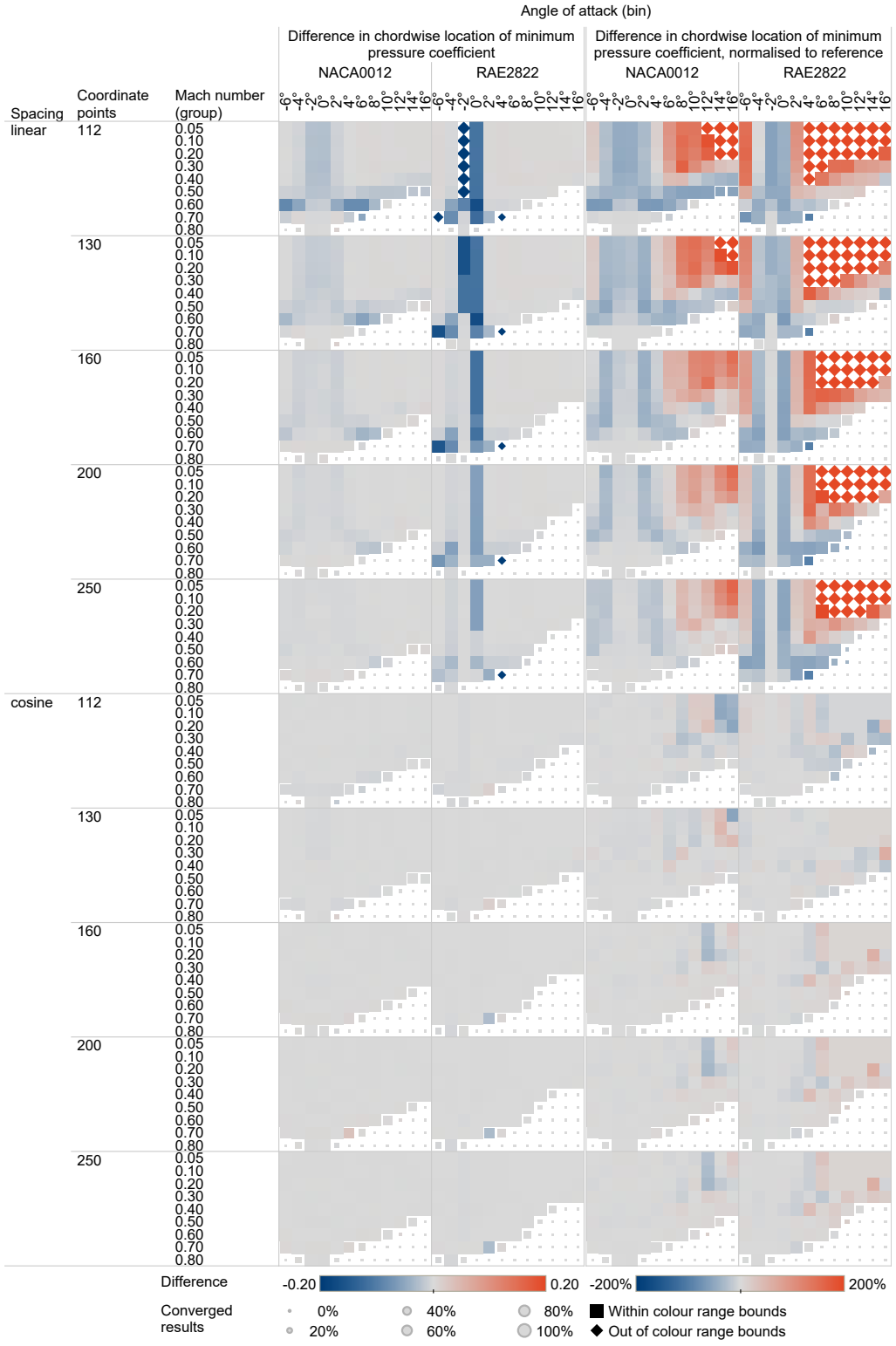
(b) Pitching moment coefficient

Figure F.13: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



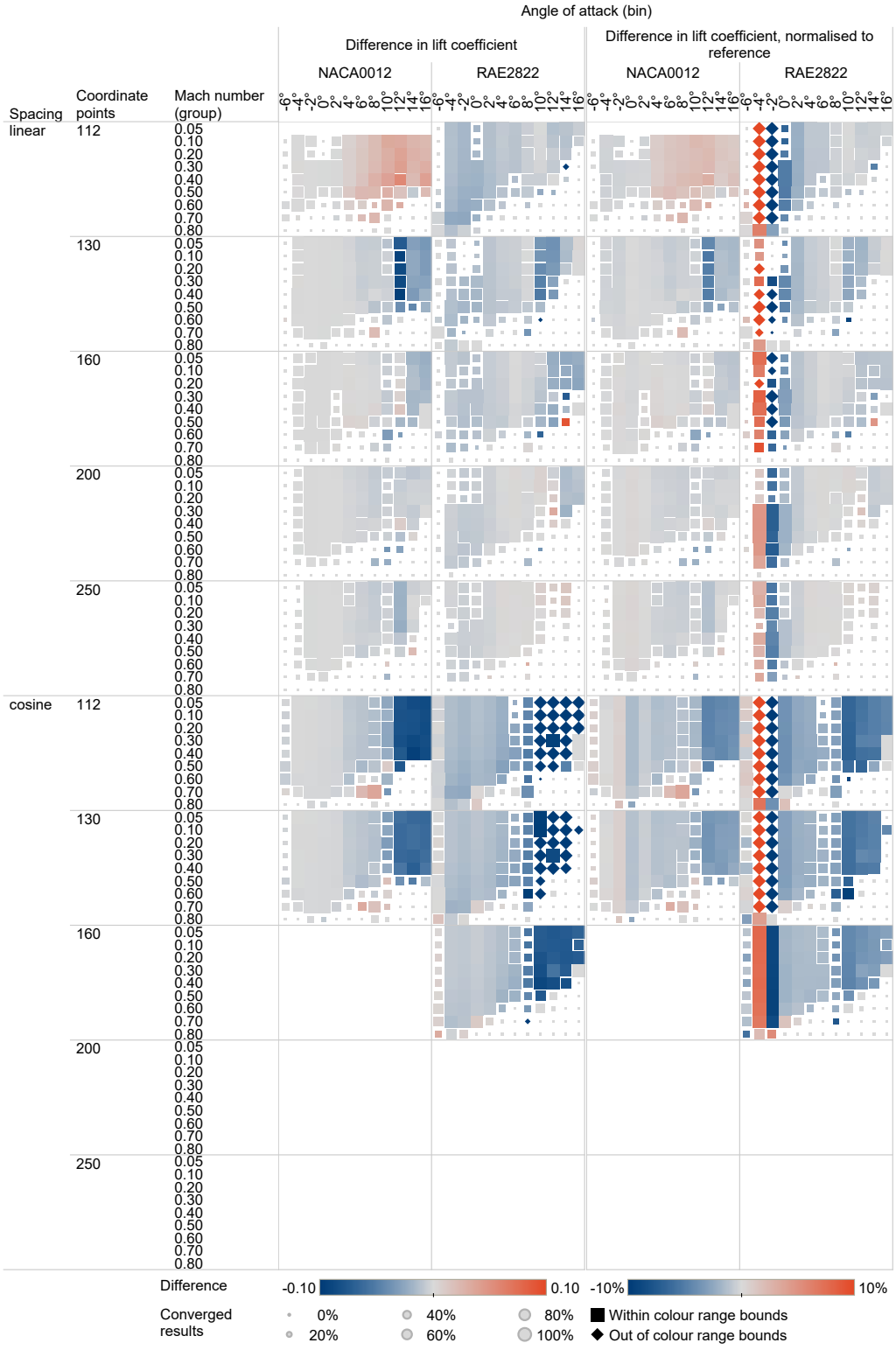
(c) Minimum pressure coefficient

Figure F.13: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



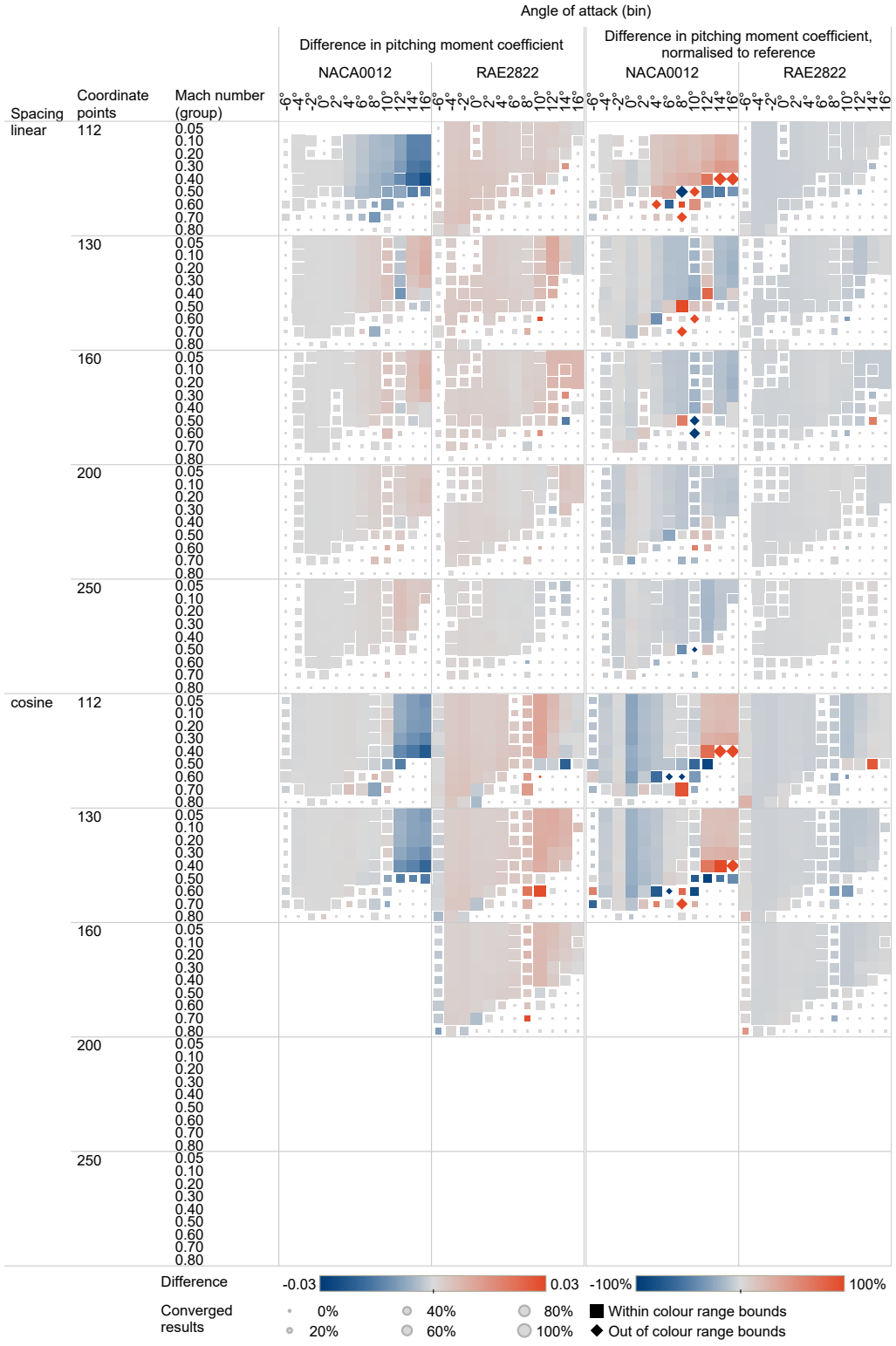
(d) Chordwise location of minimum pressure coefficient

Figure F.13: Difference in quantities of interest (true and normalised w.r.t. reference) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



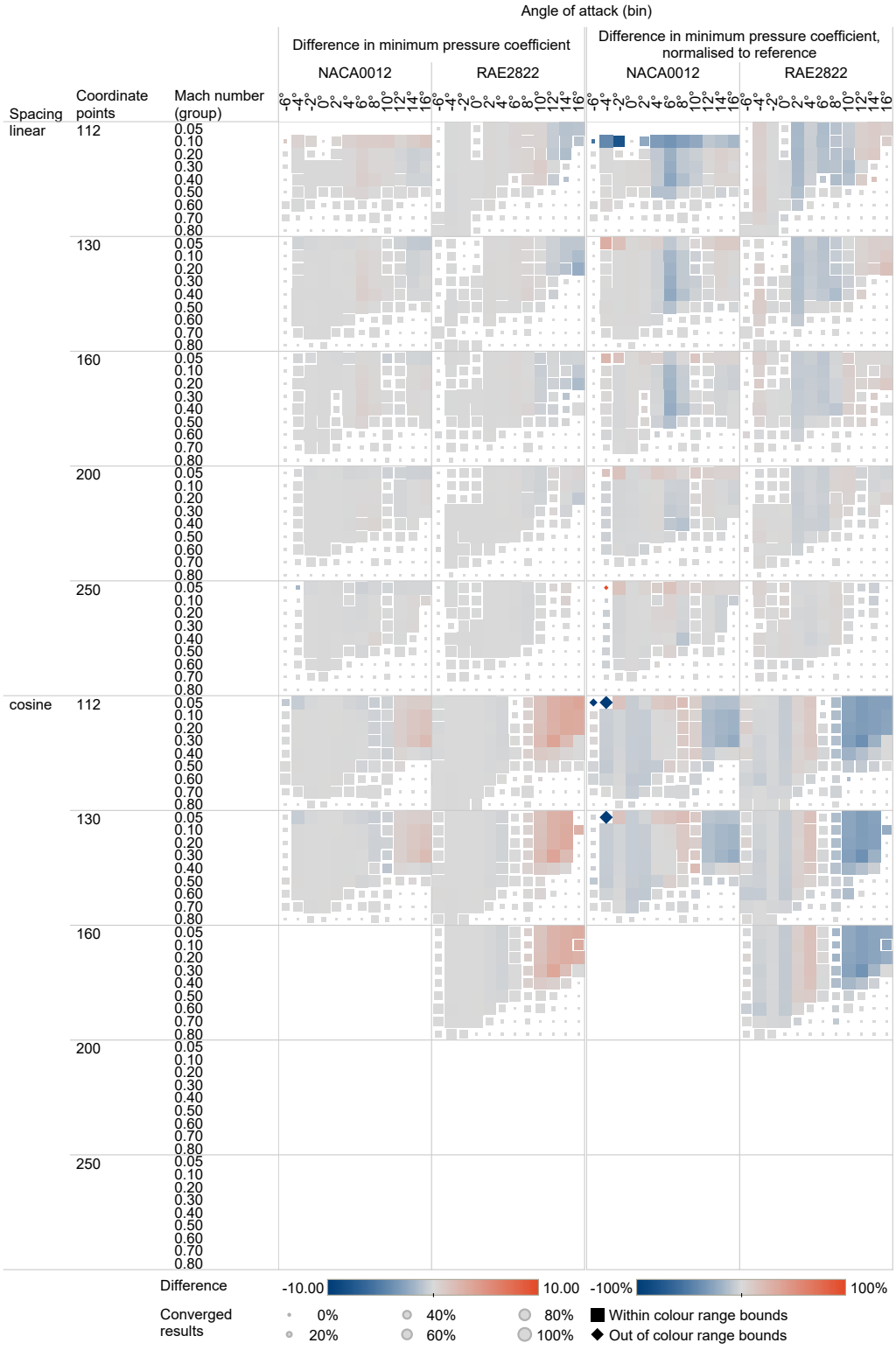
(a) Lift coefficient

Figure F.14: Difference in quantities of interest (true and normalised w.r.t. reference) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack



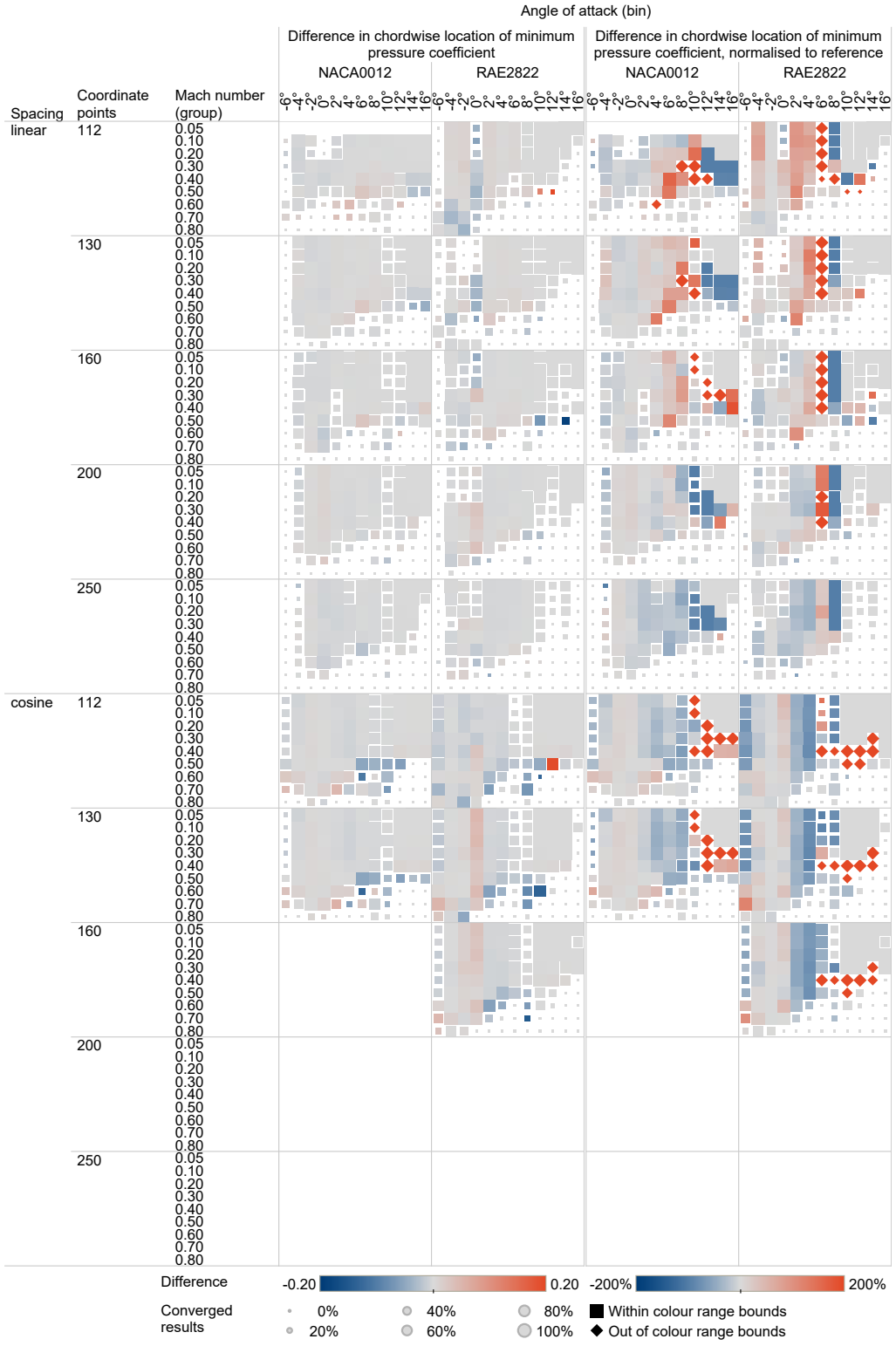
(b) Pitching moment coefficient

Figure F.14: Difference in quantities of interest (true and normalised w.r.t. reference) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



(c) Minimum pressure coefficient

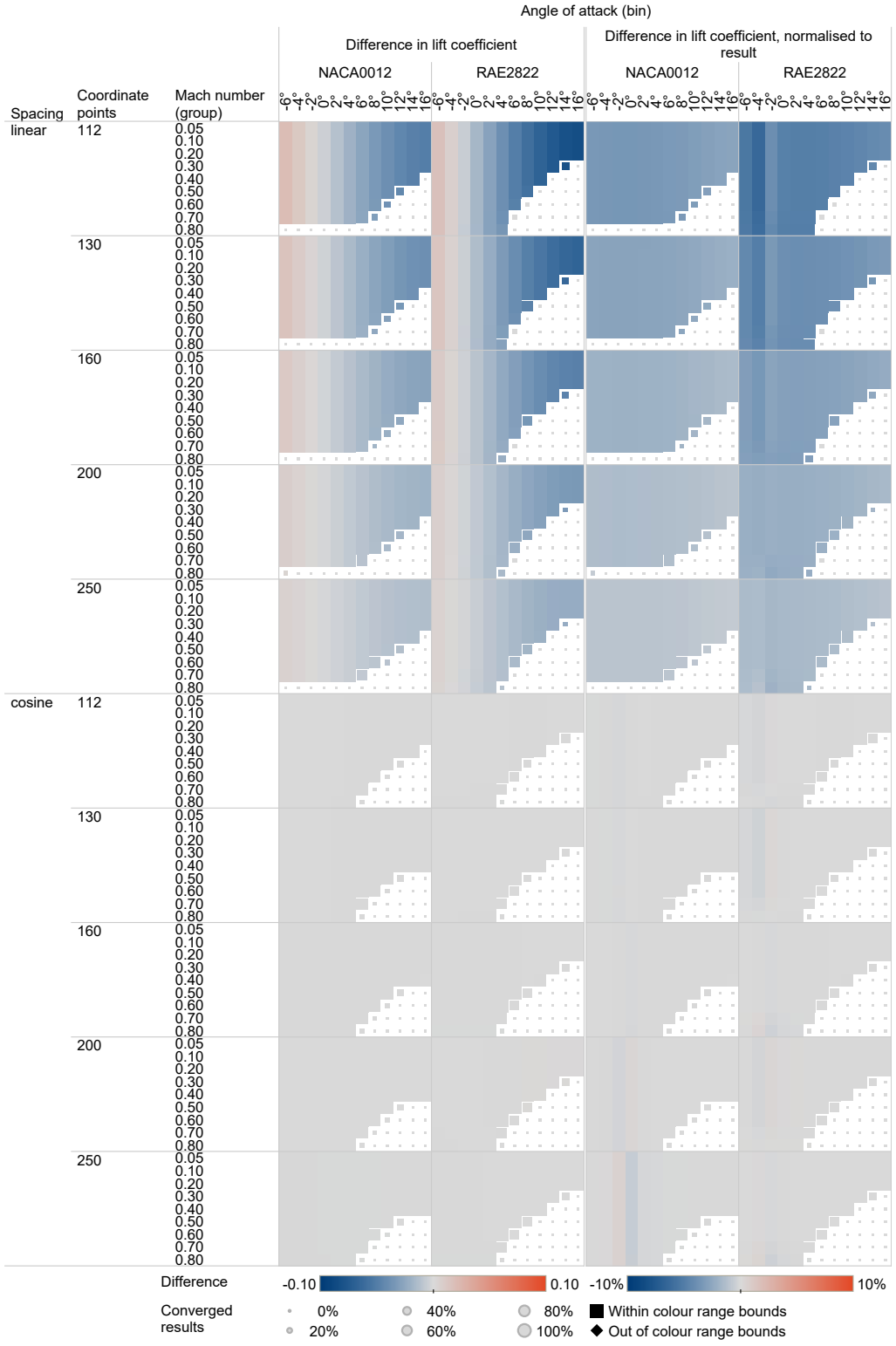
Figure F.14: Difference in quantities of interest (true and normalised w.r.t. reference) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



(d) Chordwise location of minimum pressure coefficient

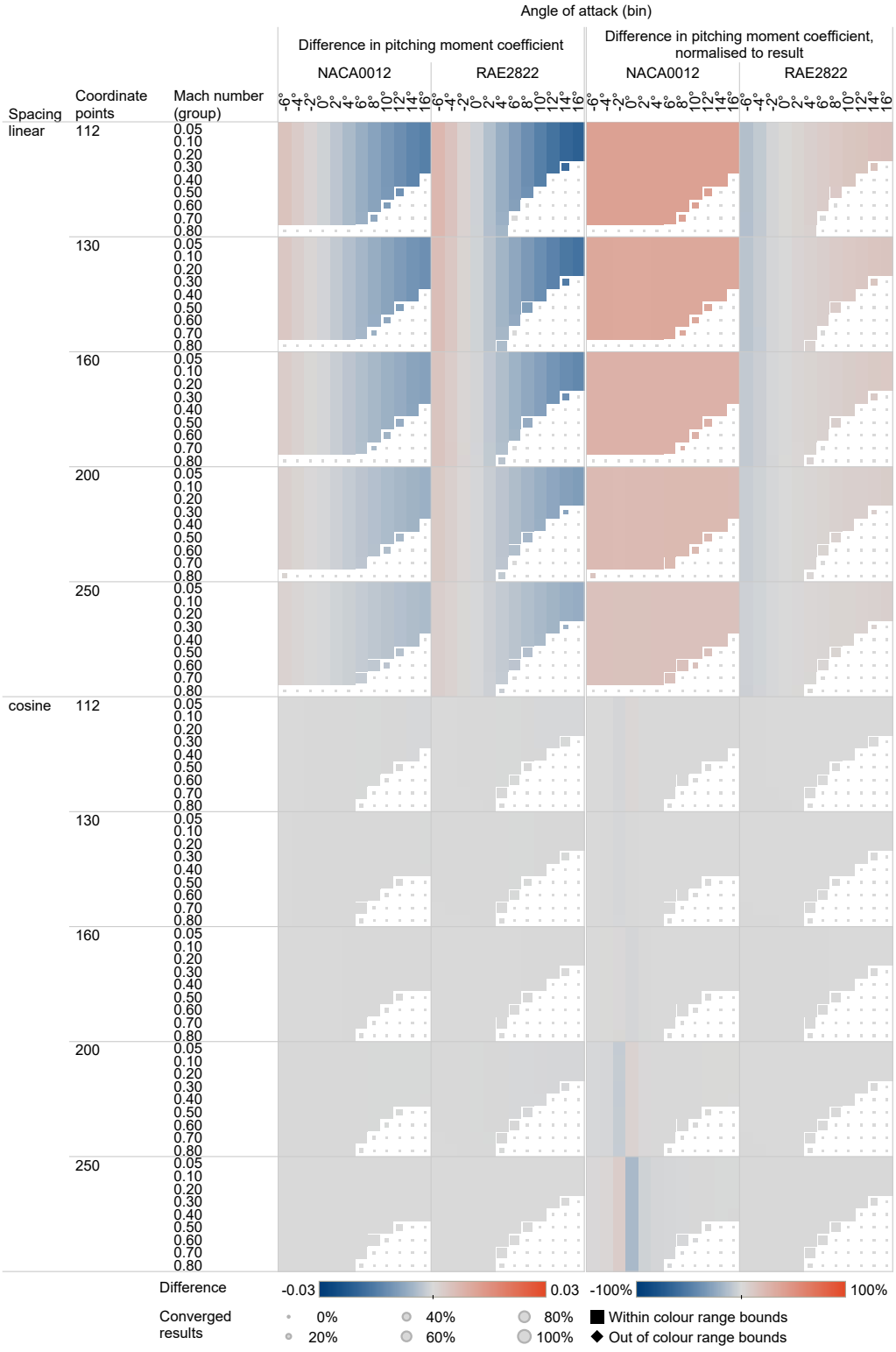
Figure F.14: Difference in quantities of interest (true and normalised w.r.t. reference) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)

Normalised to result



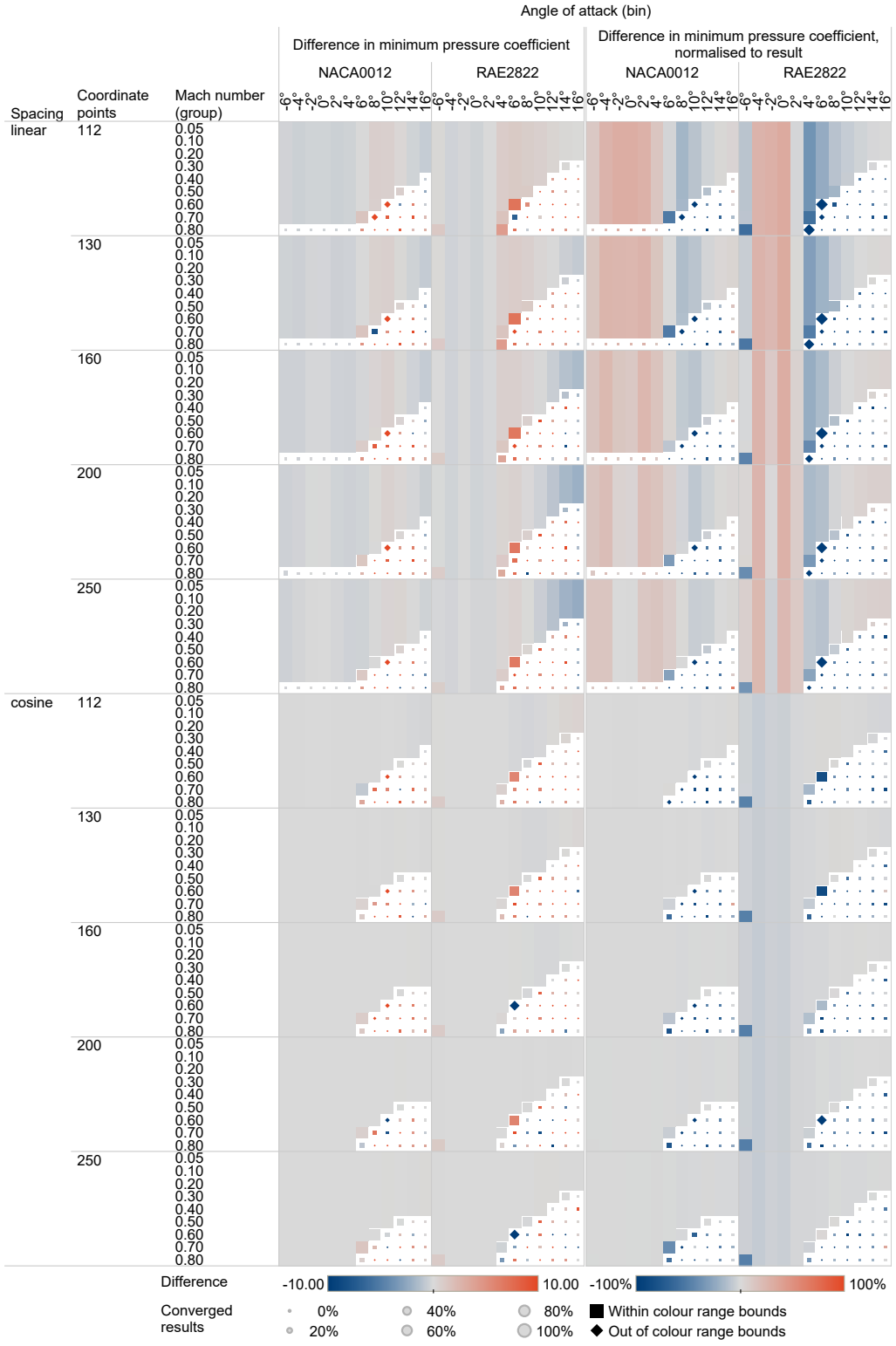
(a) Lift coefficient

Figure F.15: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack



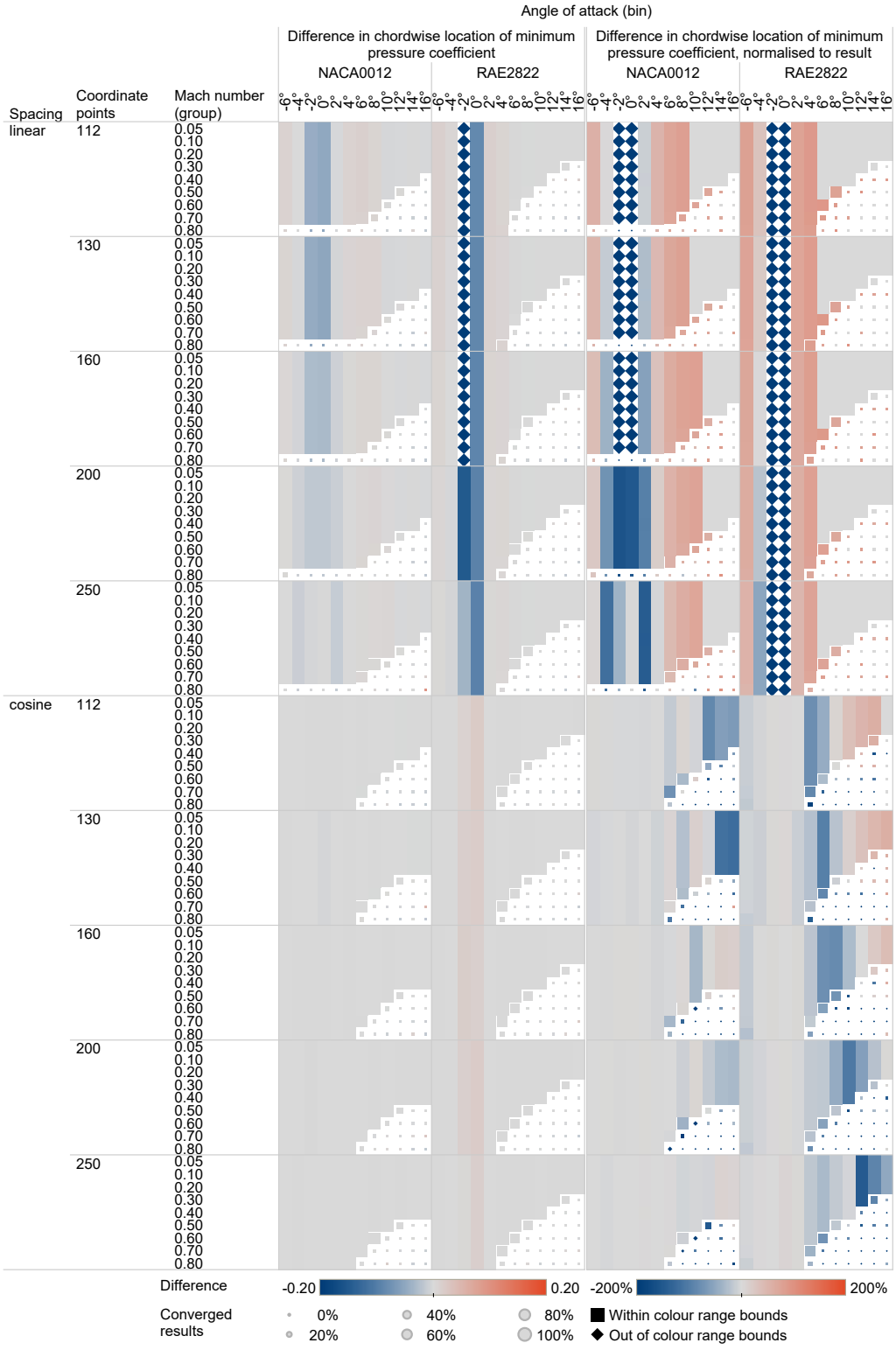
(b) Pitching moment coefficient

Figure F.15: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



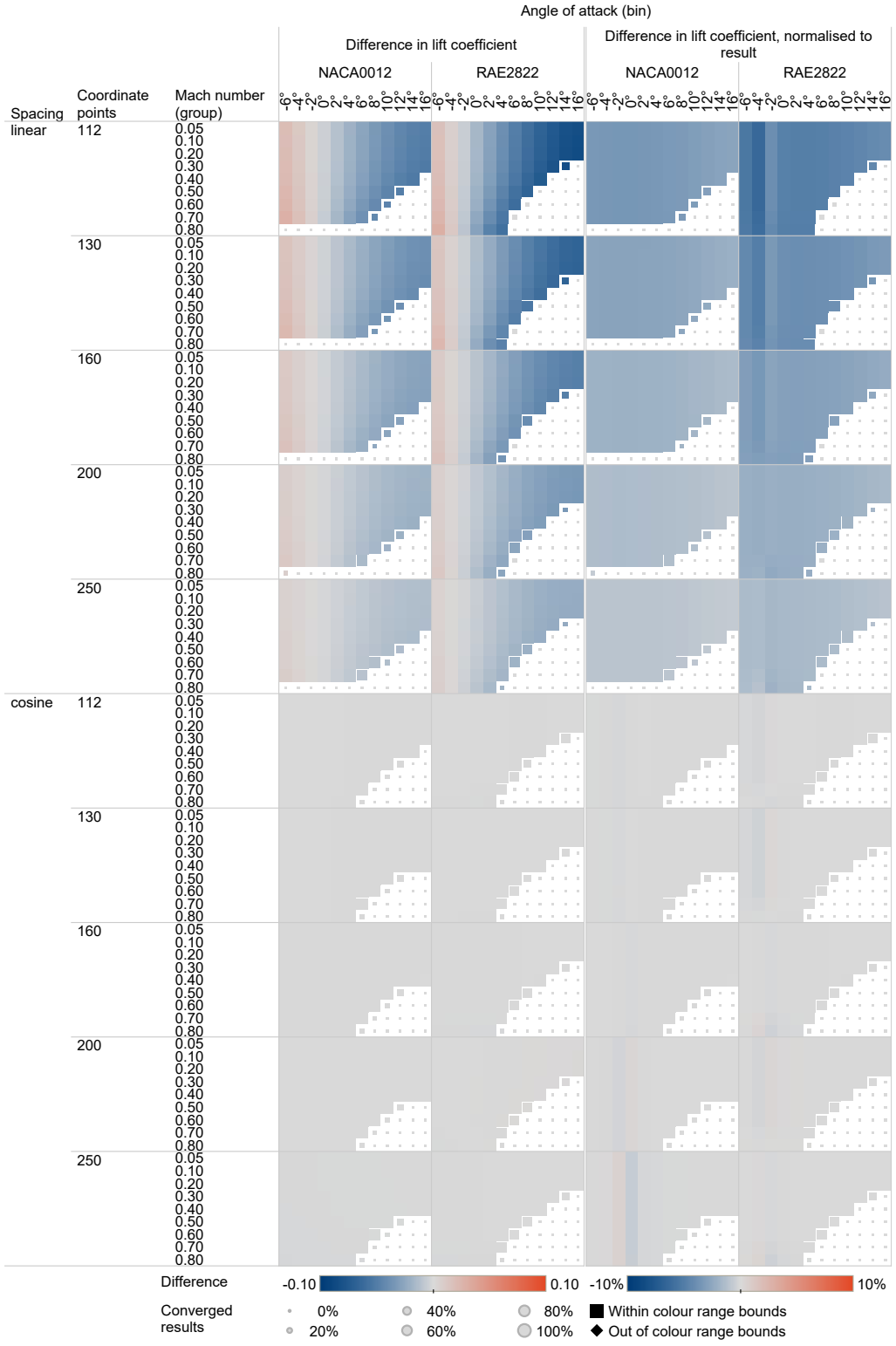
(c) Minimum pressure coefficient

Figure F.15: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



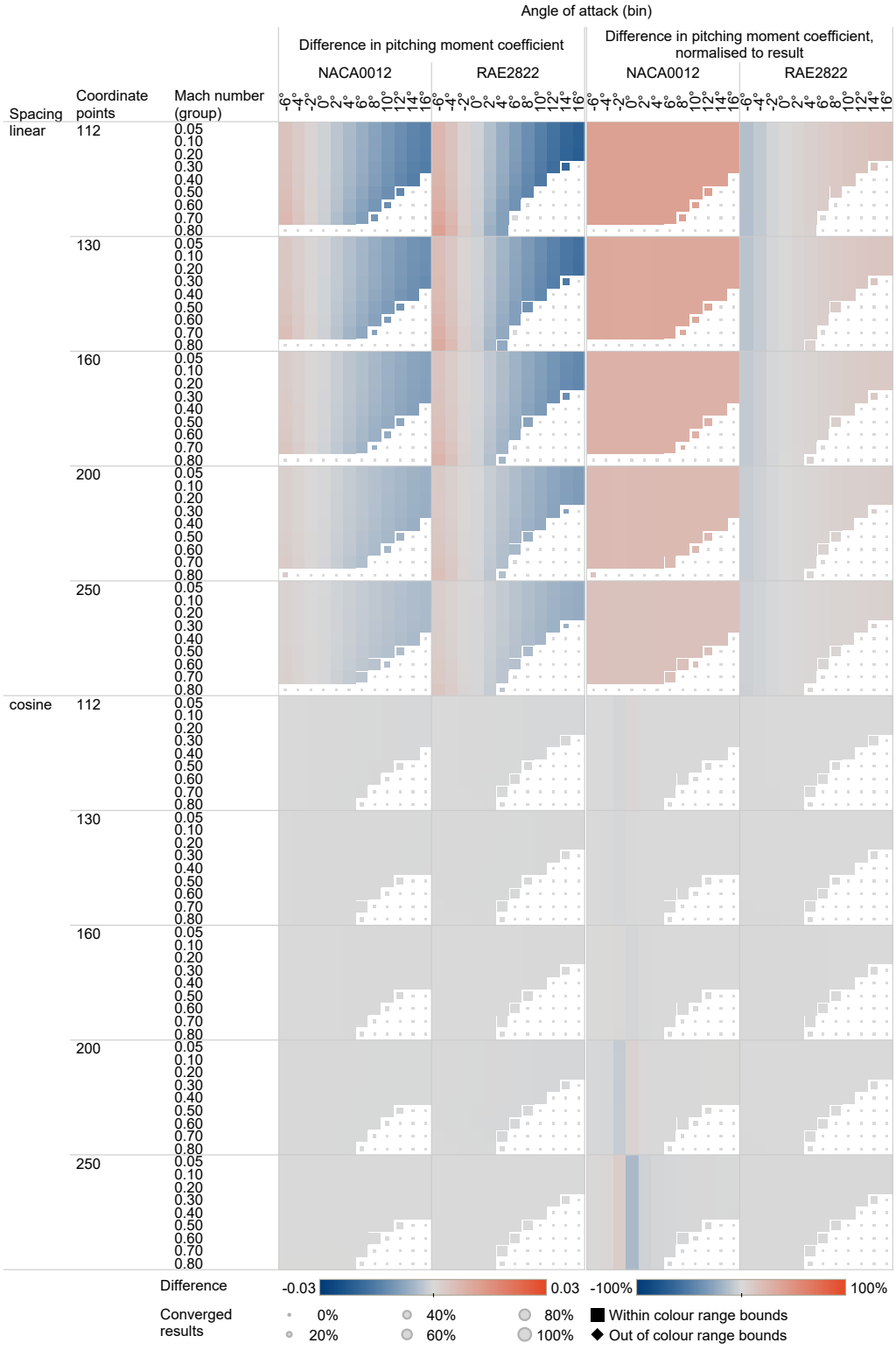
(d) Chordwise location of minimum pressure coefficient

Figure F.15: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



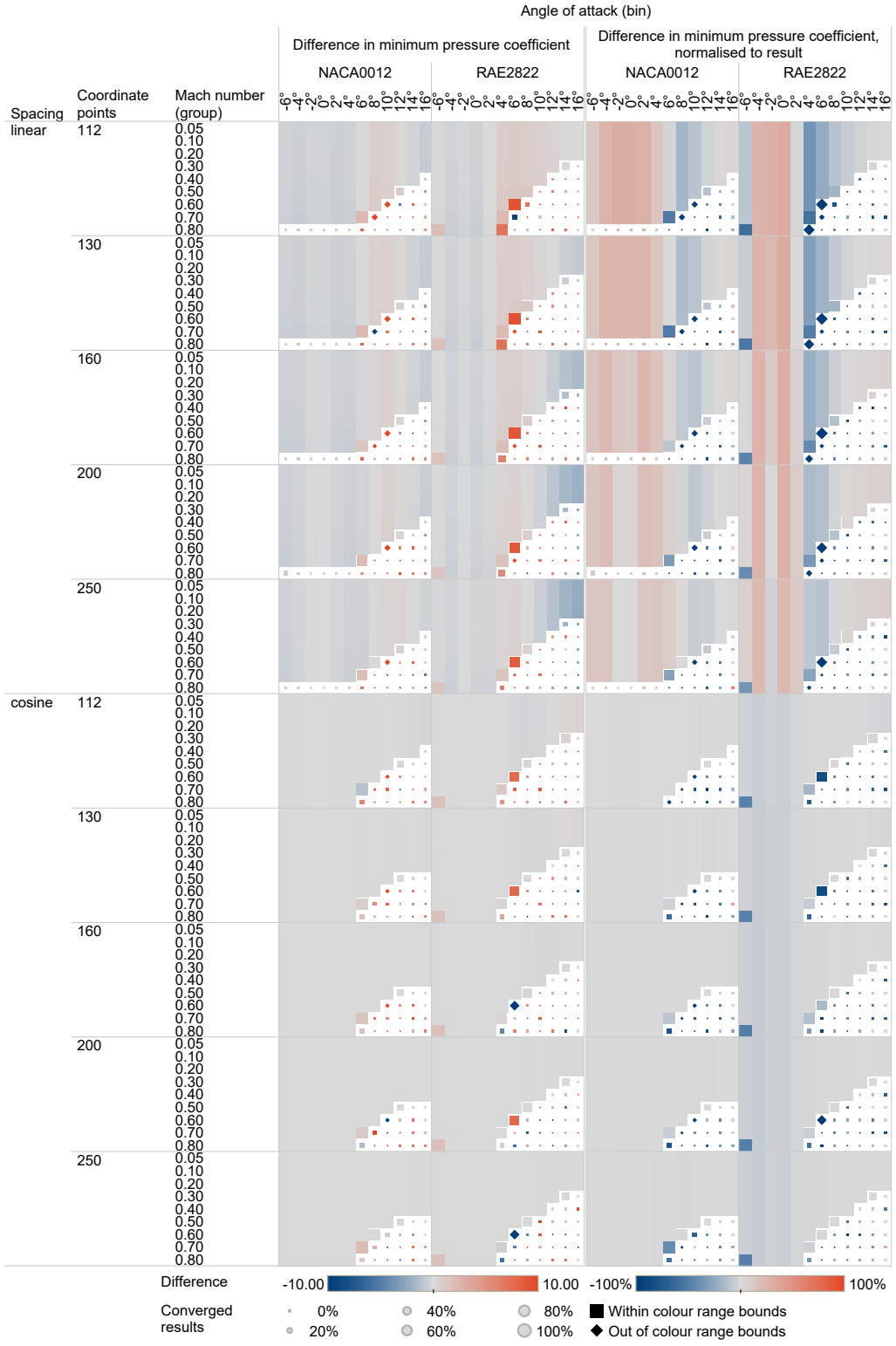
(a) Lift coefficient

Figure F.16: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack



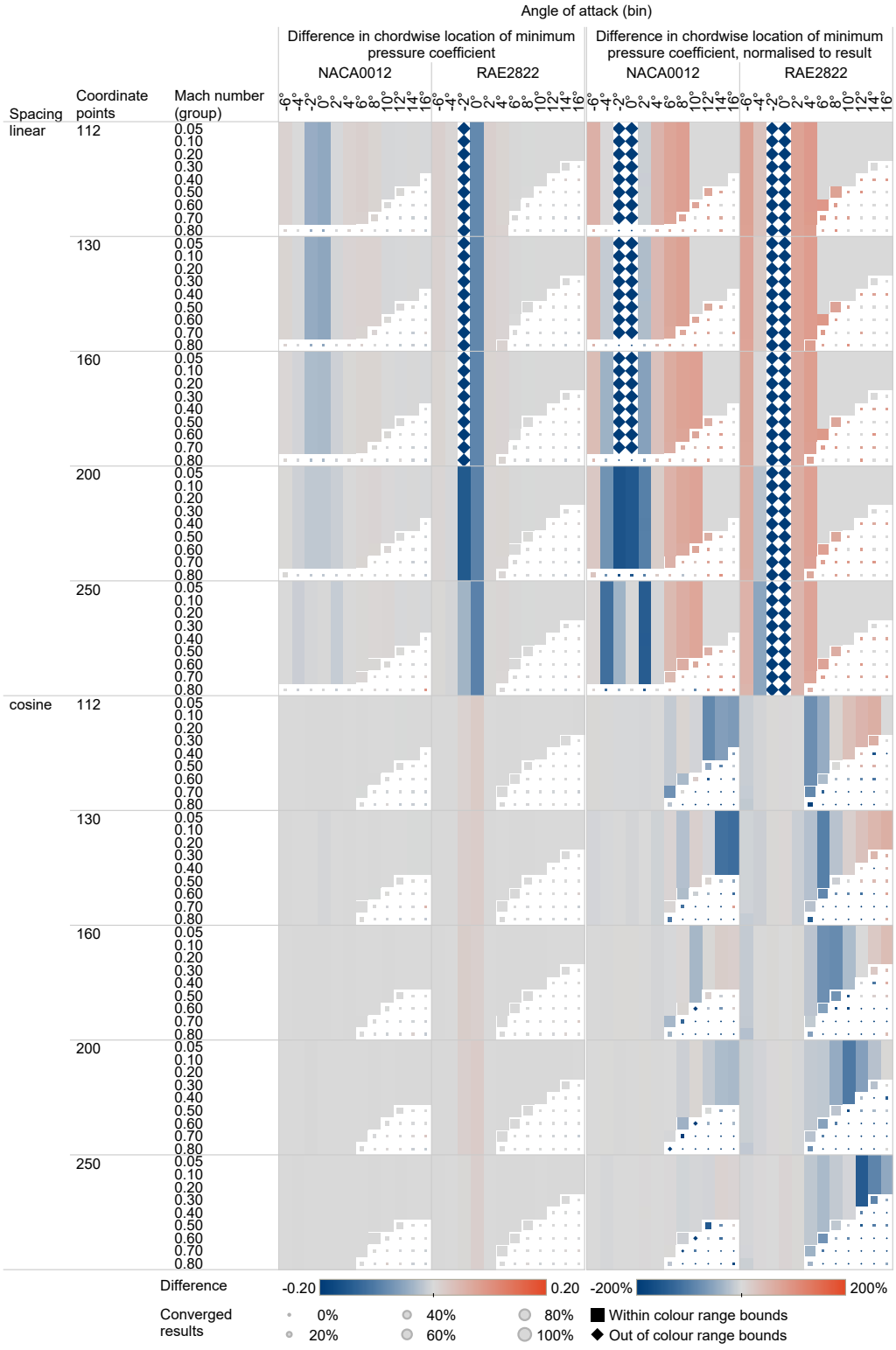
(b) Pitching moment coefficient

Figure F.16: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



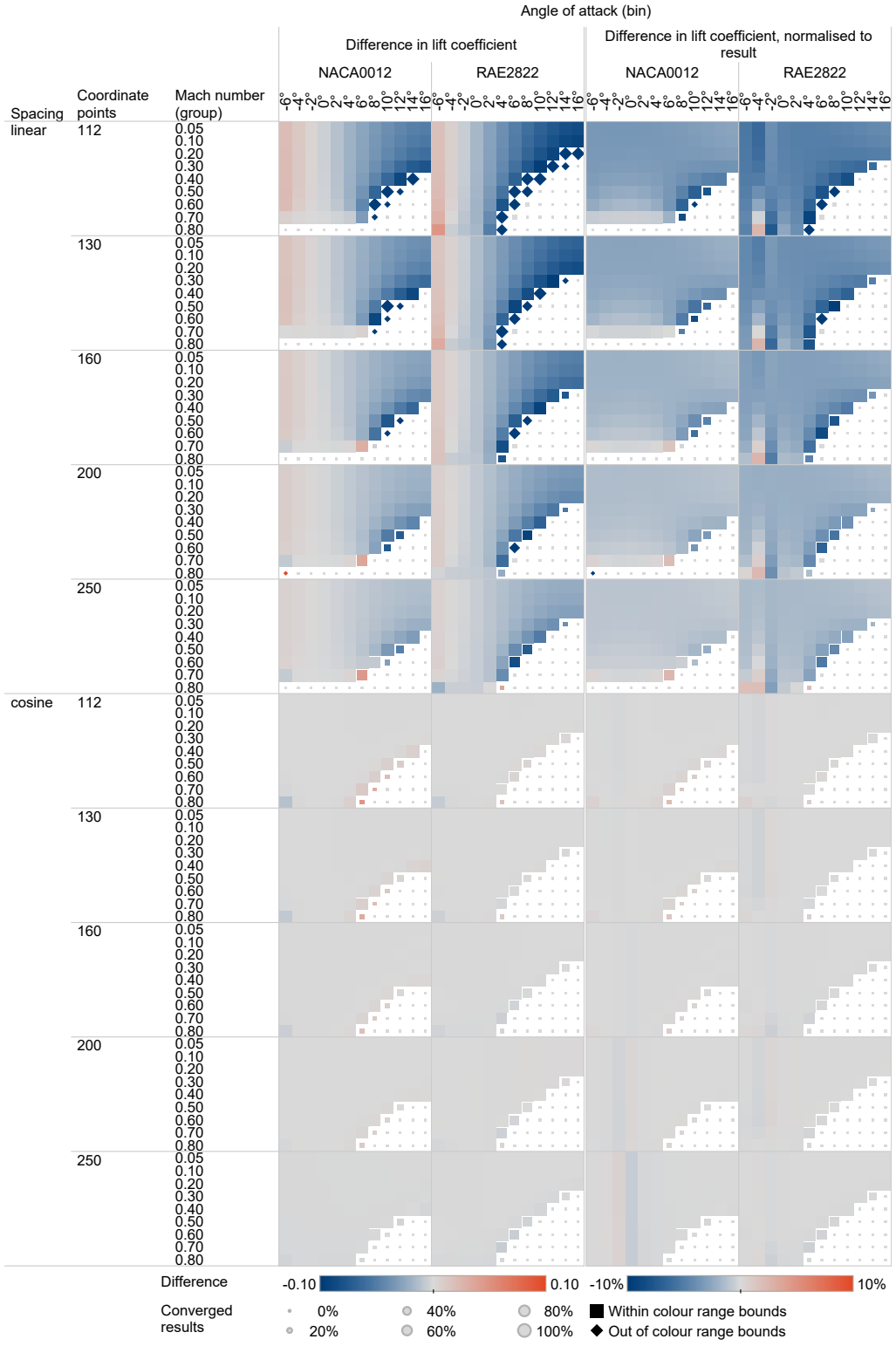
(c) Minimum pressure coefficient

Figure F.16: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



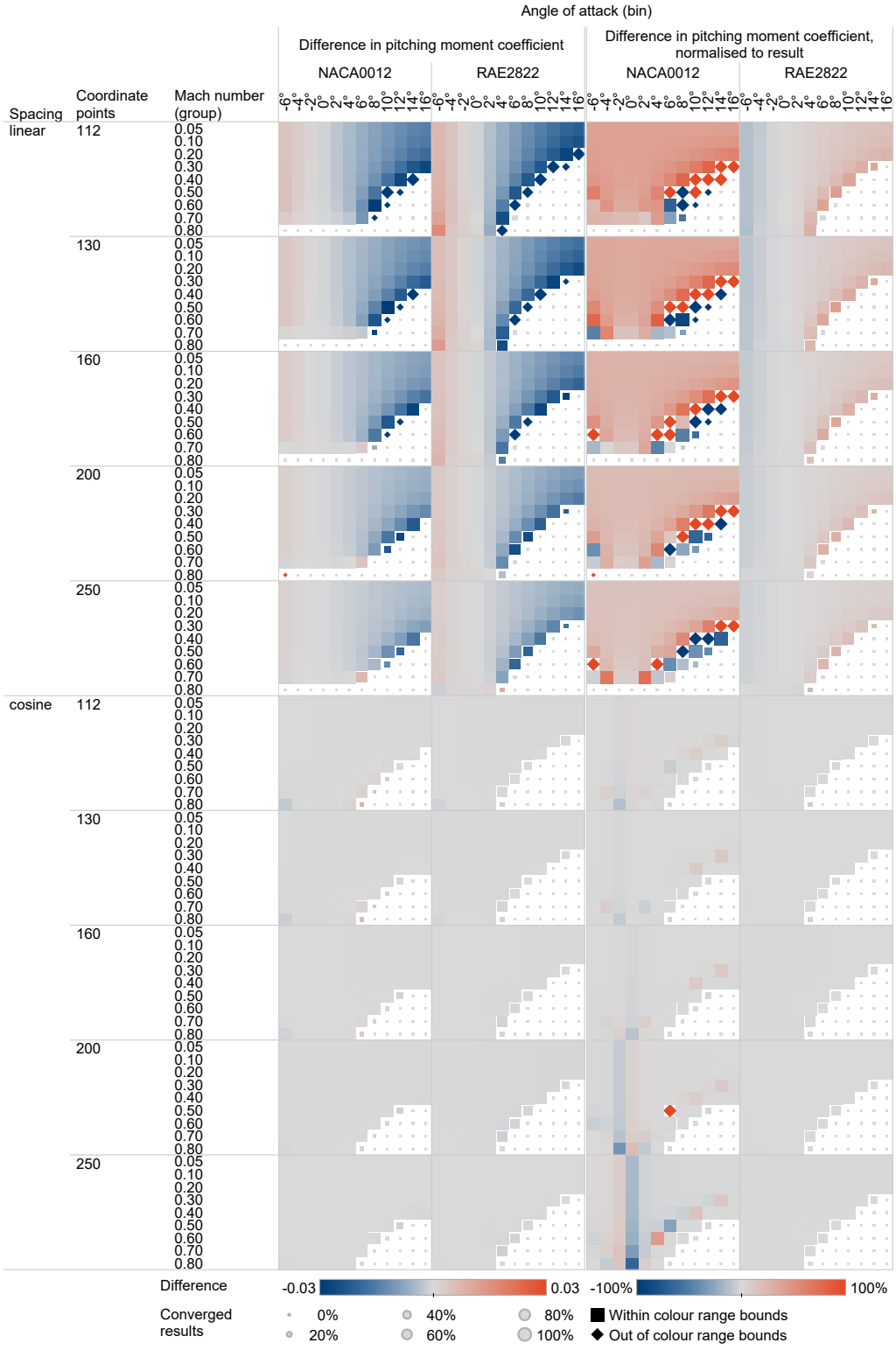
(d) Chordwise location of minimum pressure coefficient

Figure F.16: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



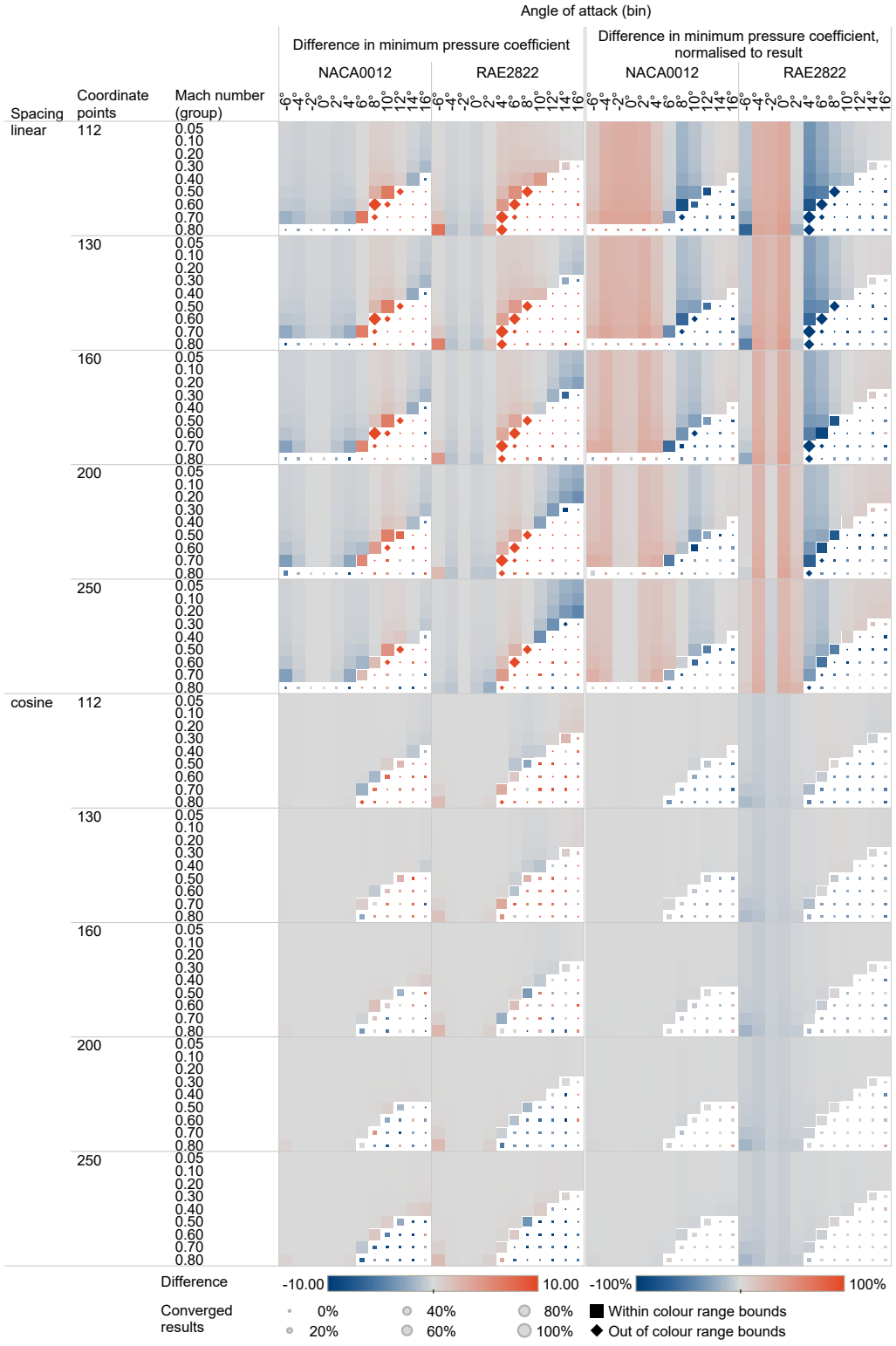
(a) Lift coefficient

Figure F.17: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack



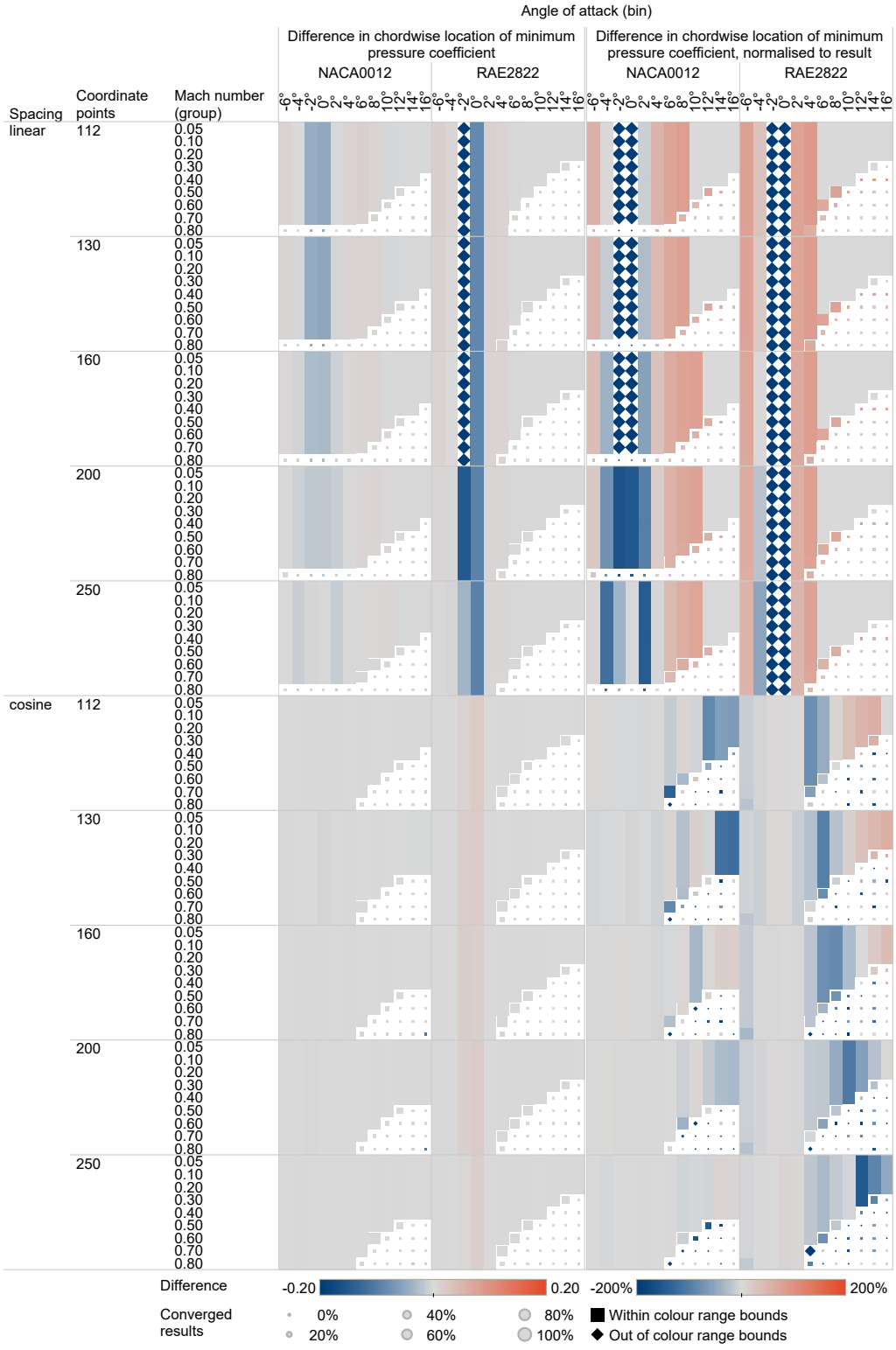
(b) Pitching moment coefficient

Figure F.17: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



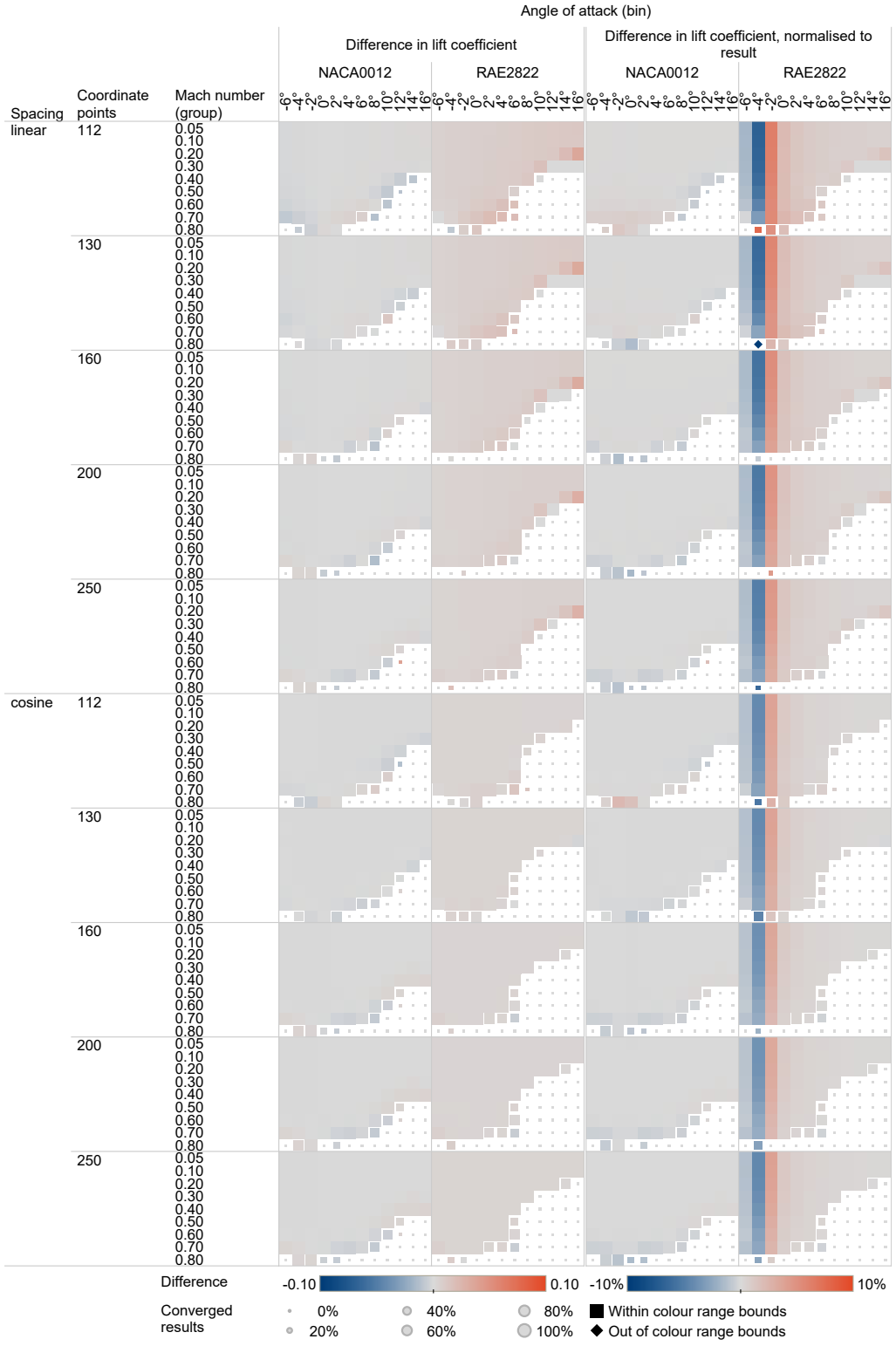
(c) Minimum pressure coefficient

Figure F.17: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



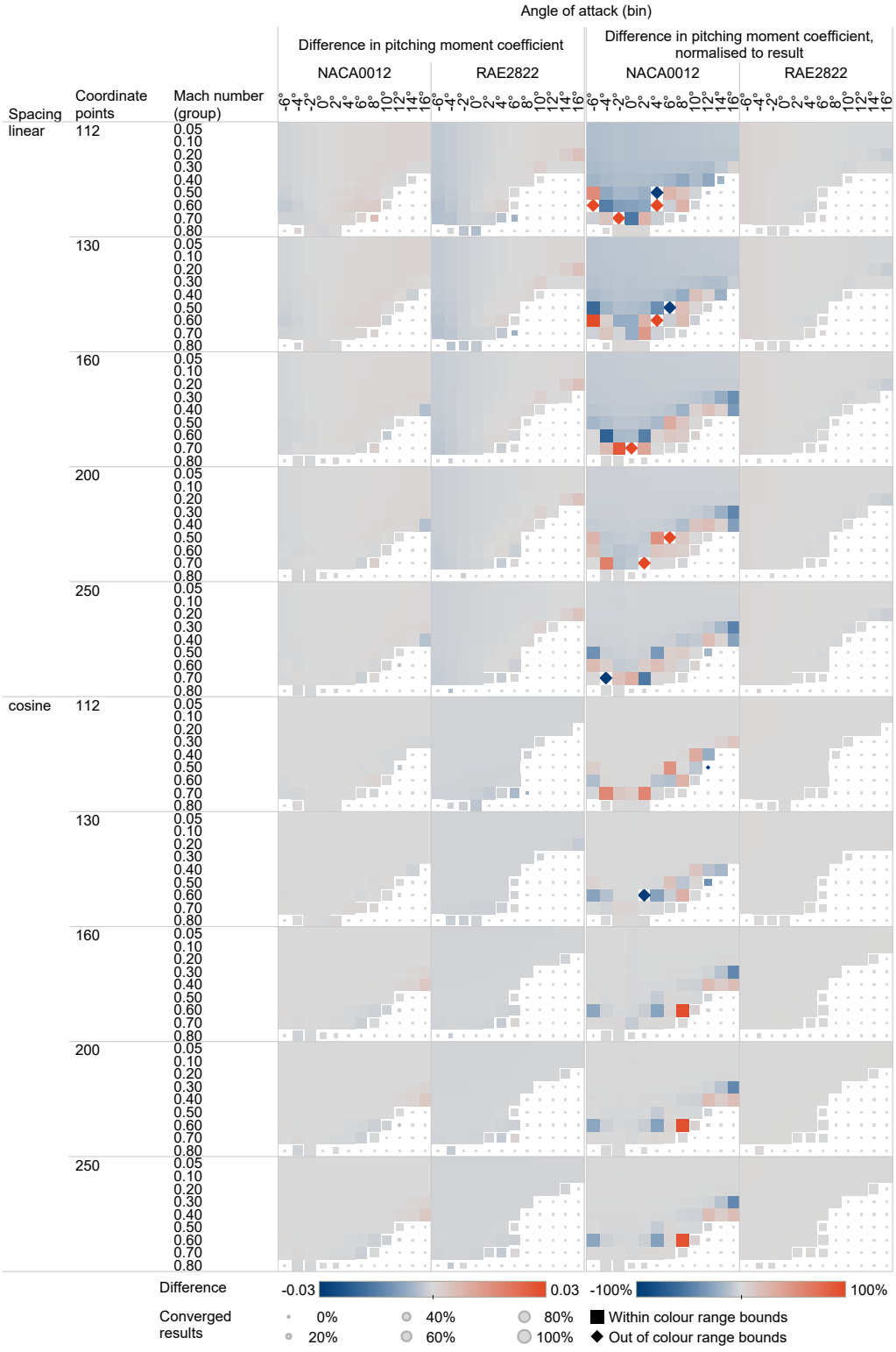
(d) Chordwise location of minimum pressure coefficient

Figure F.17: Difference in quantities of interest (true and normalised w.r.t. result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



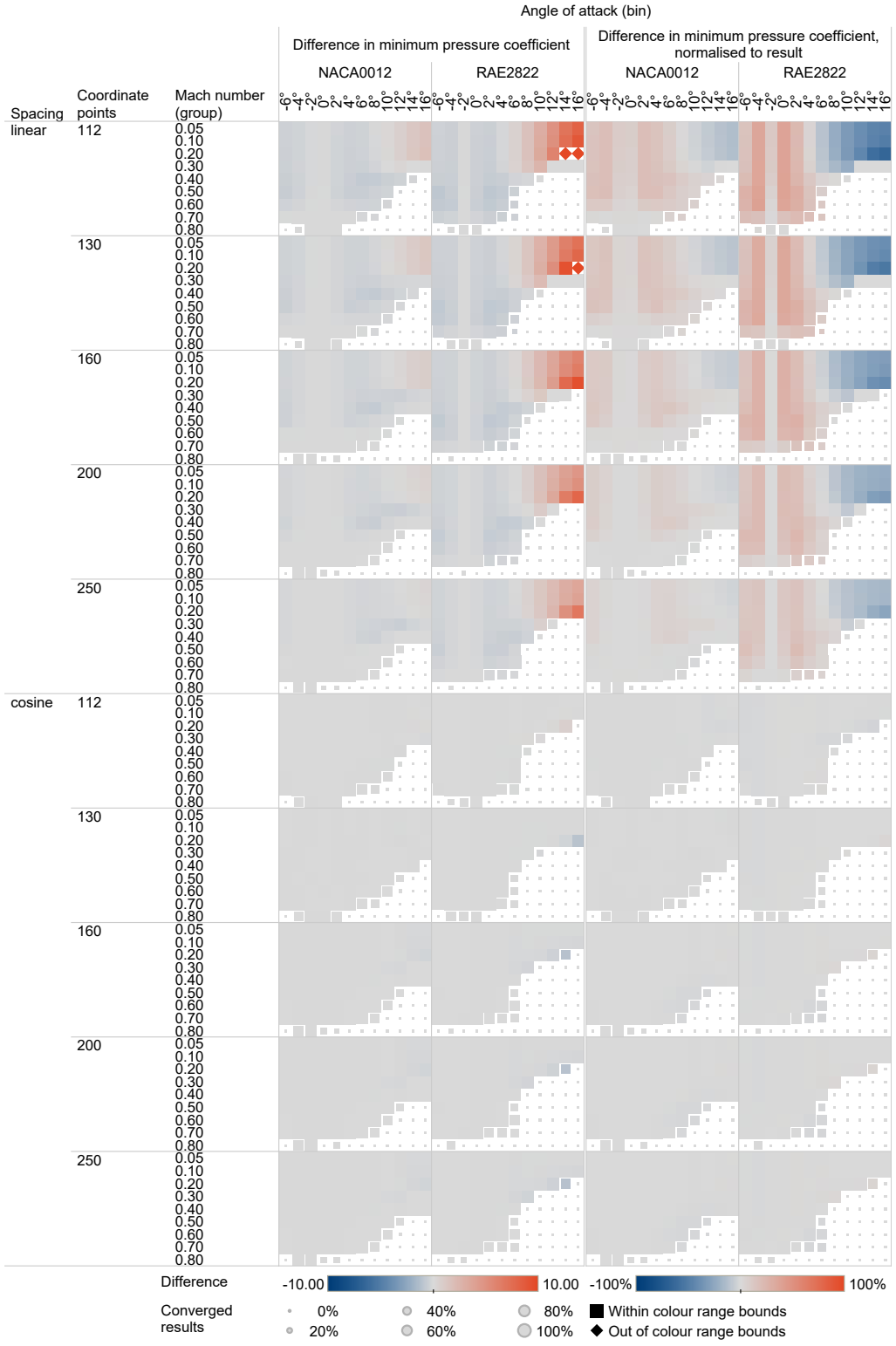
(a) Lift coefficient

Figure F.18: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack



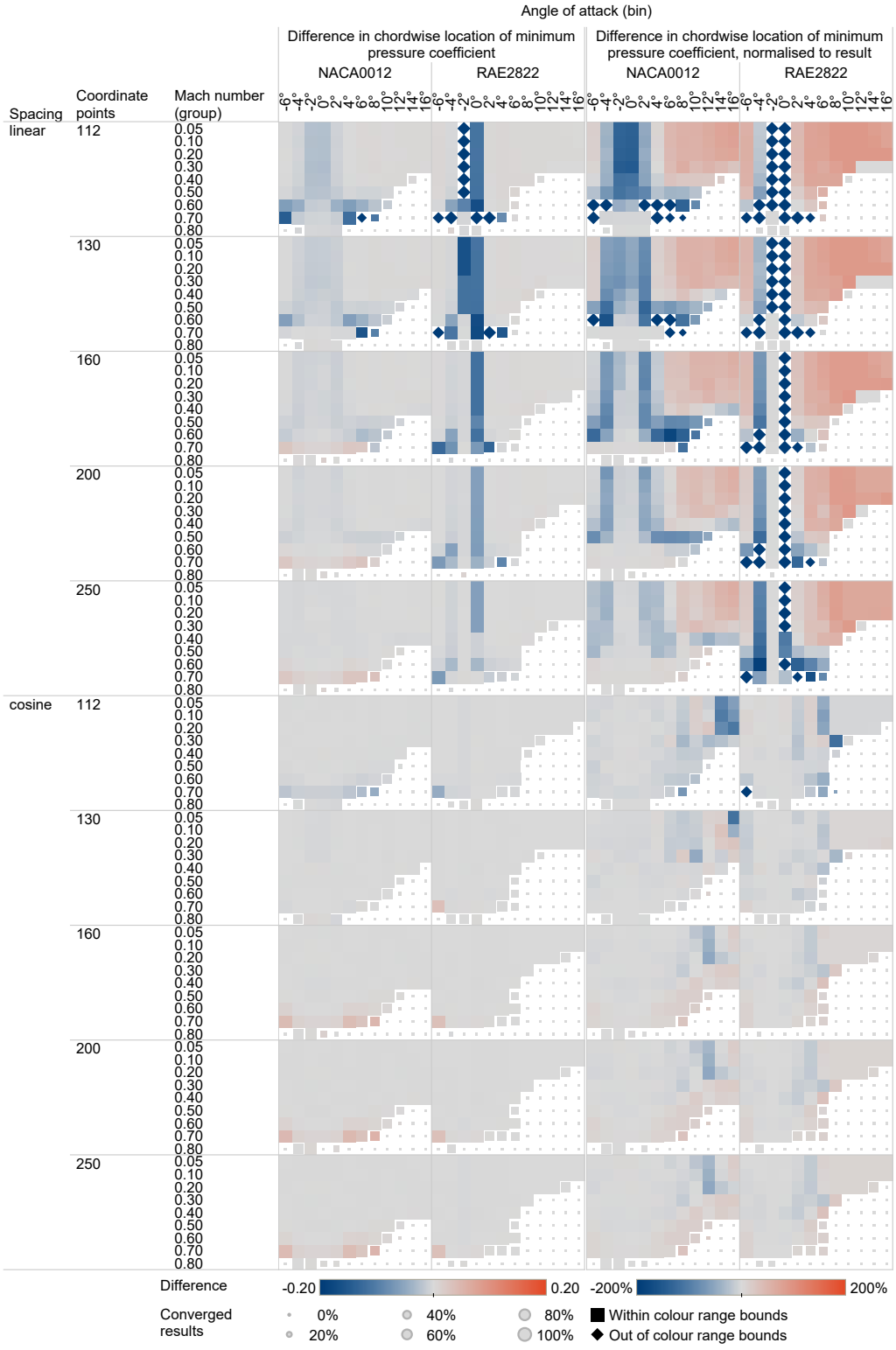
(b) Pitching moment coefficient

Figure F.18: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



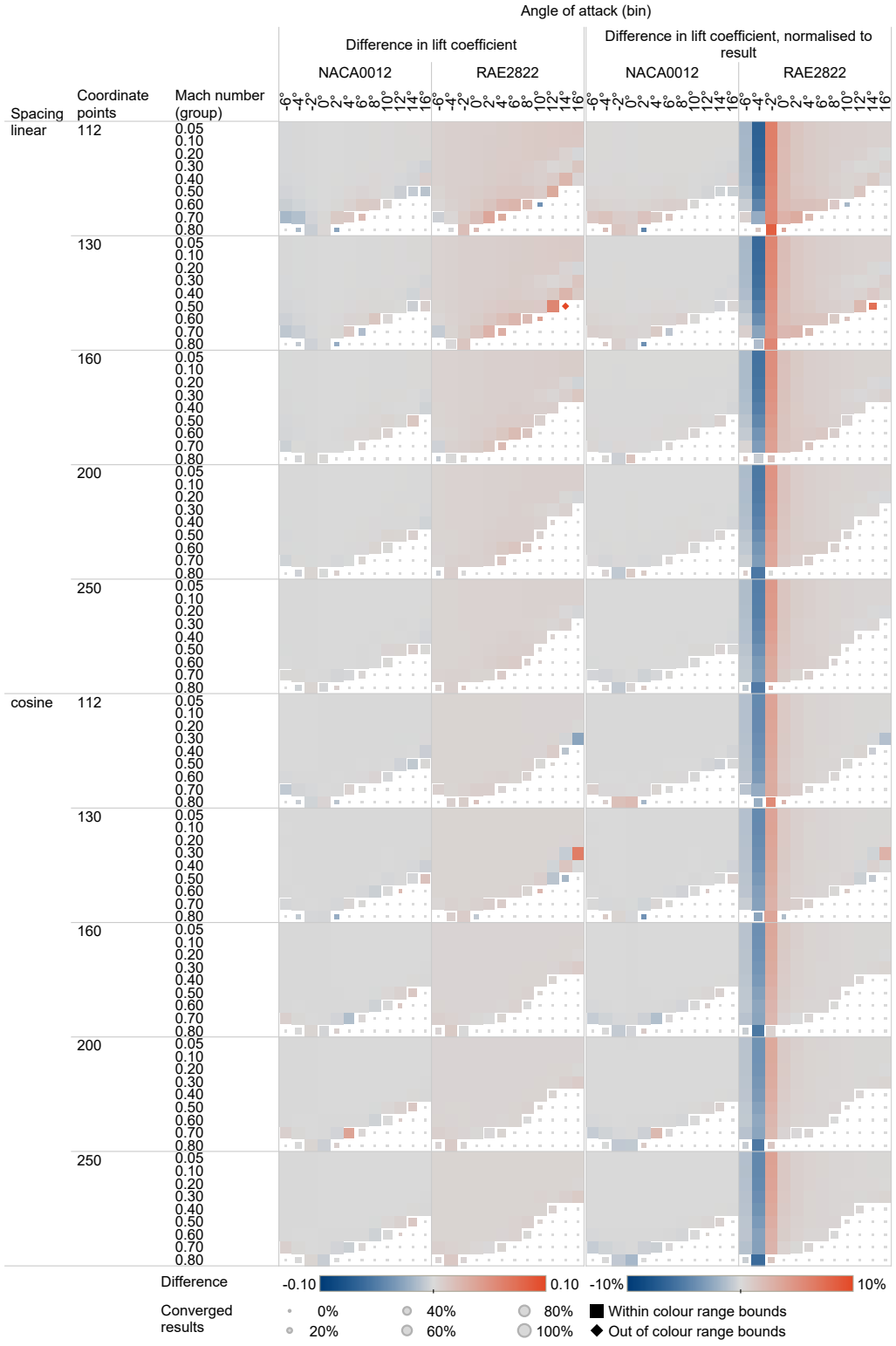
(c) Minimum pressure coefficient

Figure F.18: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



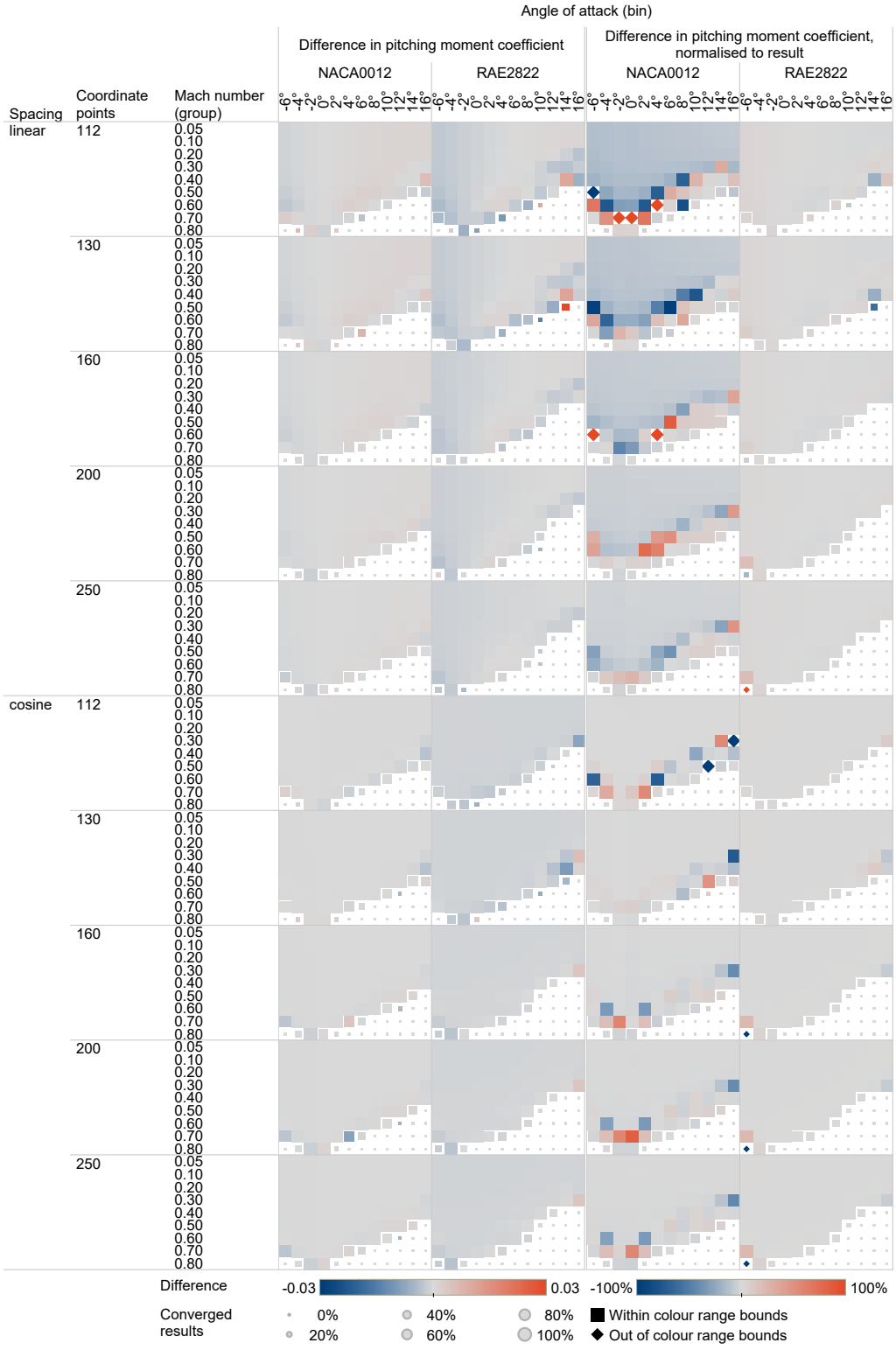
(d) Chordwise location of minimum pressure coefficient

Figure F.18: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK-NC results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



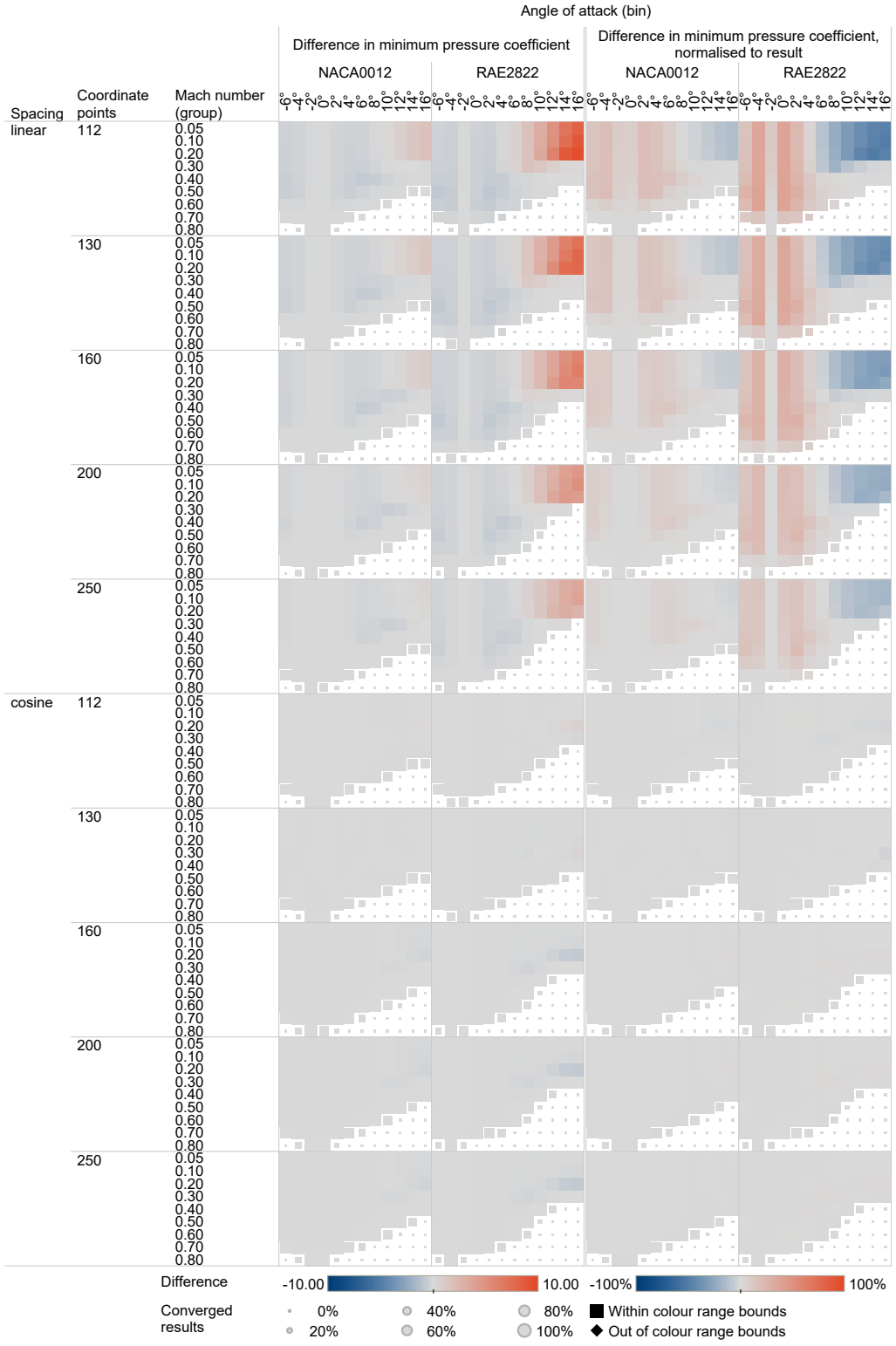
(a) Lift coefficient

Figure F.19: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack



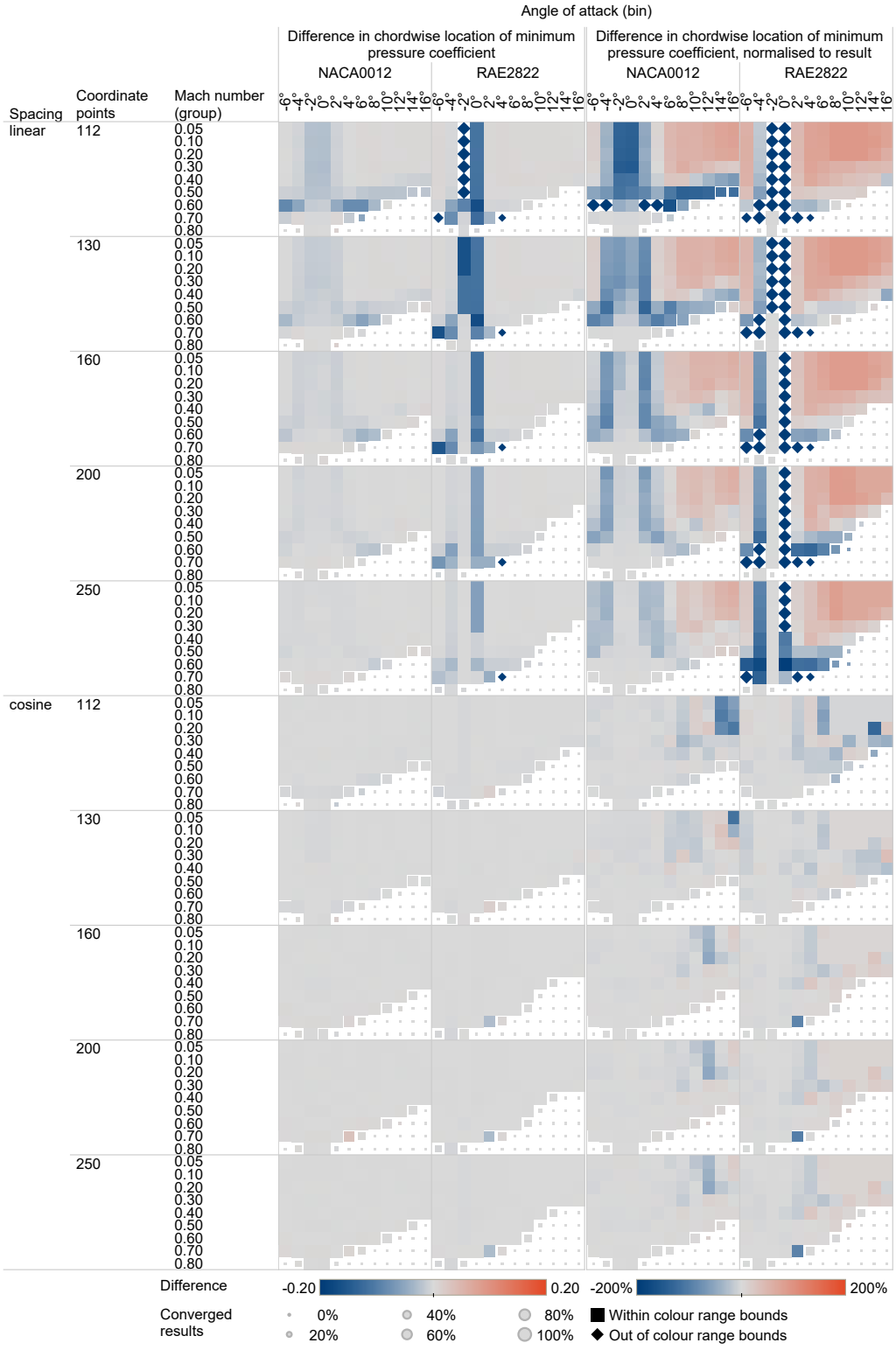
(b) Pitching moment coefficient

Figure F.19: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



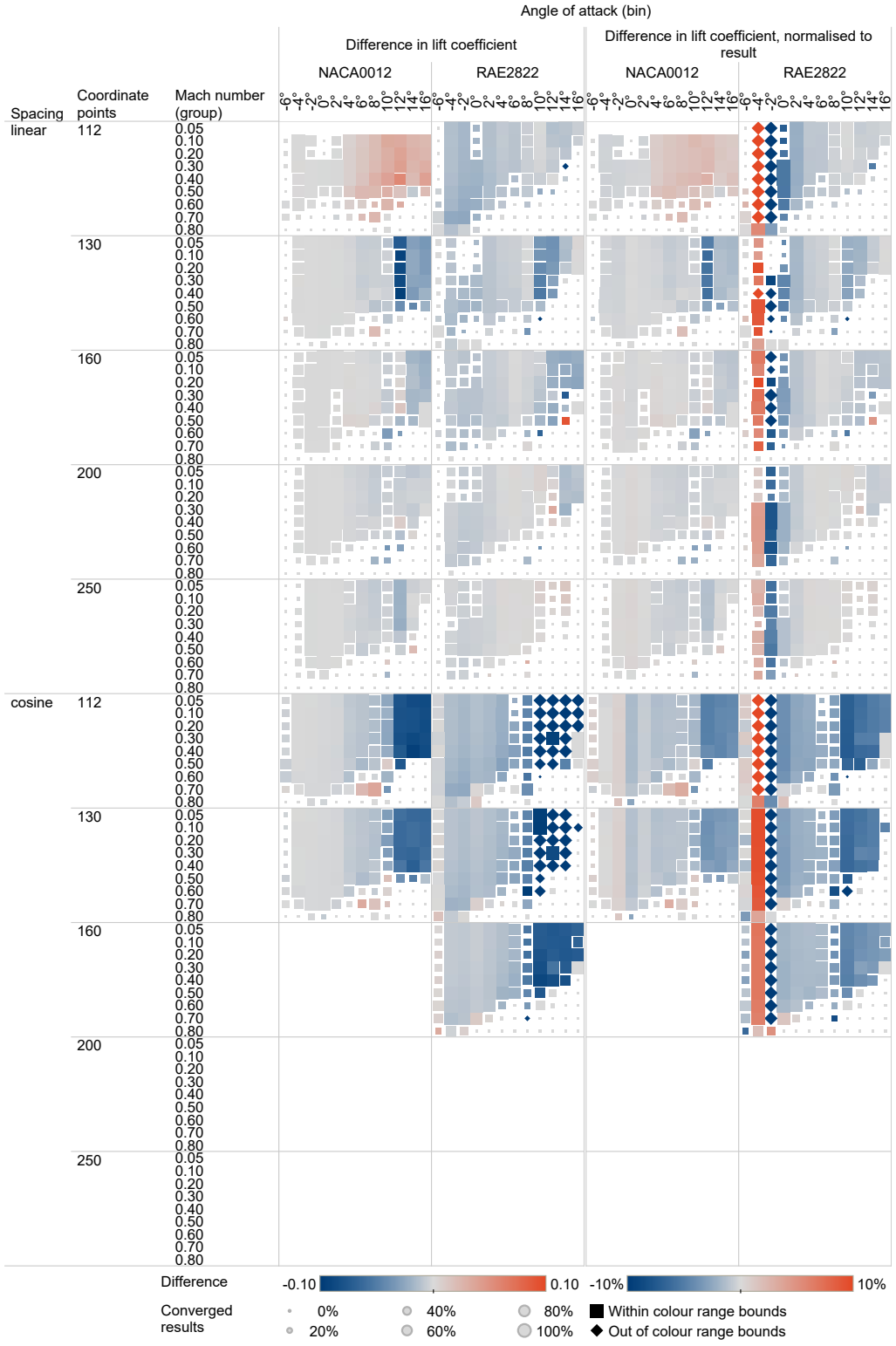
(c) Minimum pressure coefficient

Figure F.19: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



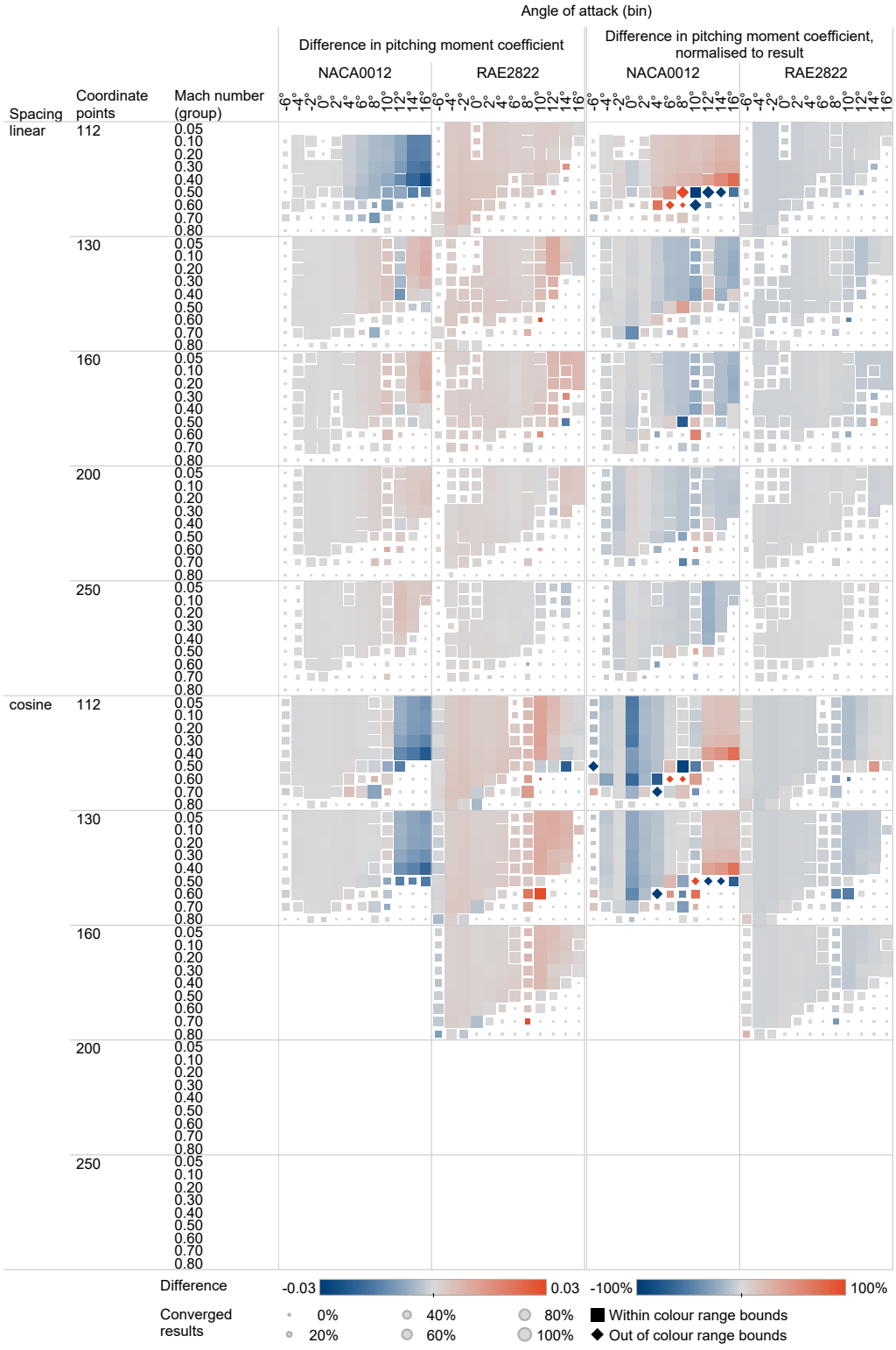
(d) Chordwise location of minimum pressure coefficient

Figure F.19: Difference in quantities of interest (true and normalised w.r.t. result) observed in VGK results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



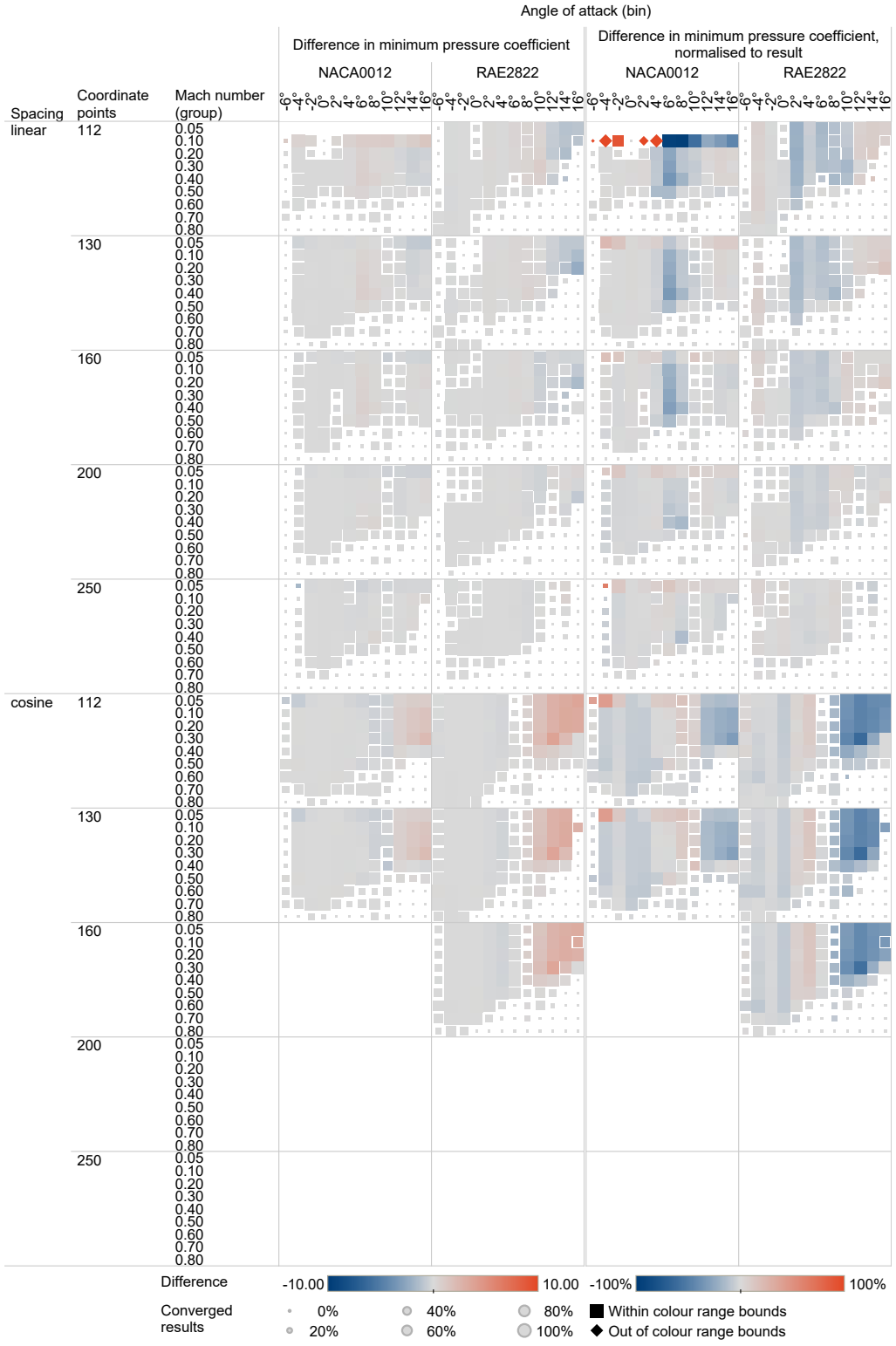
(a) Lift coefficient

Figure F.20: Difference in quantities of interest (true and normalised w.r.t. result) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack



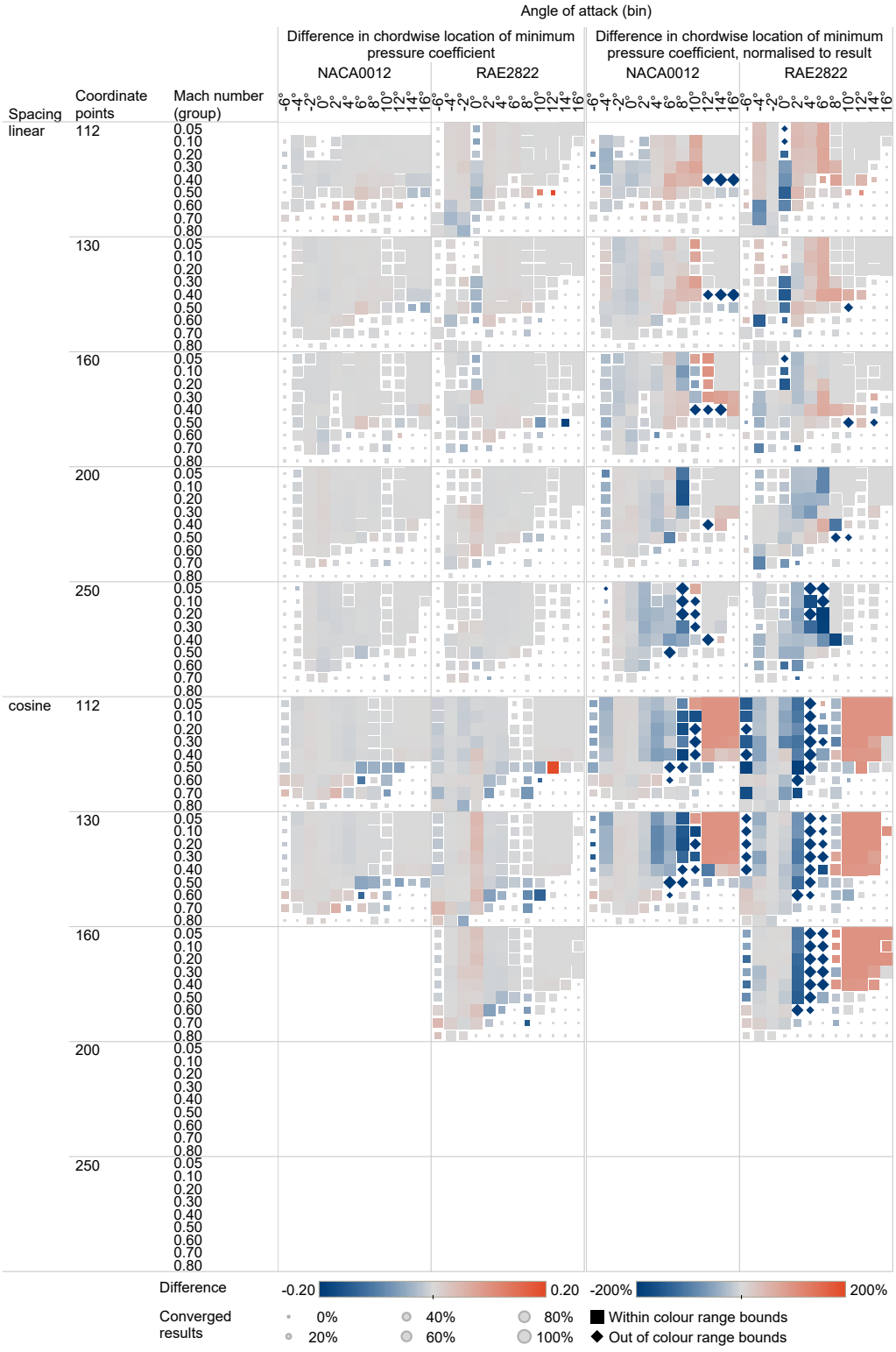
(b) Pitching moment coefficient

Figure F.20: Difference in quantities of interest (true and normalised w.r.t. result) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



(c) Minimum pressure coefficient

Figure F.20: Difference in quantities of interest (true and normalised w.r.t. result) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)



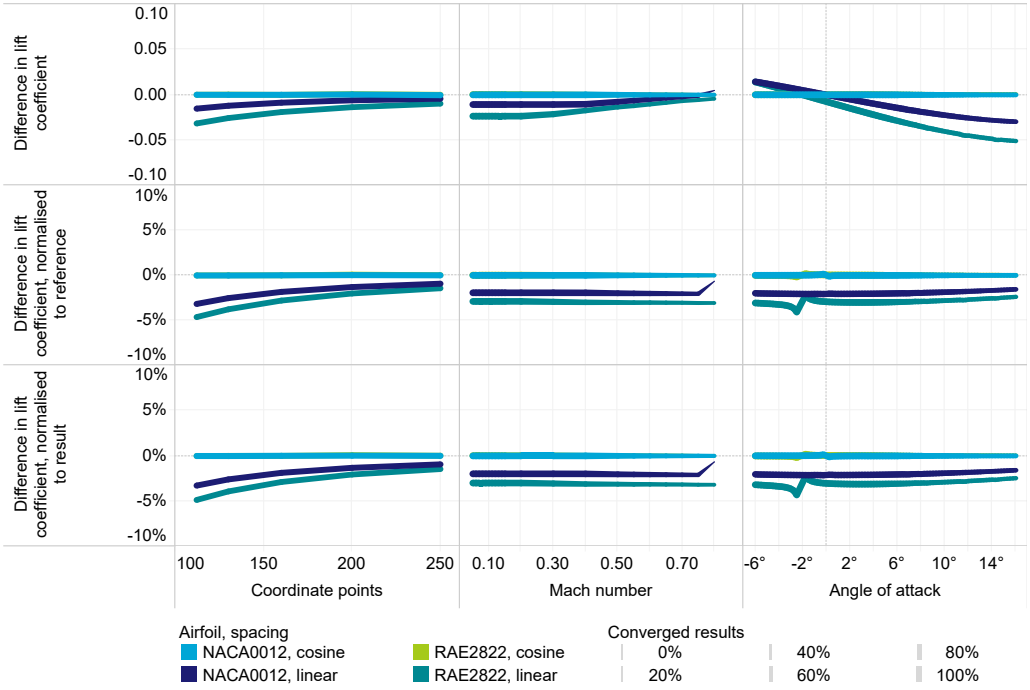
(d) Chordwise location of minimum pressure coefficient

Figure F.20: Difference in quantities of interest (true and normalised w.r.t. result) observed in MSES results for different geometries, geometric representations, Mach number and (binned) angles of attack (continued)

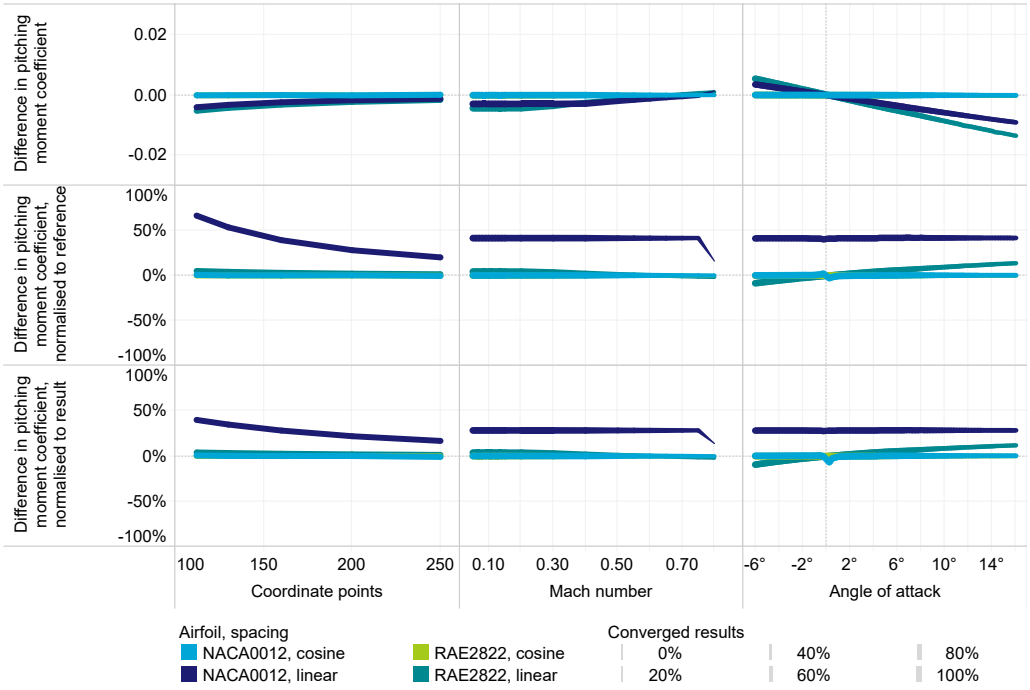
Per influence

The figures presented in this section show the influence of the solution method on various quantities of interest using line graphs. They show the same information as presented in the heat maps shown previously, but aggregated over three isolated dimensions. From left to right, the figures indicate the difference with respect to the number of coordinate points, the Mach number and the angle of attack. Although this representation is somewhat simpler than the heat maps used earlier, an important limitation is the fact that it hides co-dependencies from view: in order to arrive at the line representing the influence of the number of coordinate points, all Mach numbers and angles of attack have been averaged.

The line colour indicates both the geometry as well as the spacing used to distribute the coordinate points over the chordwise-axis. The line thickness is a measure for the number of converged results, equivalent to the marker size in the heat maps shown before.

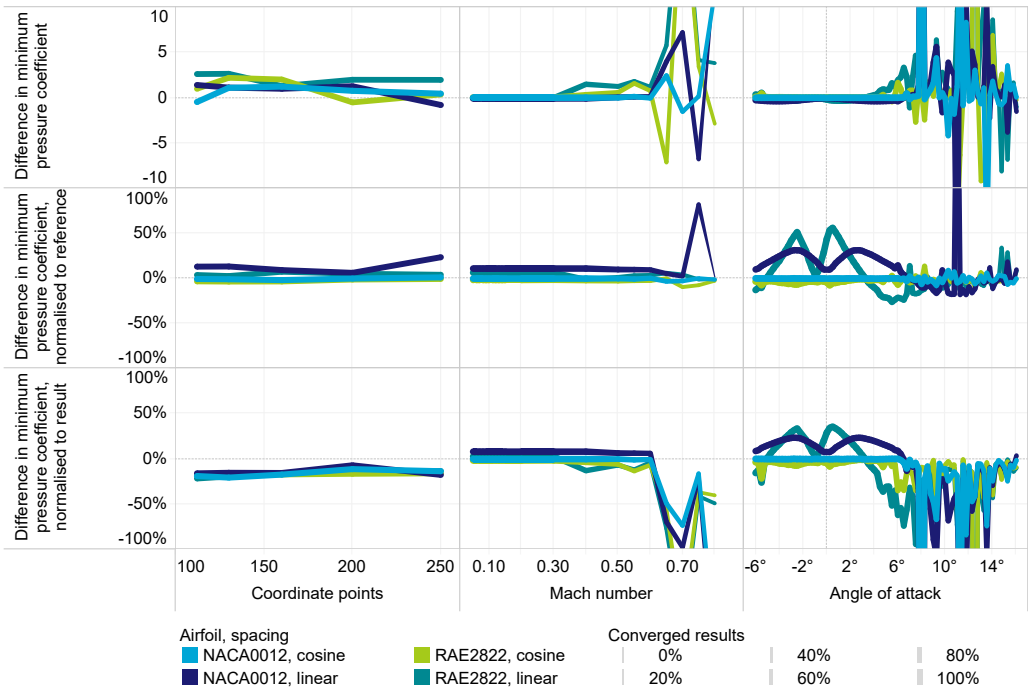


(a) Lift coefficient

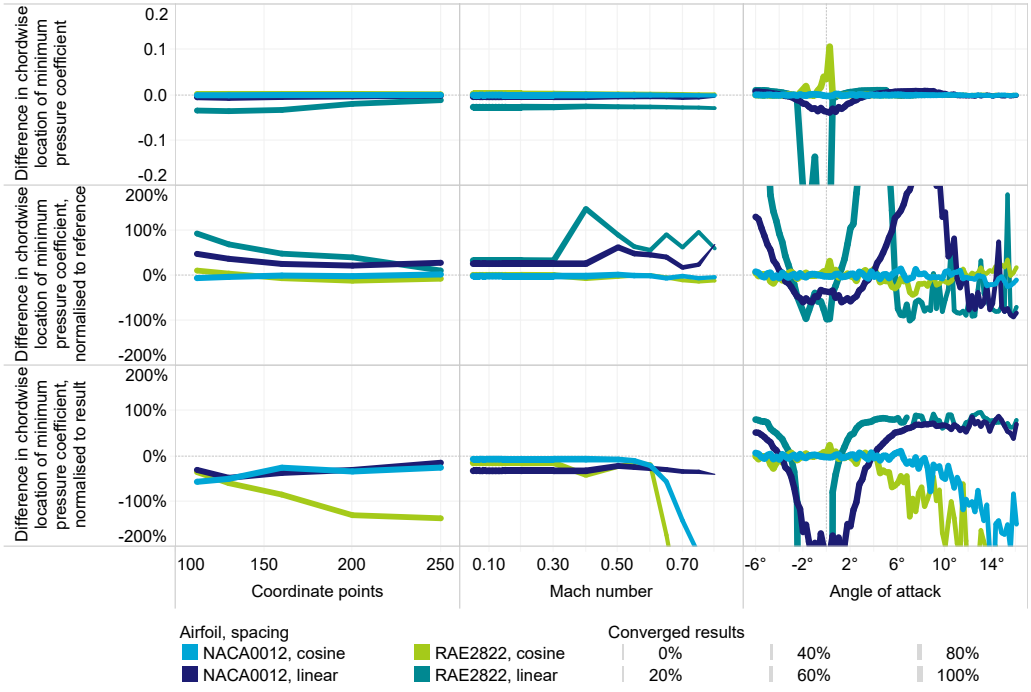


(b) Pitching moment coefficient

Figure F.21: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and angles of attack

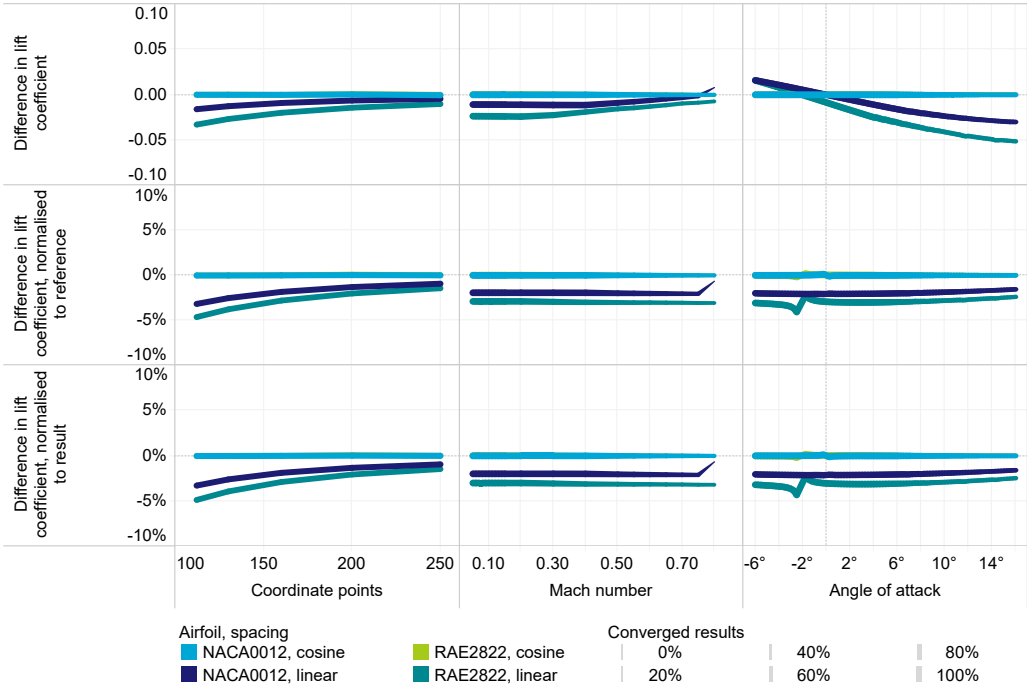


(c) Minimum pressure coefficient

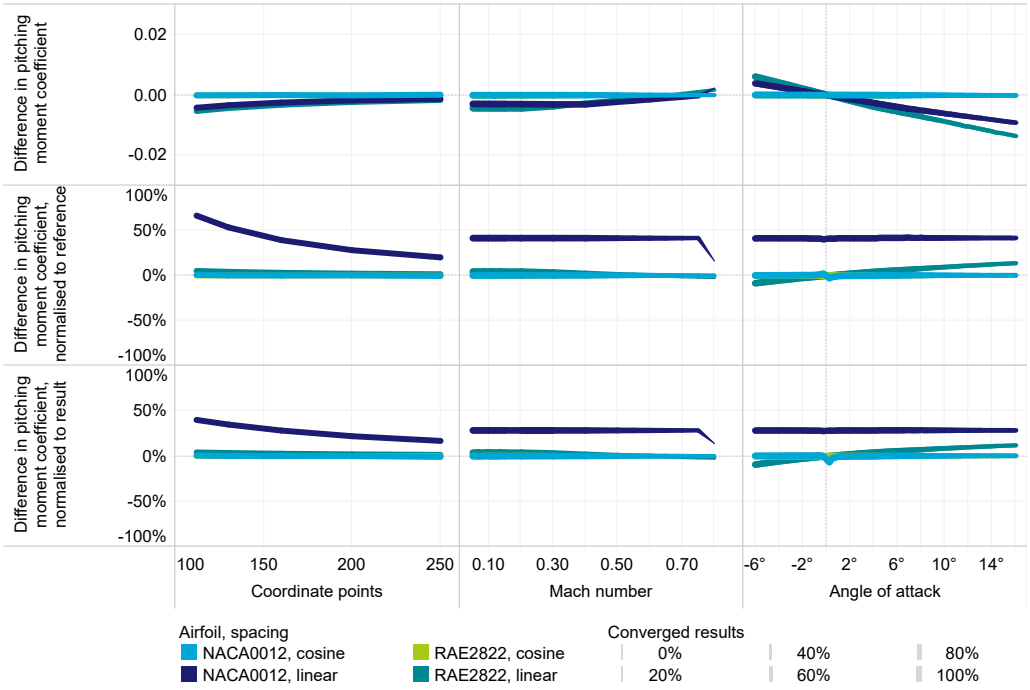


(d) Chordwise location of minimum pressure coefficient

Figure F.21: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-U results for different geometries, geometric representations, Mach number and angles of attack (continued)

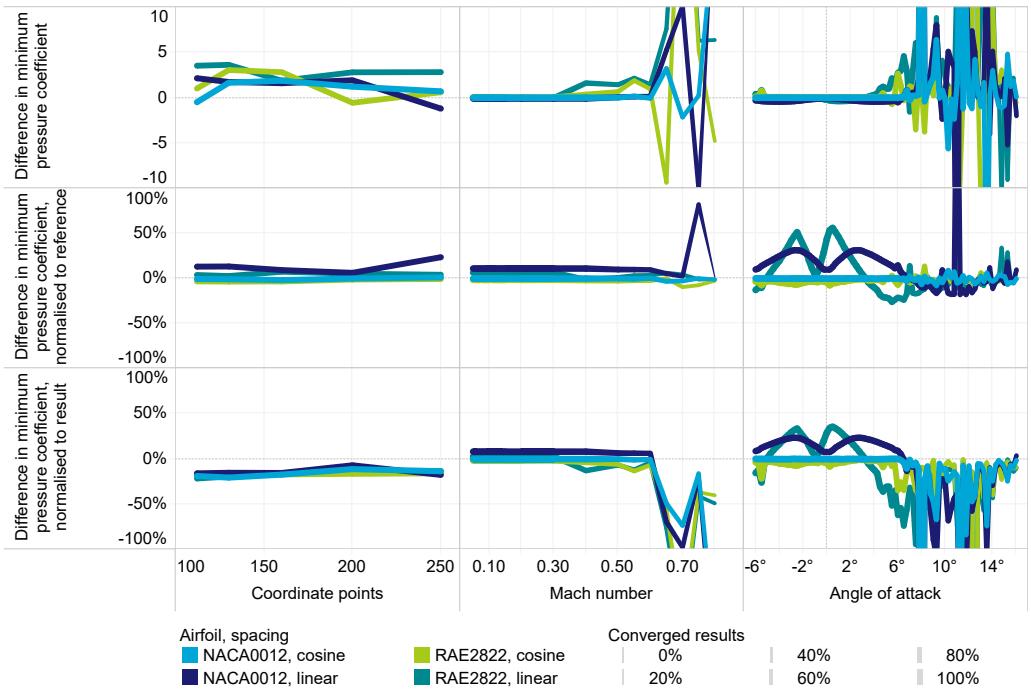


(a) Lift coefficient

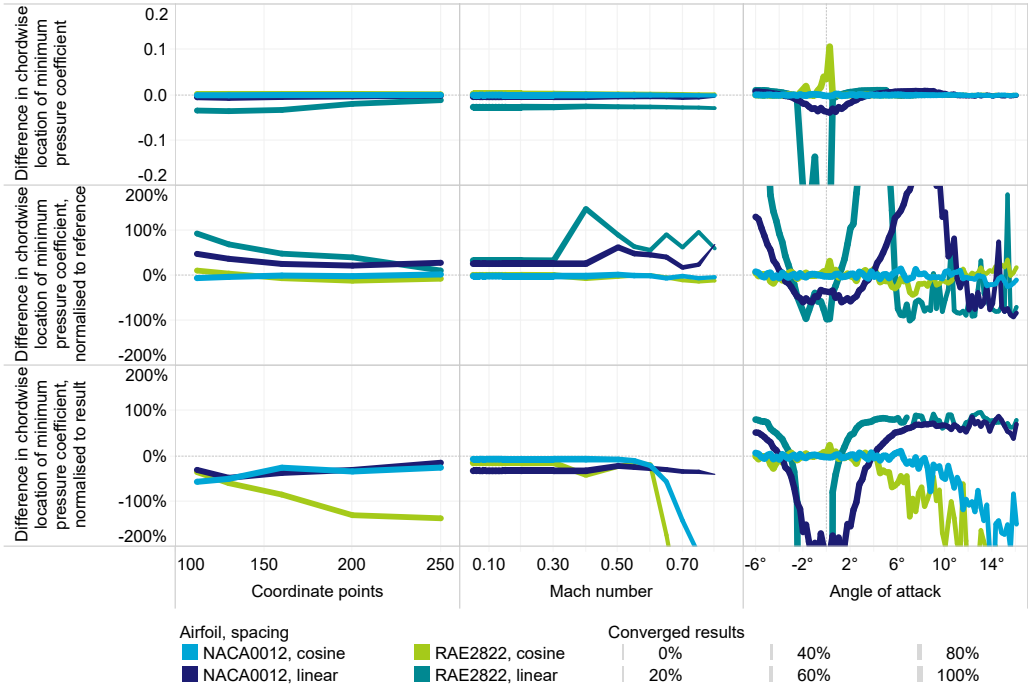


(b) Pitching moment coefficient

Figure F.22: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and angles of attack

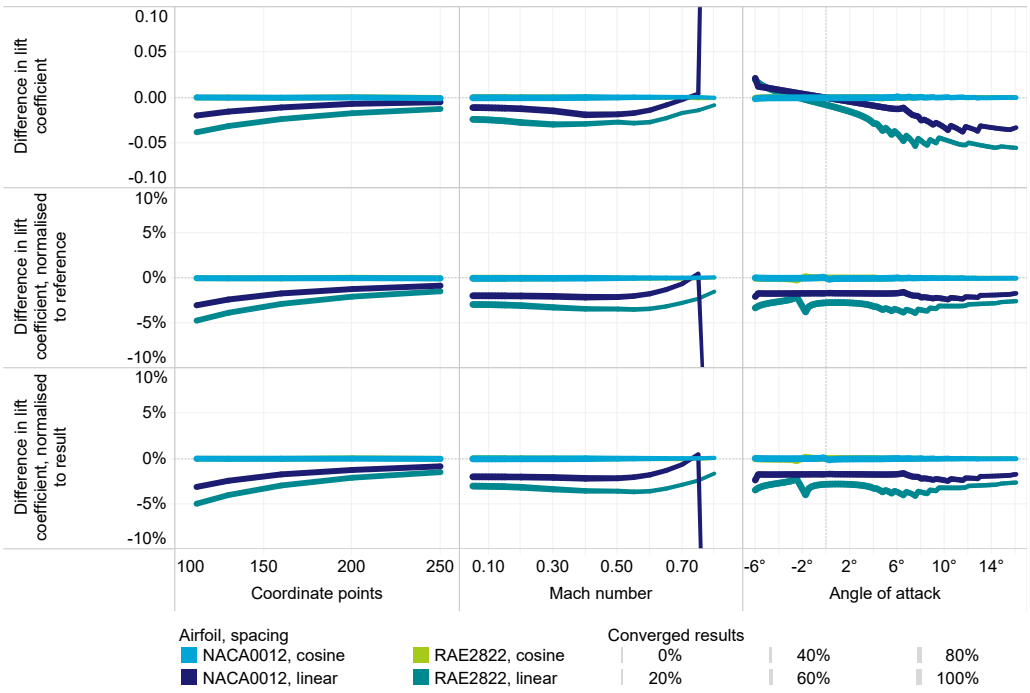


(c) Minimum pressure coefficient

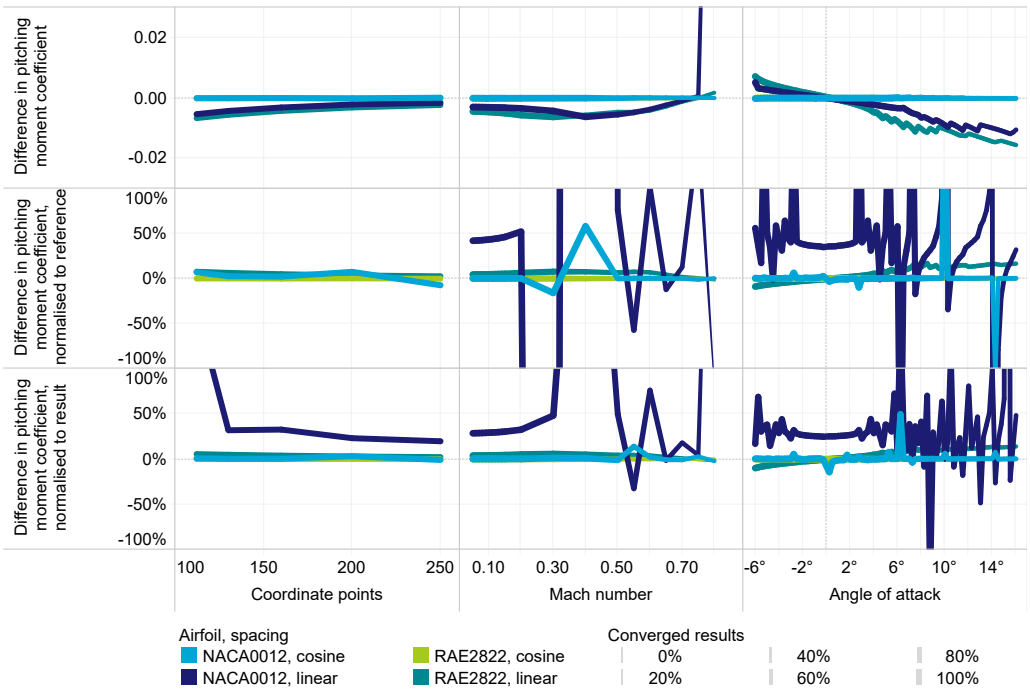


(d) Chordwise location of minimum pressure coefficient

Figure F.22: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-PG results for different geometries, geometric representations, Mach number and angles of attack (continued)

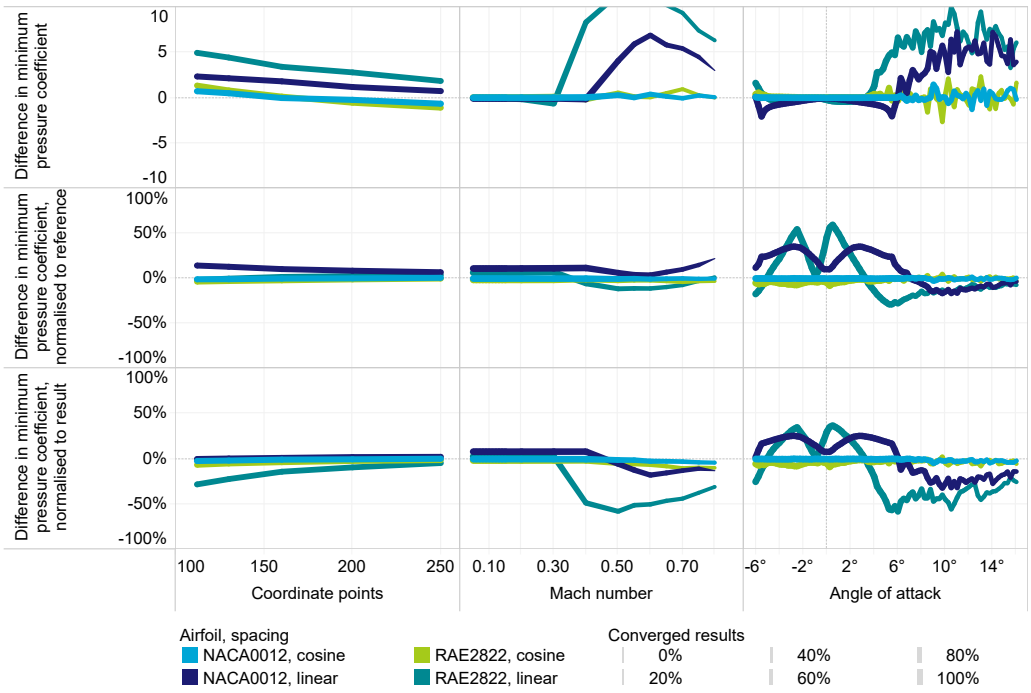


(a) Lift coefficient

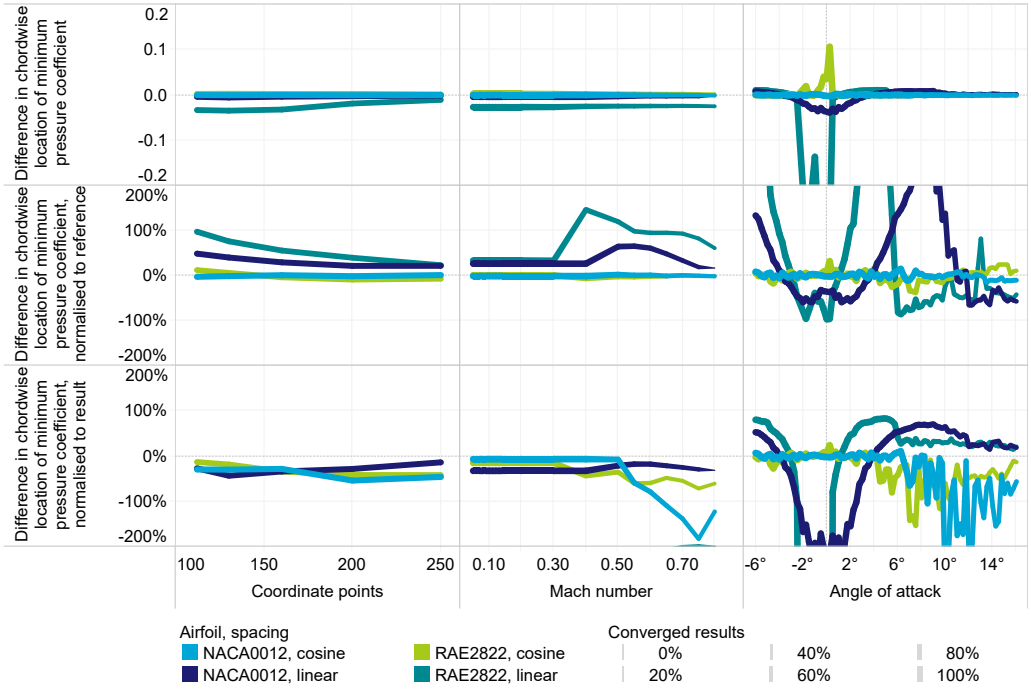


(b) Pitching moment coefficient

Figure F.23: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and angles of attack

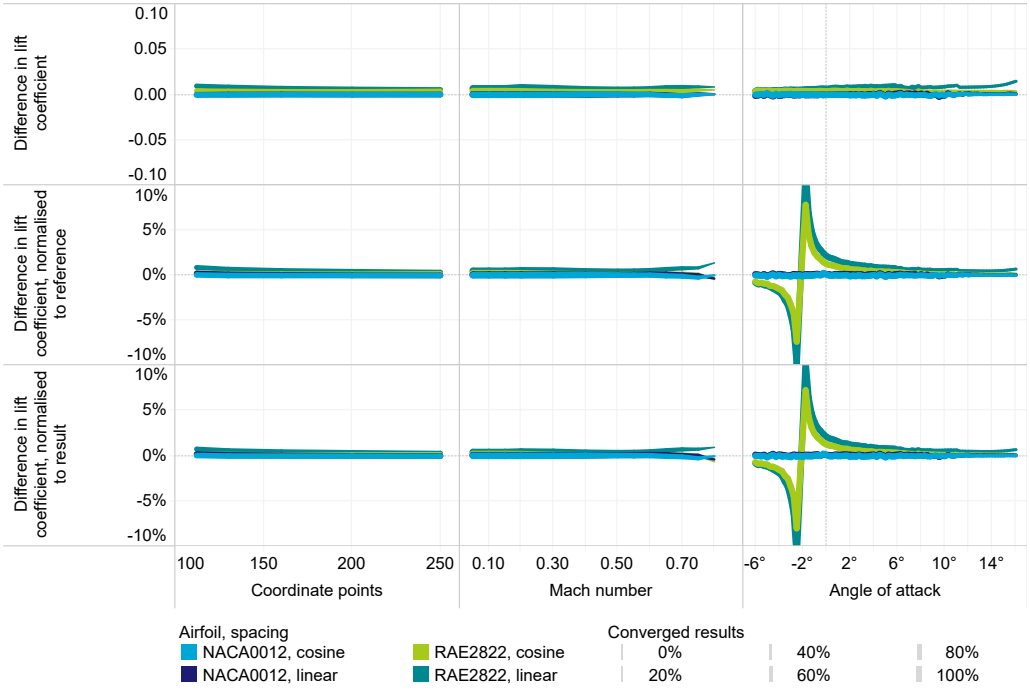


(c) Minimum pressure coefficient

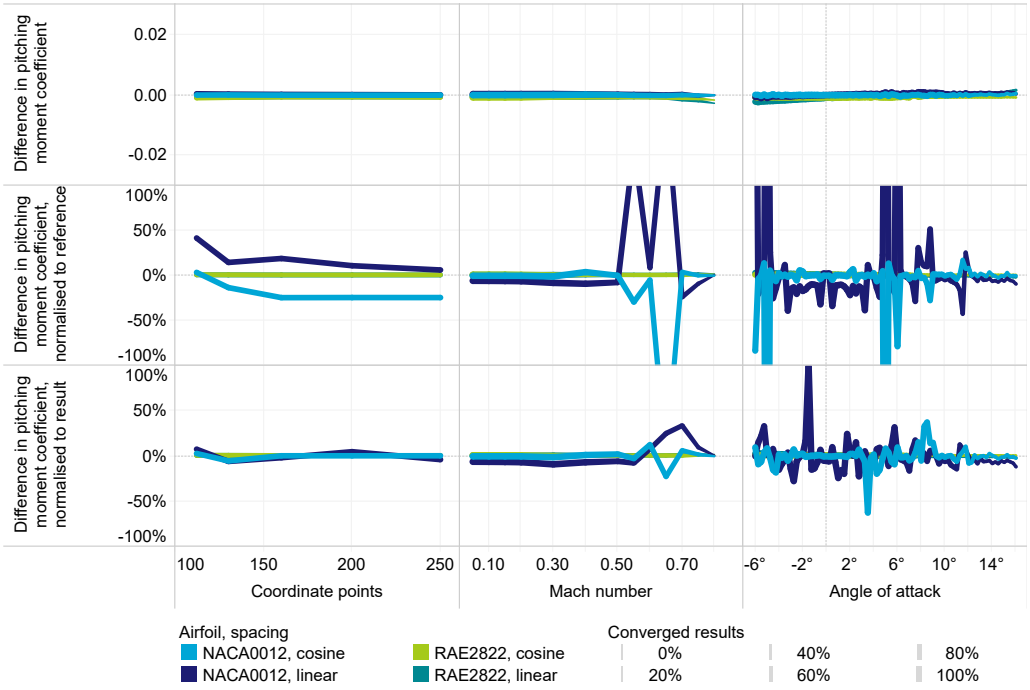


(d) Chordwise location of minimum pressure coefficient

Figure F.23: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in XFOIL-KT results for different geometries, geometric representations, Mach number and angles of attack (continued)

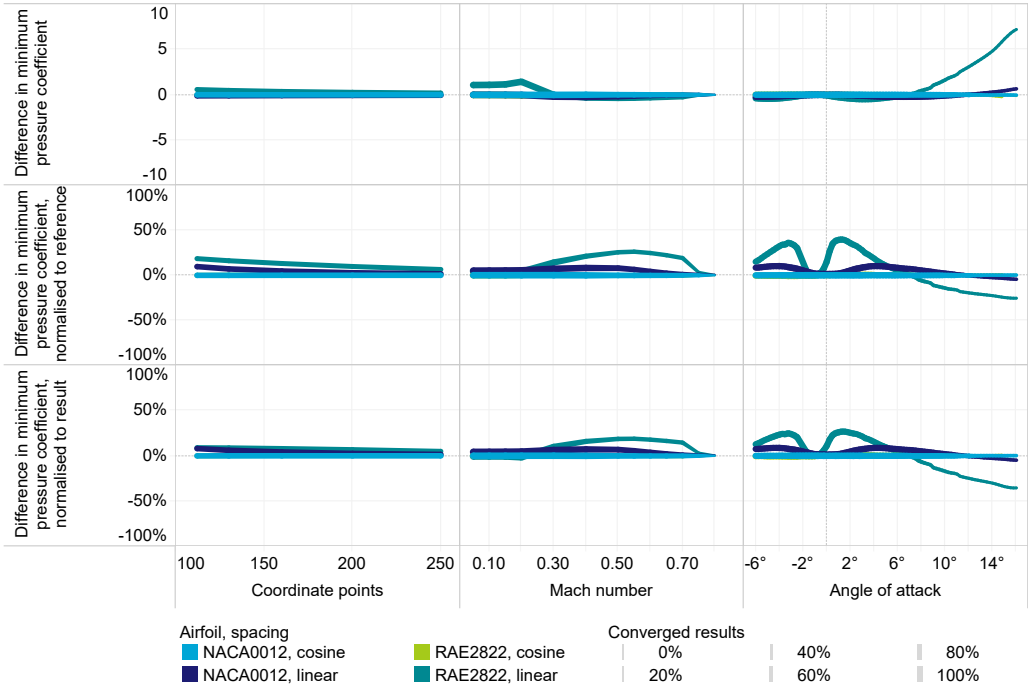


(a) Lift coefficient

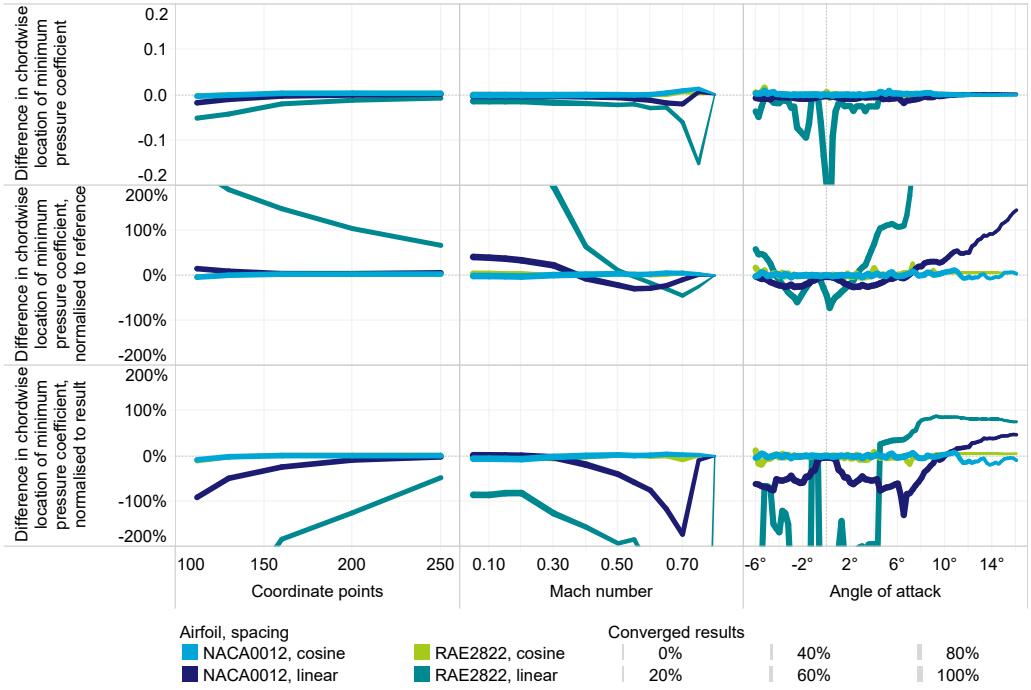


(b) Pitching moment coefficient

Figure F.24: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in VGK-NC results for different geometries, geometric representations, Mach number and angles of attack

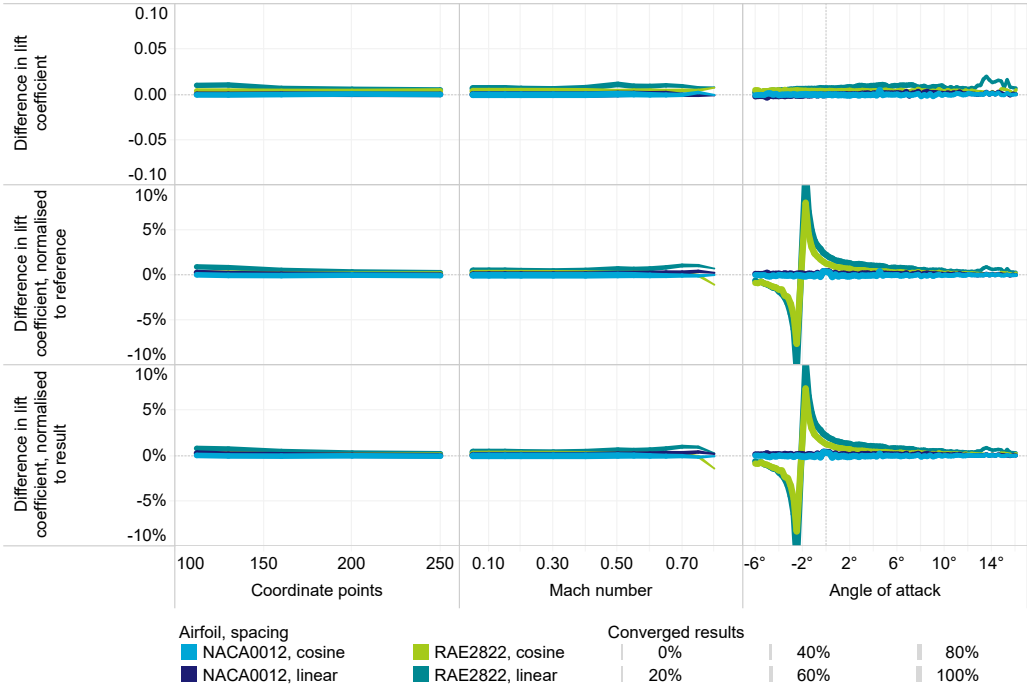


(c) Minimum pressure coefficient

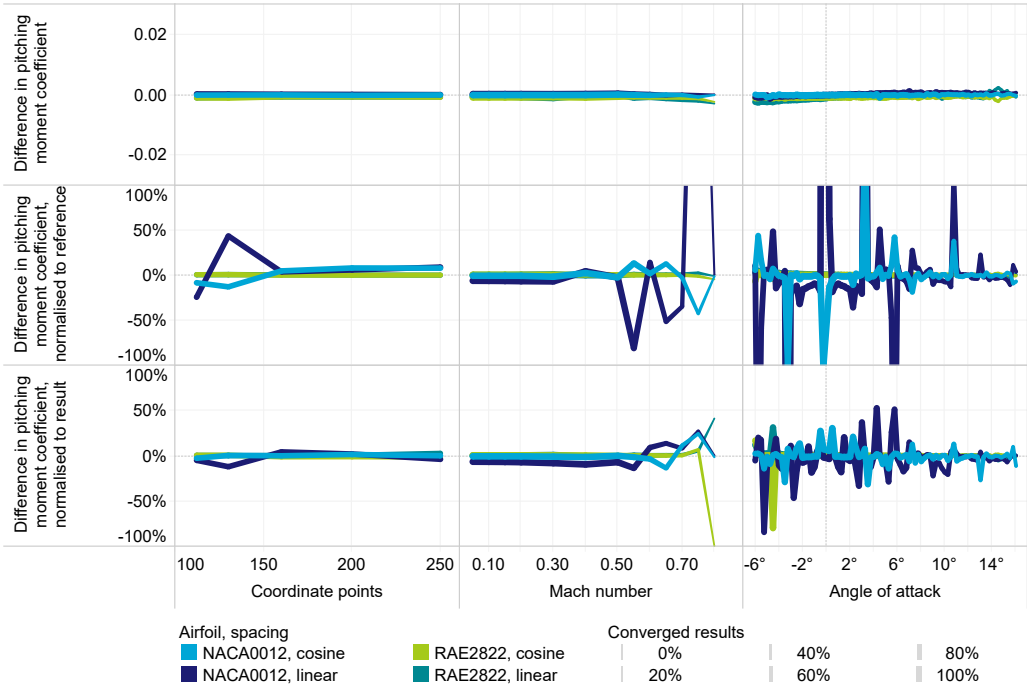


(d) Chordwise location of minimum pressure coefficient

Figure F.24: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in VGK-NC results for different geometries, geometric representations, Mach number and angles of attack (continued)

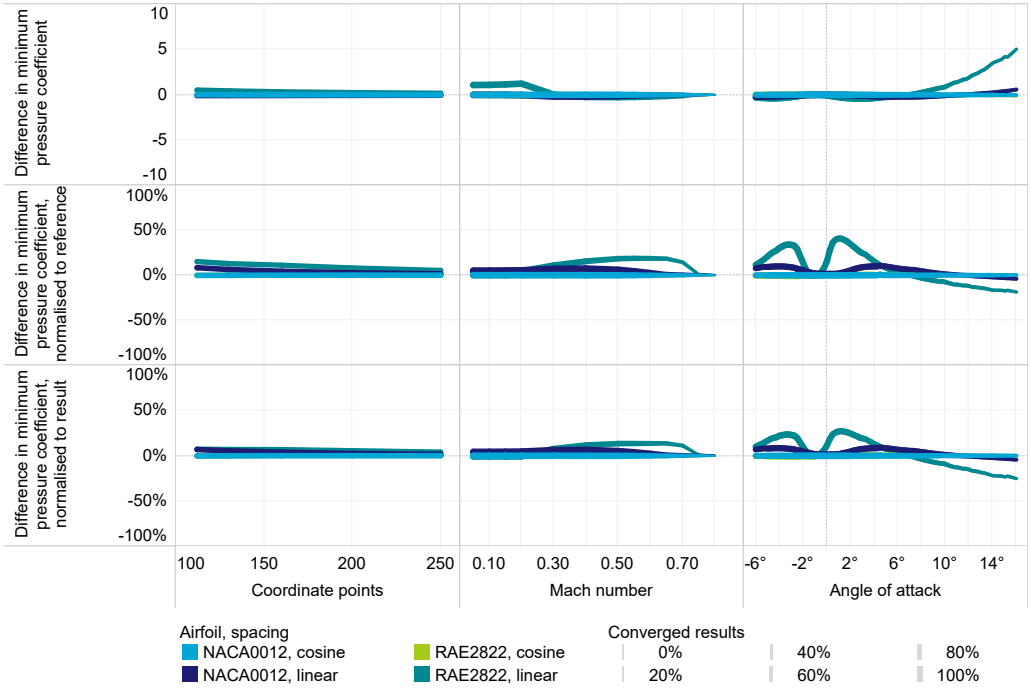


(a) Lift coefficient

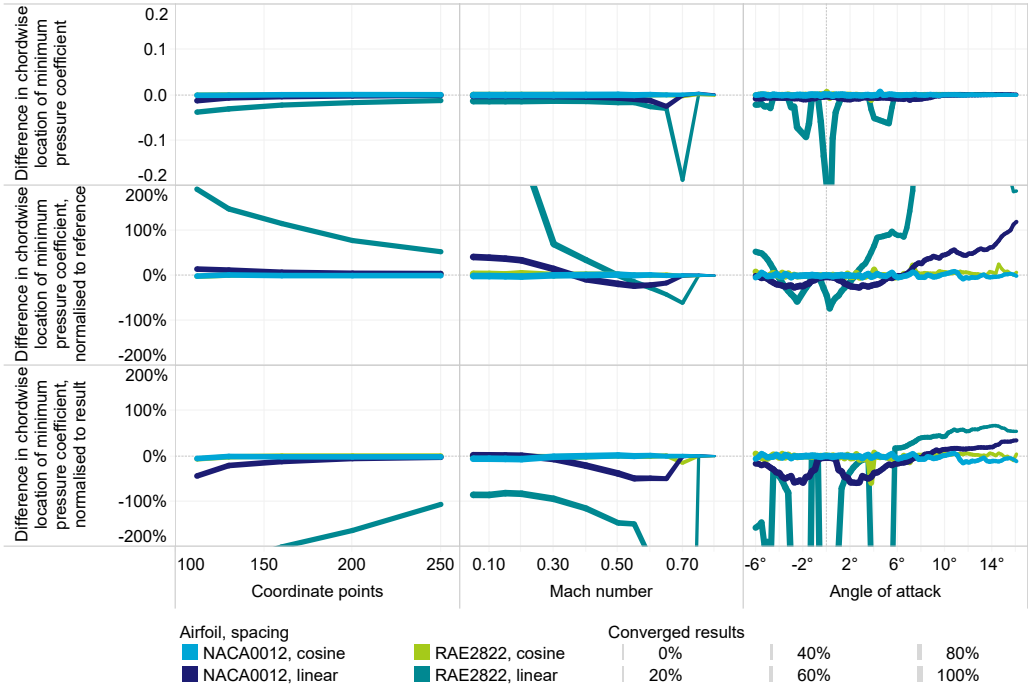


(b) Pitching moment coefficient

Figure F.25: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in VGK results for different geometries, geometric representations, Mach number and angles of attack

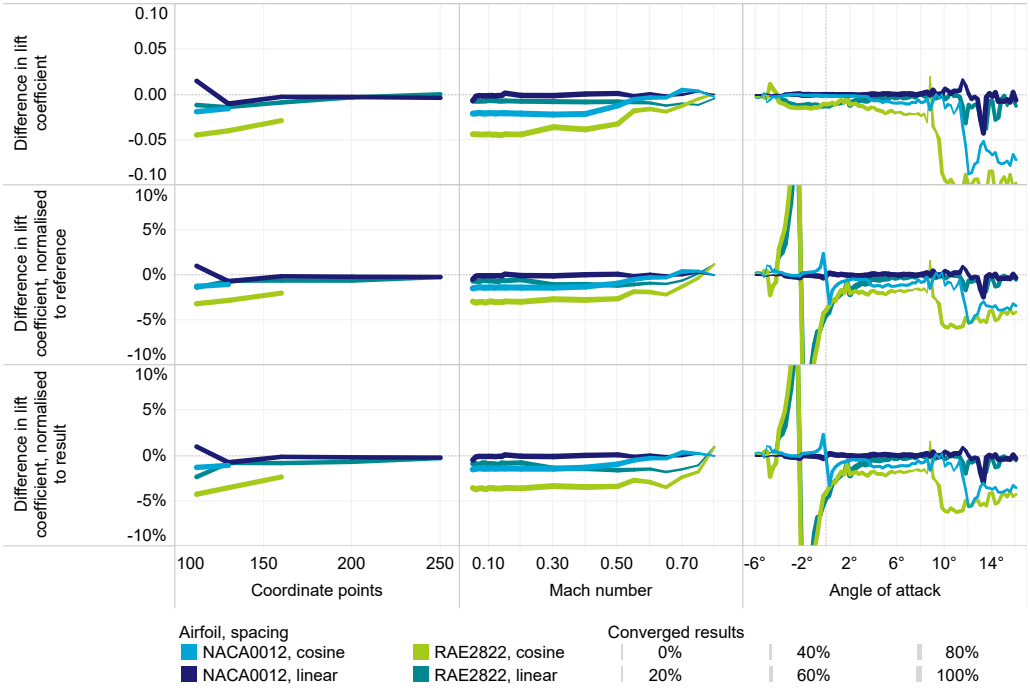


(c) Minimum pressure coefficient

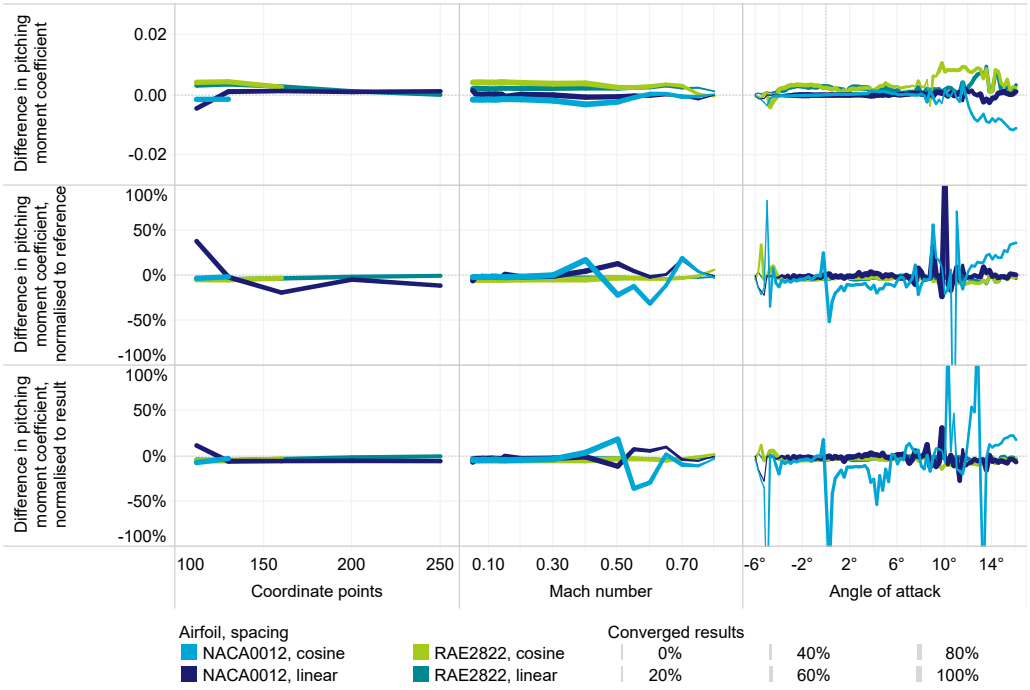


(d) Chordwise location of minimum pressure coefficient

Figure F.25: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in VGK results for different geometries, geometric representations, Mach number and angles of attack (continued)

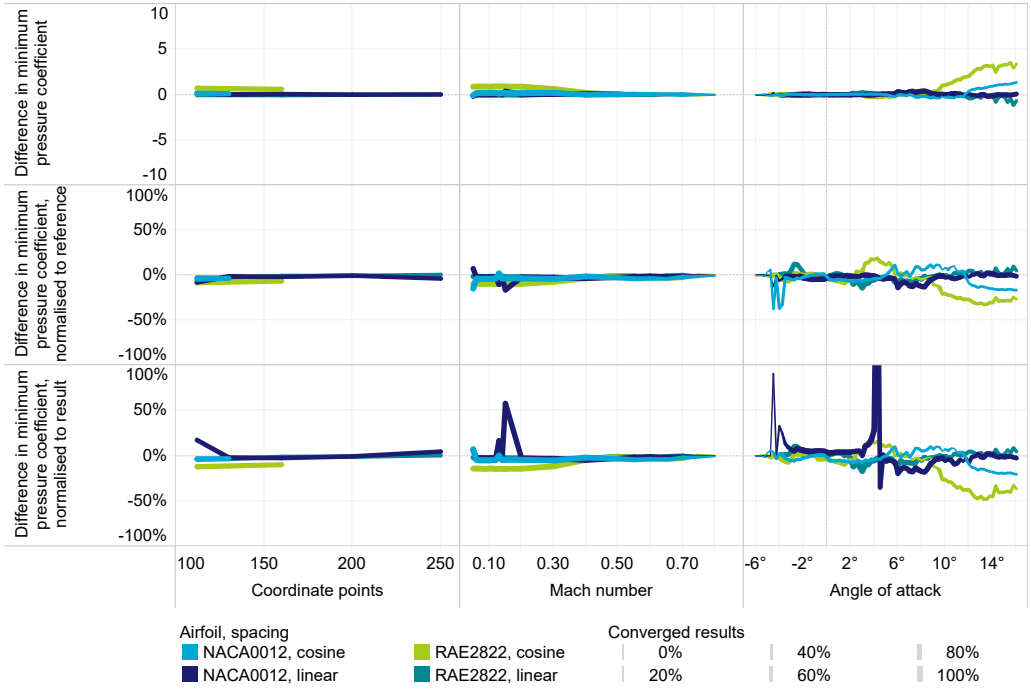


(a) Lift coefficient

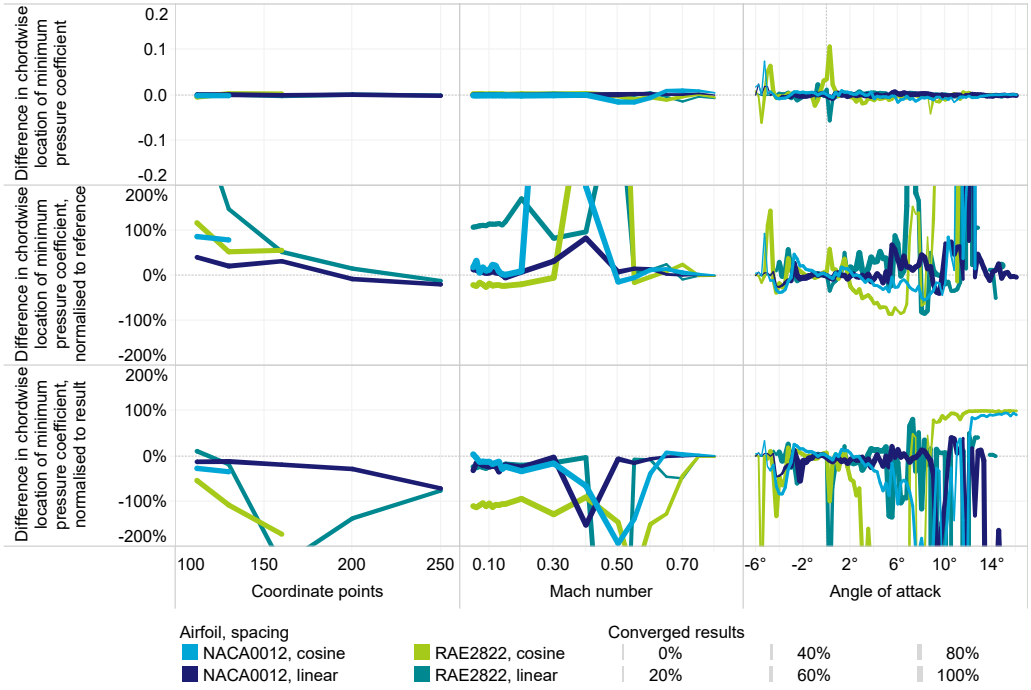


(b) Pitching moment coefficient

Figure F.26: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in MSES results for different geometries, geometric representations, Mach number and angles of attack



(c) Minimum pressure coefficient



(d) Chordwise location of minimum pressure coefficient

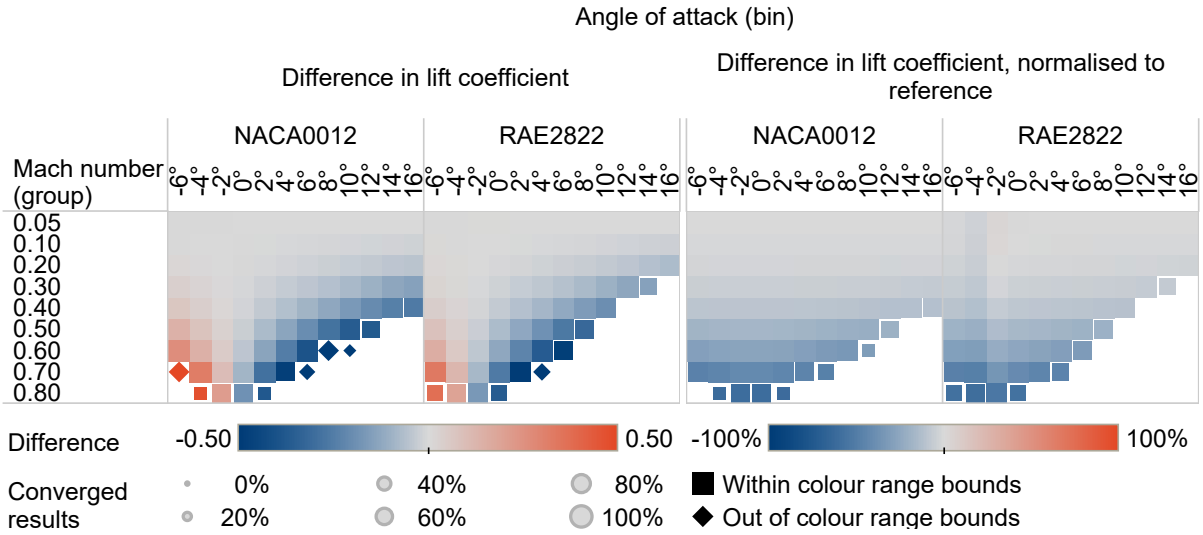
Figure F.26: Difference in quantities of interest (true and normalised w.r.t. reference and result) observed in MSES results for different geometries, geometric representations, Mach number and angles of attack (continued)

F.1.3. Influence of flow model: incompressible flow assumption

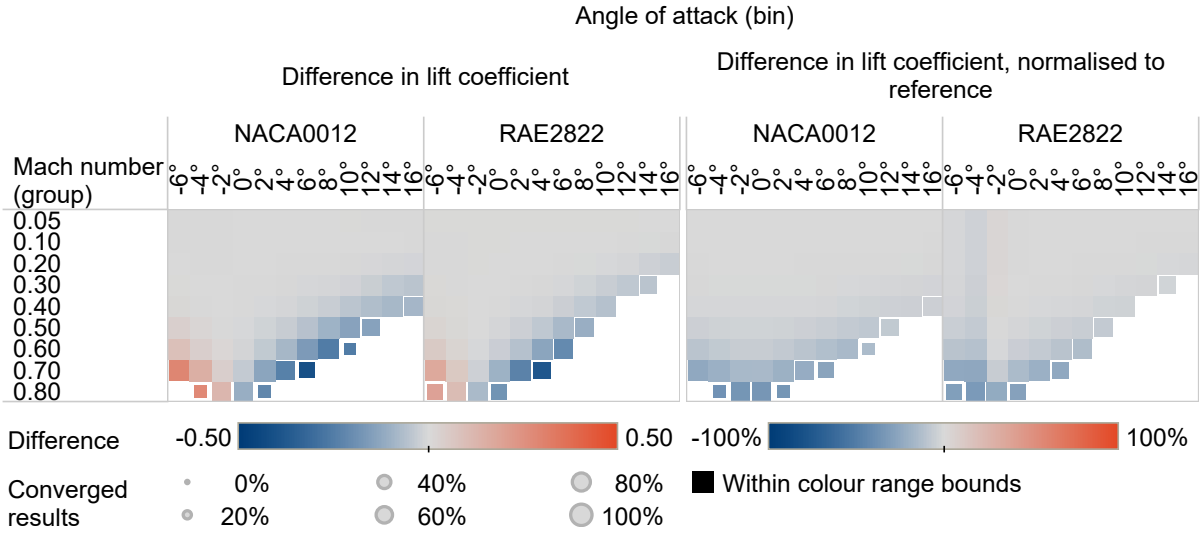
This section contains additional results showing the influence of the incompressible flow assumption on lift coefficient, pitching moment coefficient, minimum pressure coefficient and the chordwise location at which the minimum pressure coefficient is found, represented using the heat maps used in Section 6.3.3. As was the case for the previous section in this appendix, the results normalised to the reference value are shown first. These are followed by figures in which the difference is normalised with respect to the 'lower order' model. This data provides an indication of the correction factor that needs to be applied to these lower order output in order to arrive at the higher order result.

The results shown compare the results from both the completely incompressible model (XFOIL-U) as well as the corrected versions (XFOIL-PG for Prandtl-Glauert, XFOIL-KT for Karman-Tsien) to both the partially-conservative (VGK) and non-conservative (VGK-NC) compressible model.

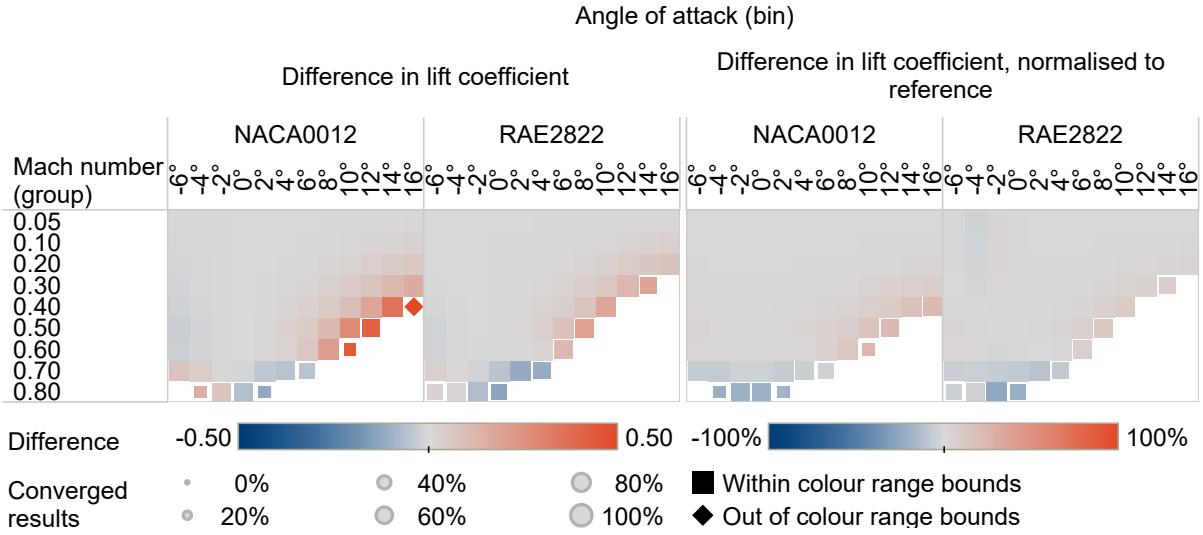
Normalised to reference



(a) Without compressibility correction (XFOIL-U)

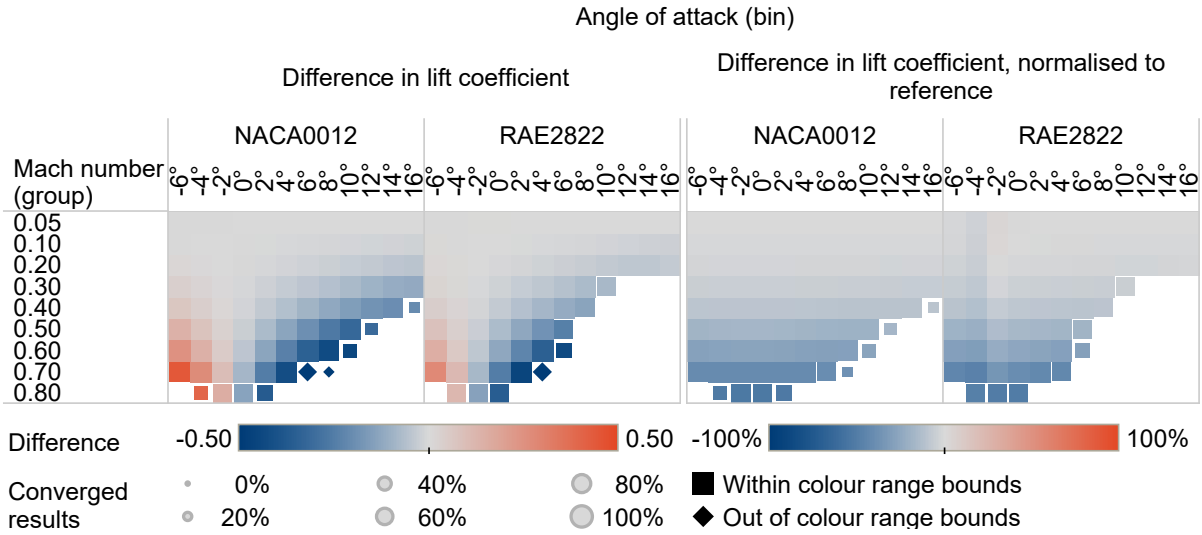


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

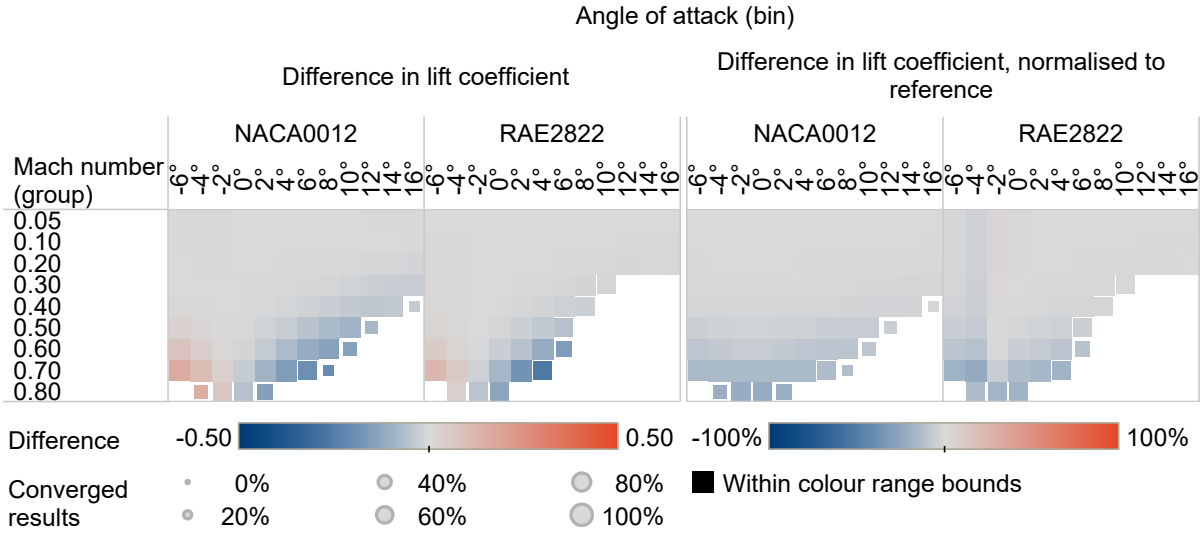


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

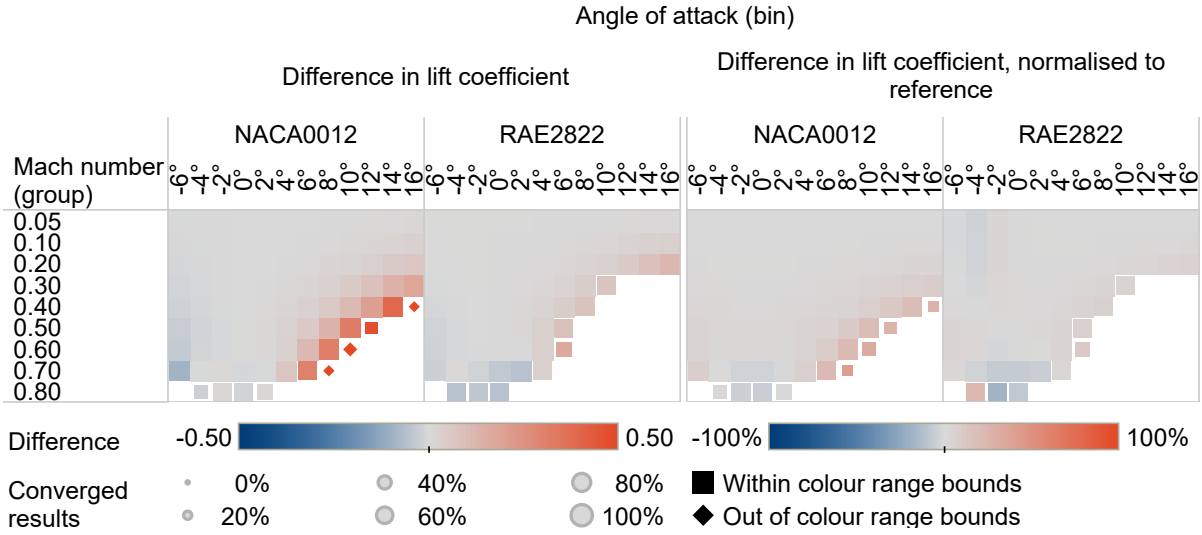
Figure F.27: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

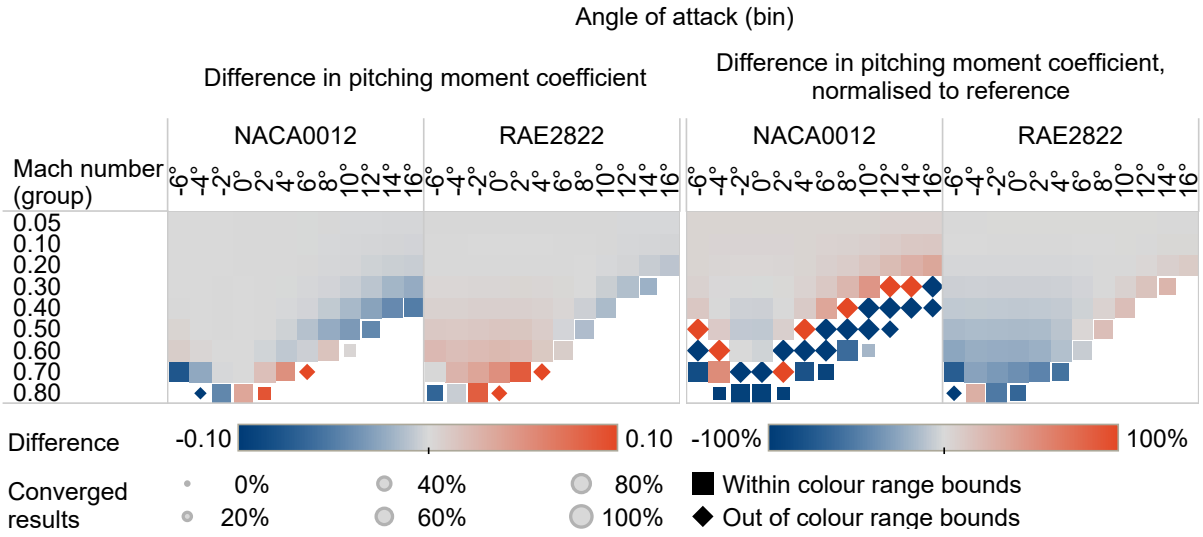


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

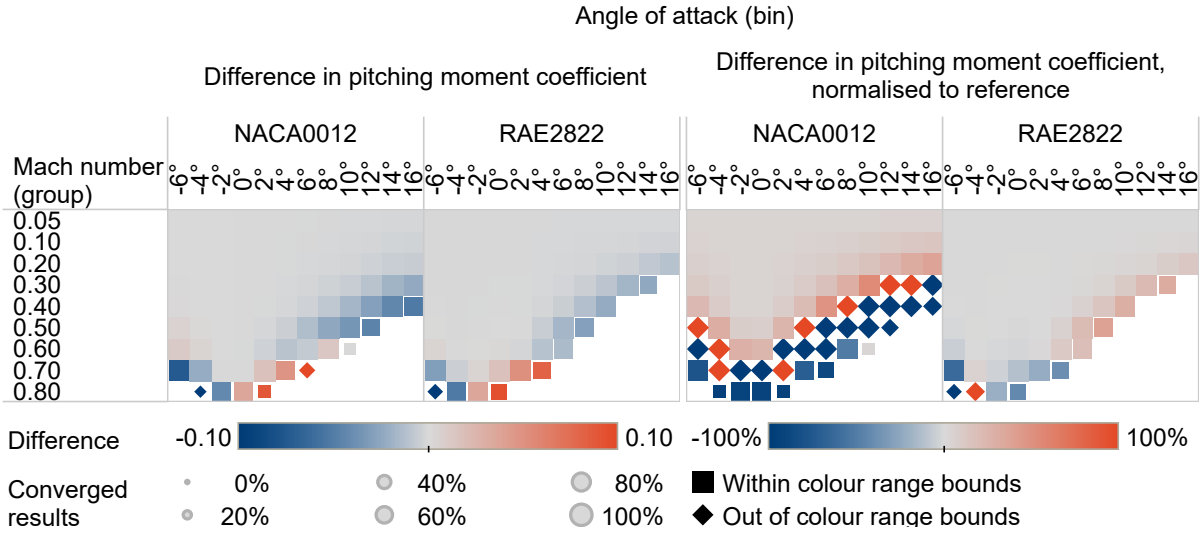


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

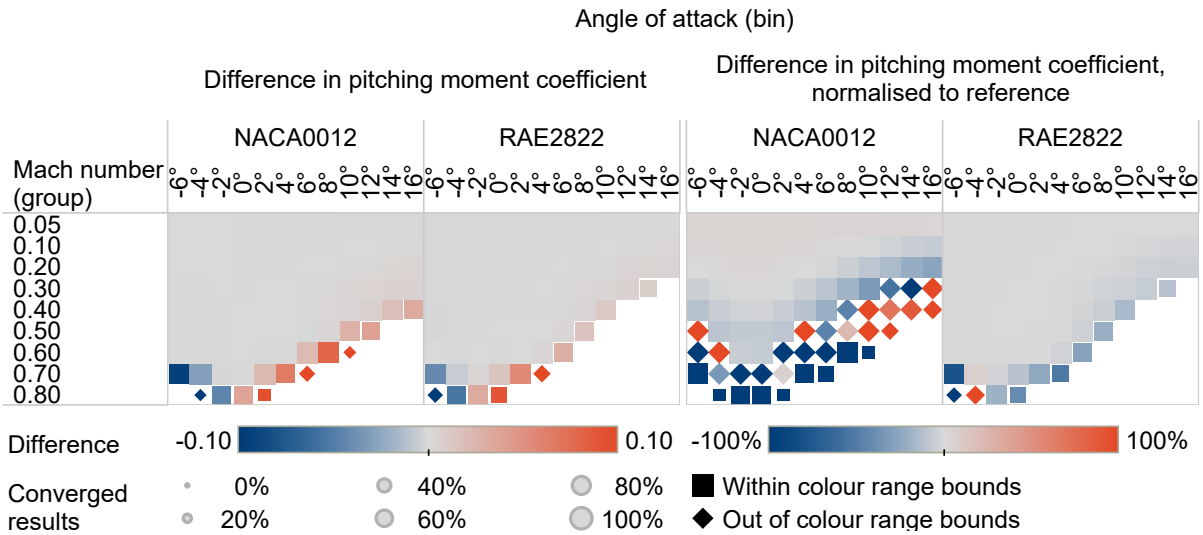
Figure F.28: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

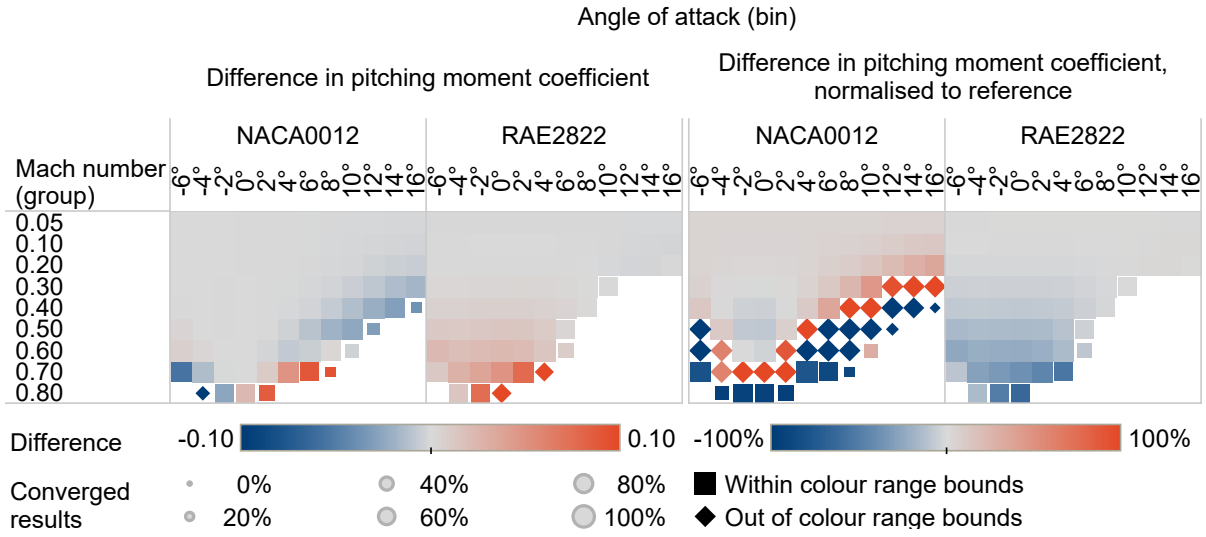


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

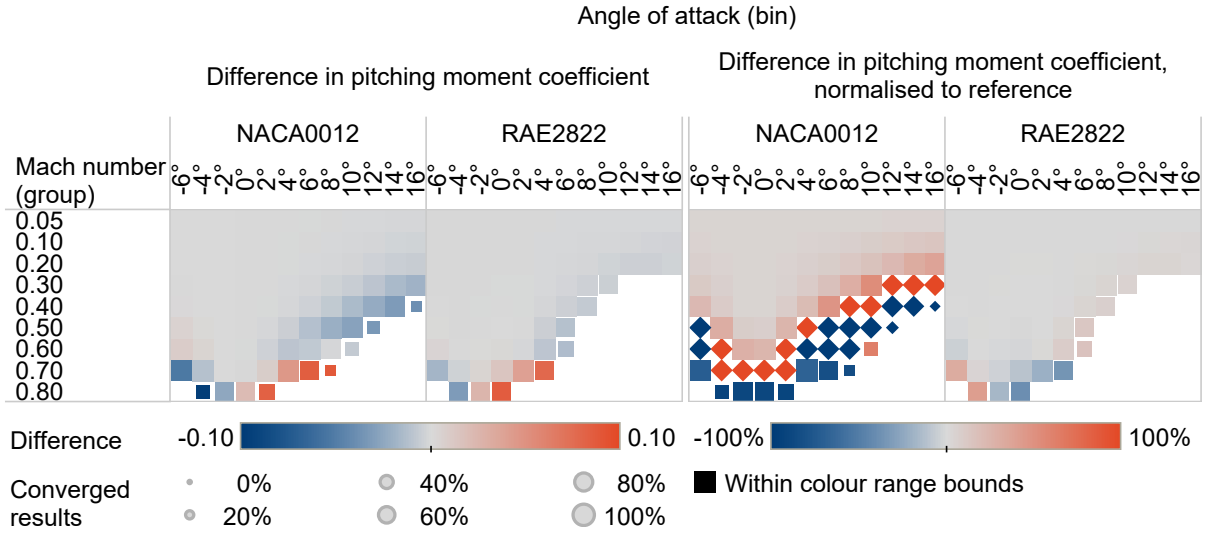


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

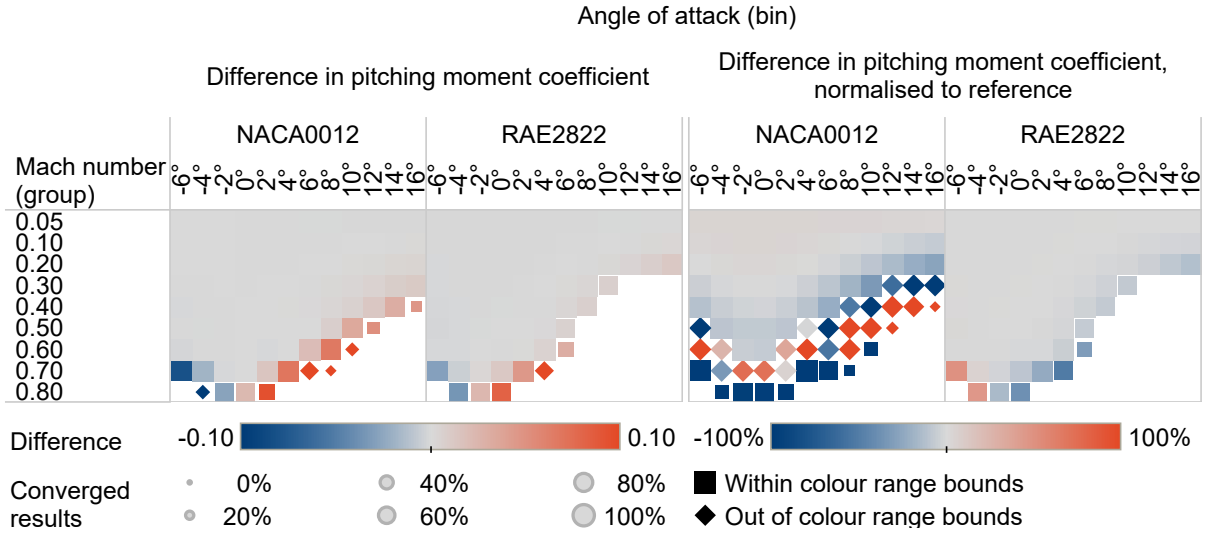
Figure F.29: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) pitching moment coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

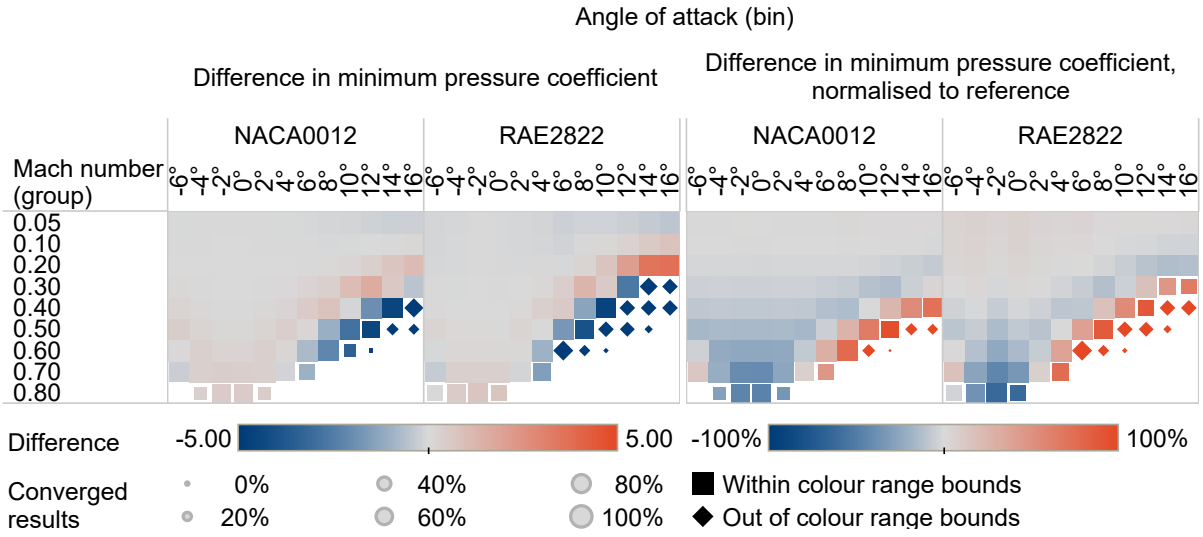


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

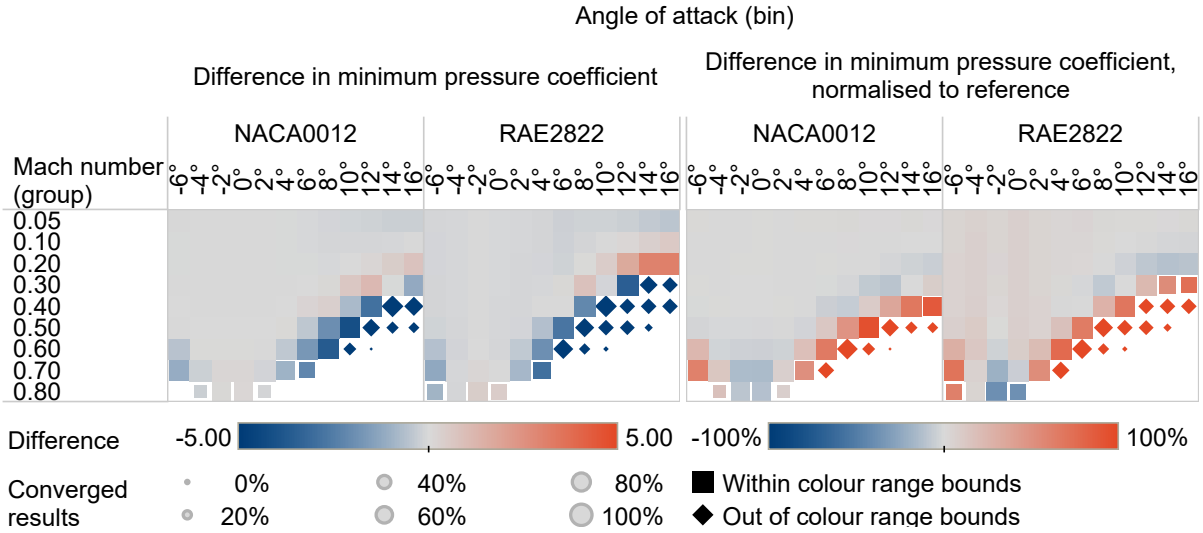


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

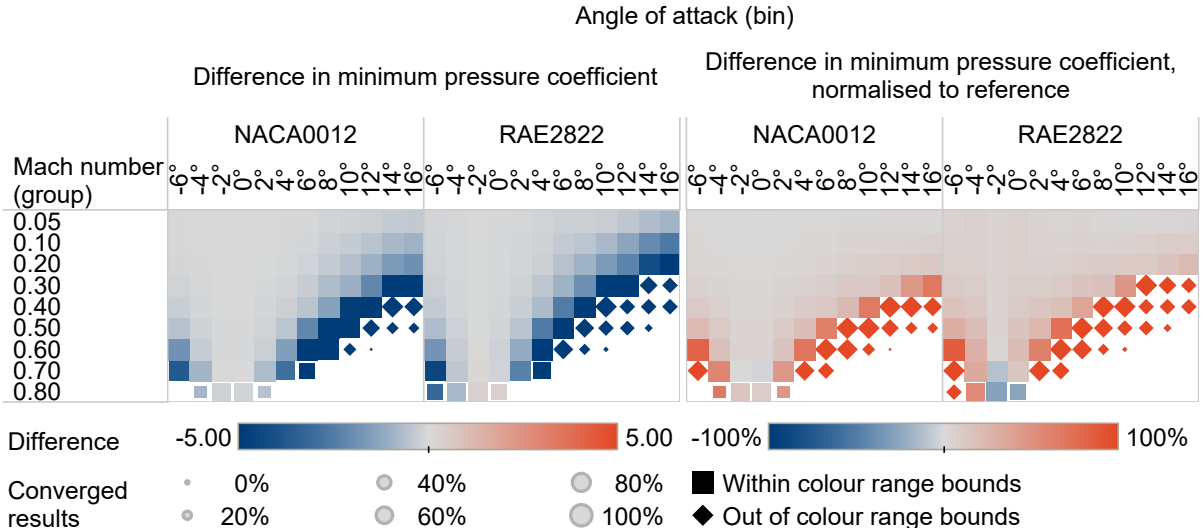
Figure F.30: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) pitching moment coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

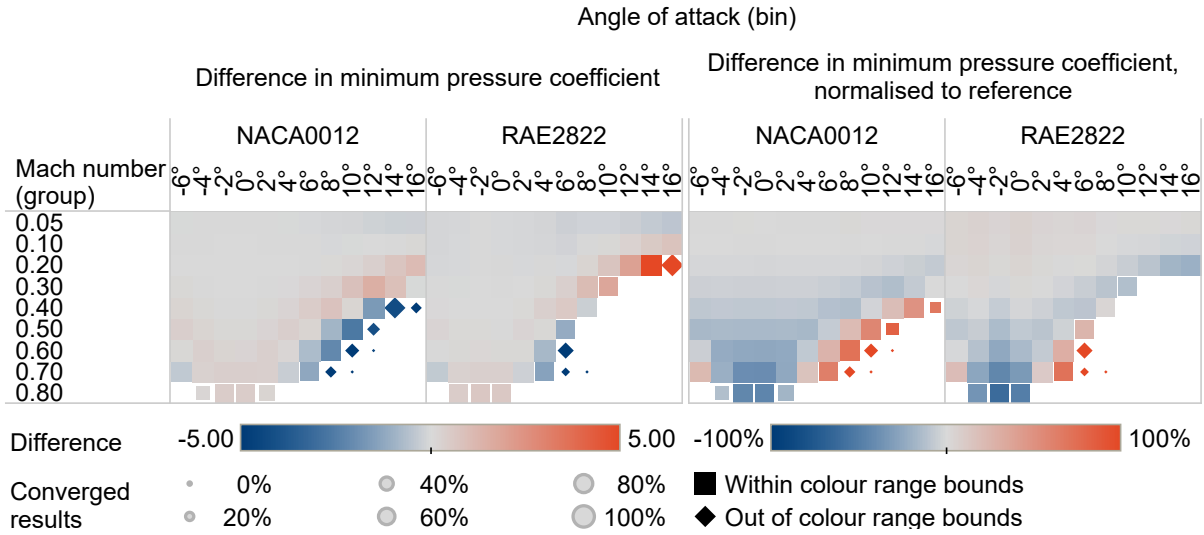


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

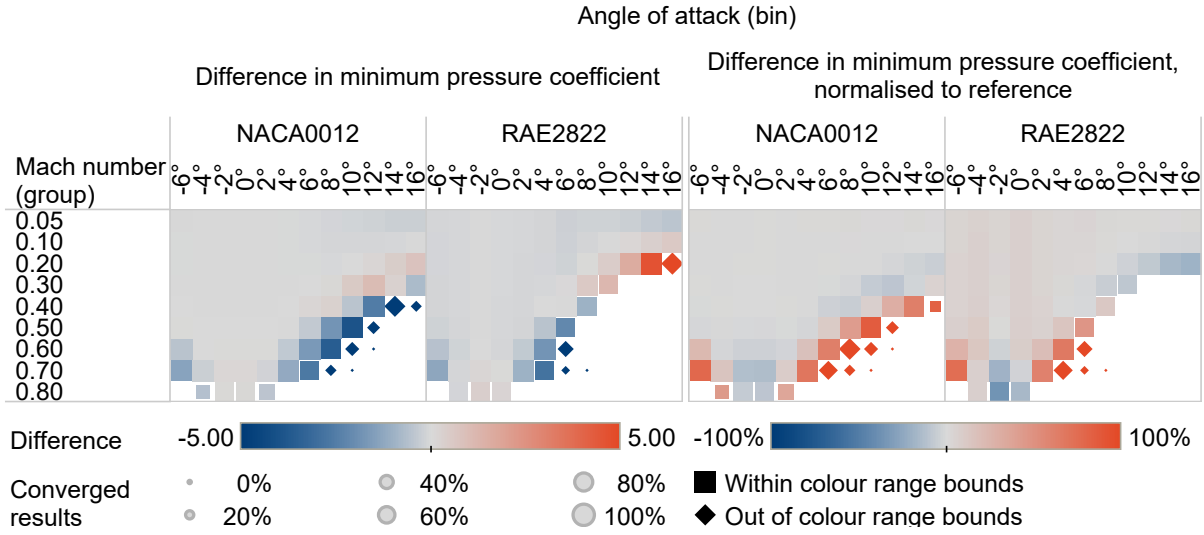


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

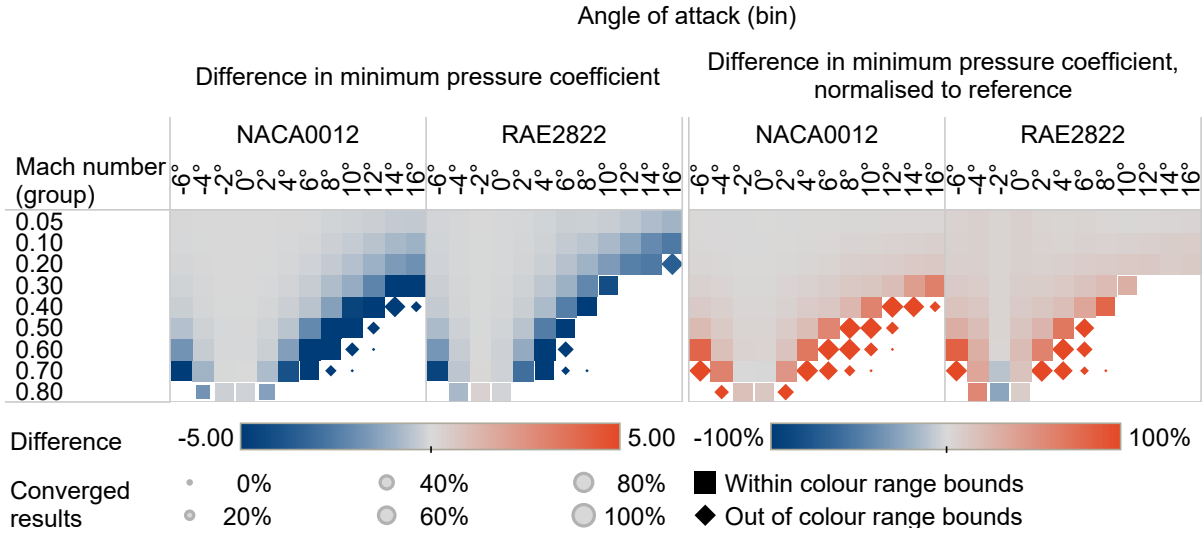
Figure F.31: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

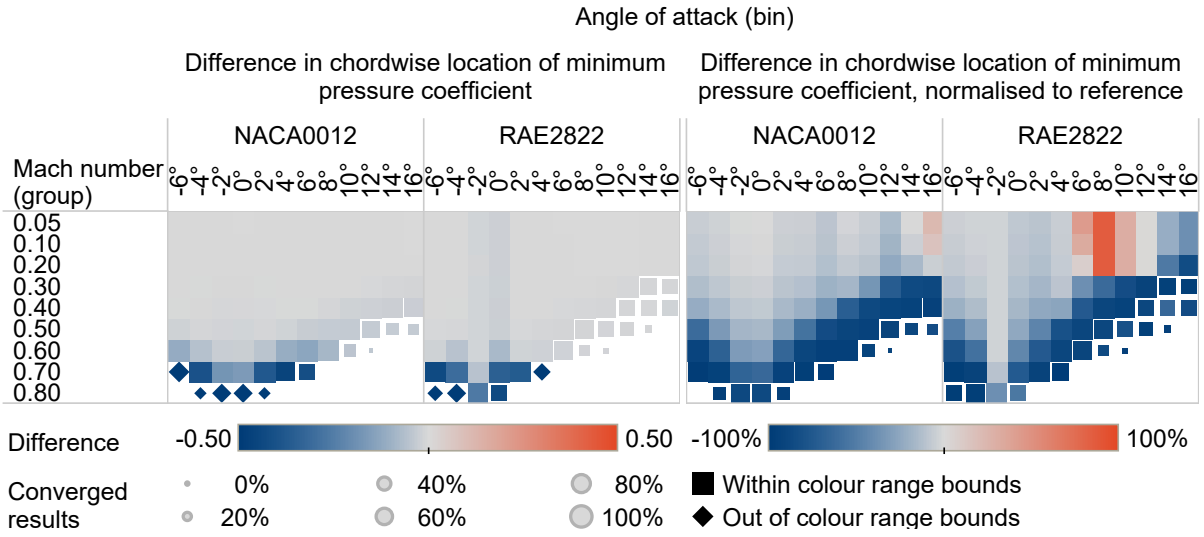


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

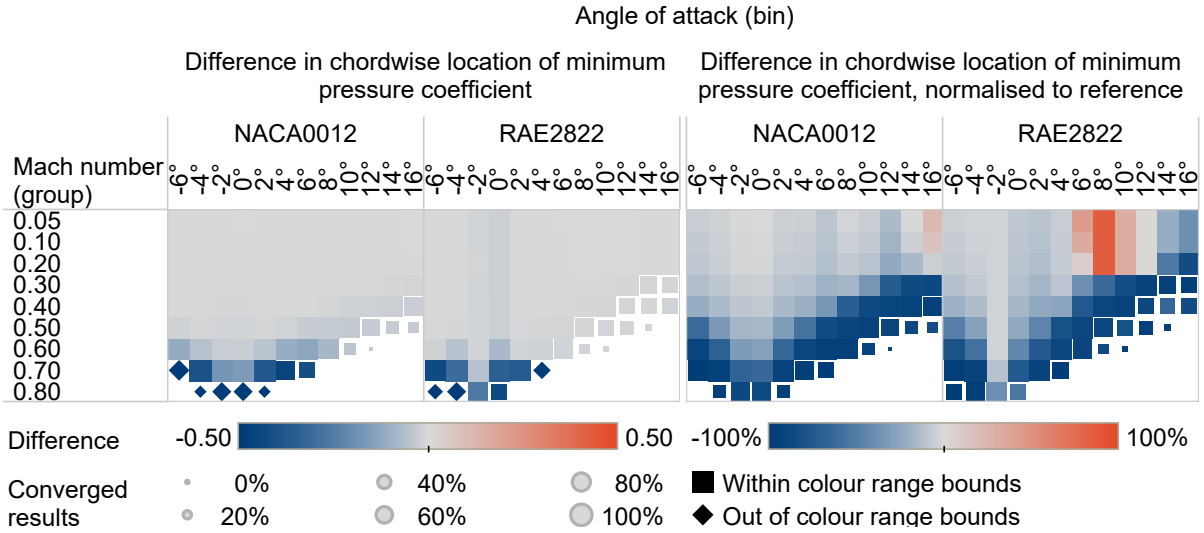


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

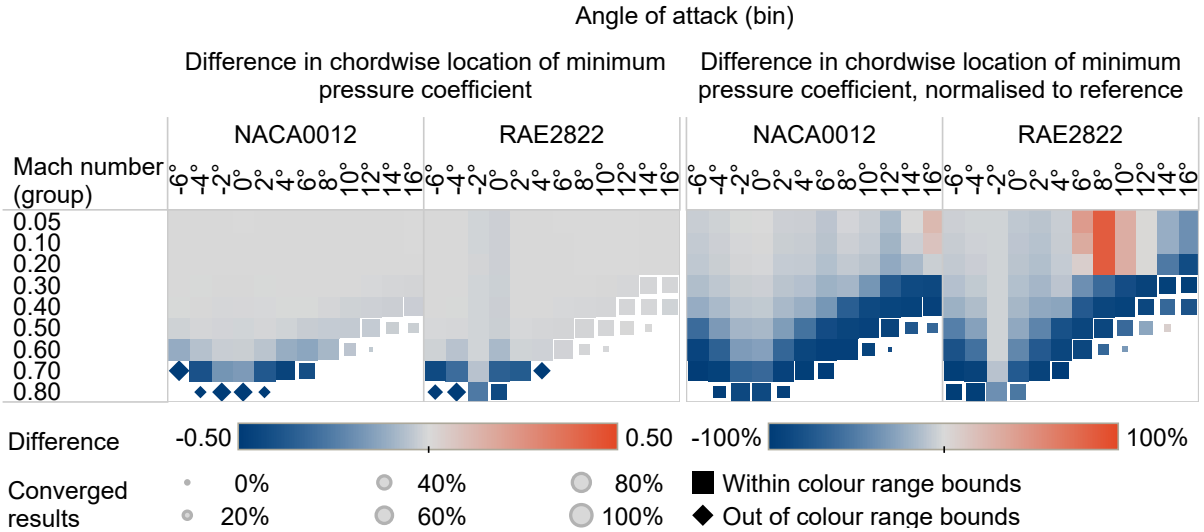
Figure F.32: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

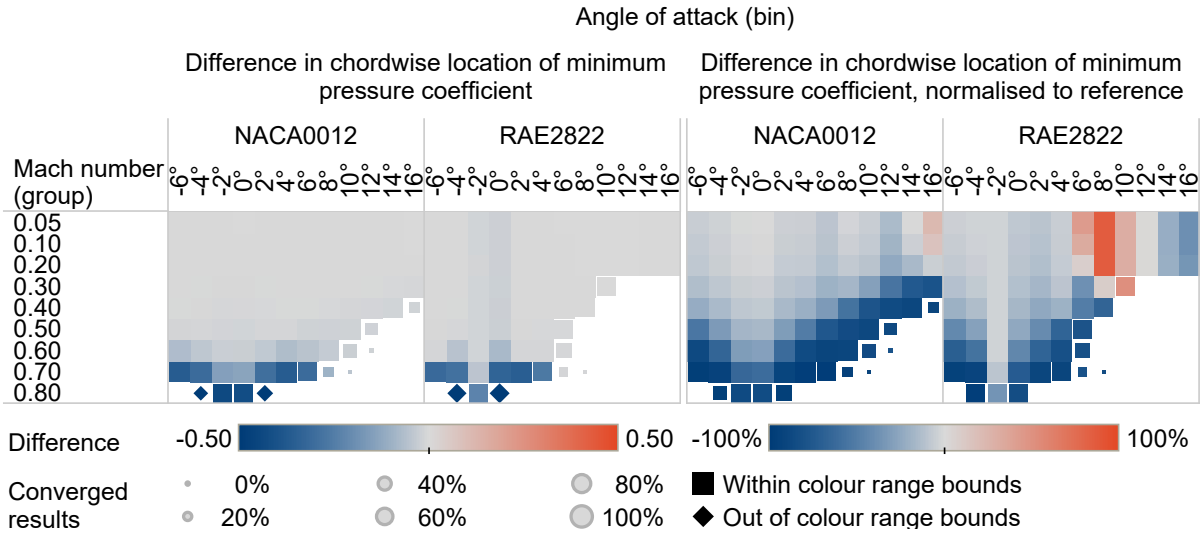


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

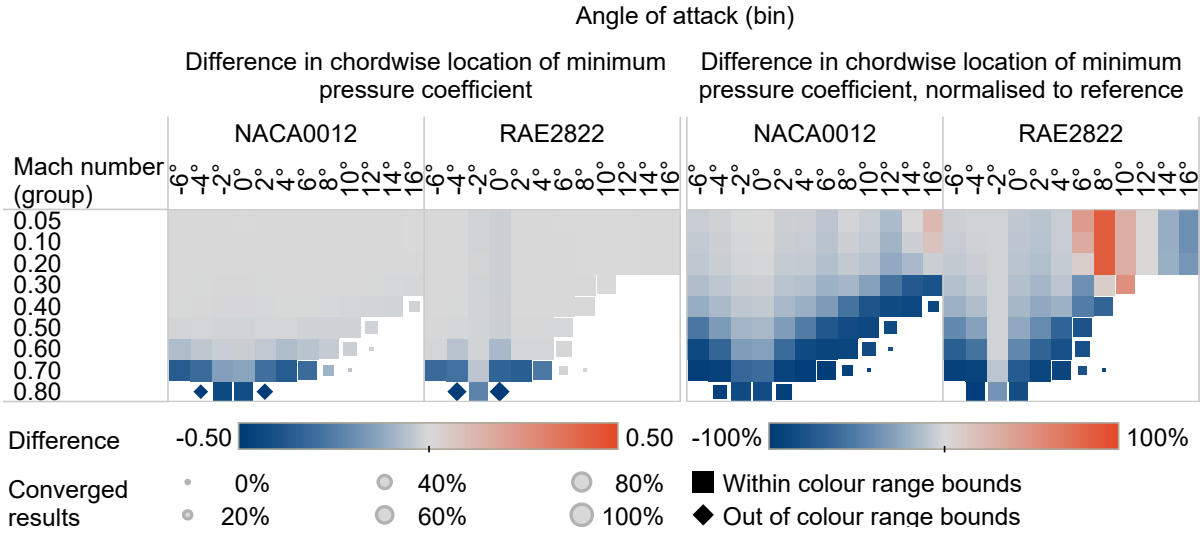


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

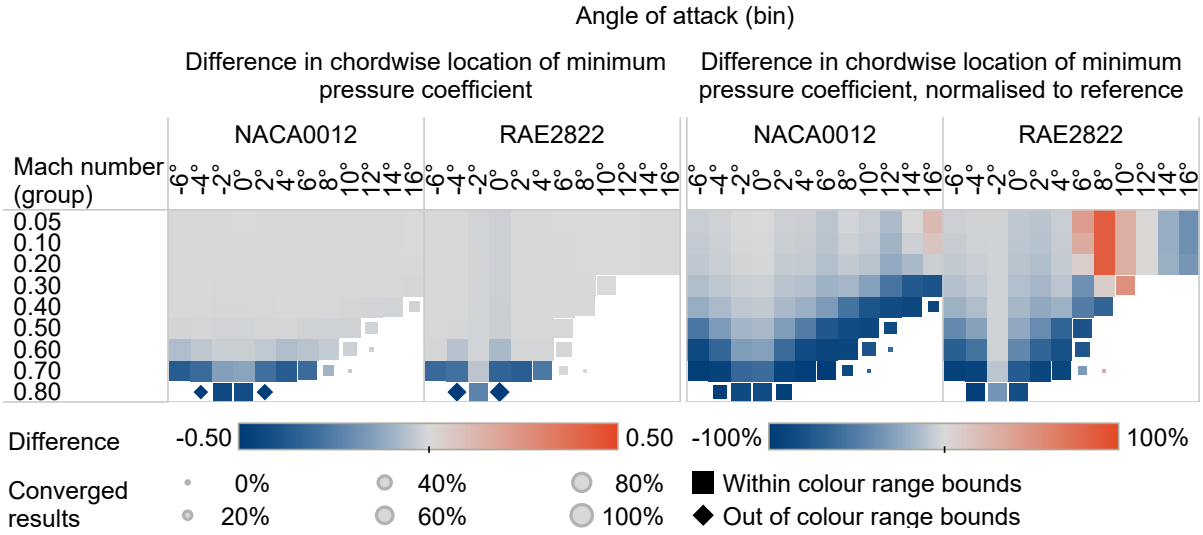
Figure F.33: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) chordwise location of minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)



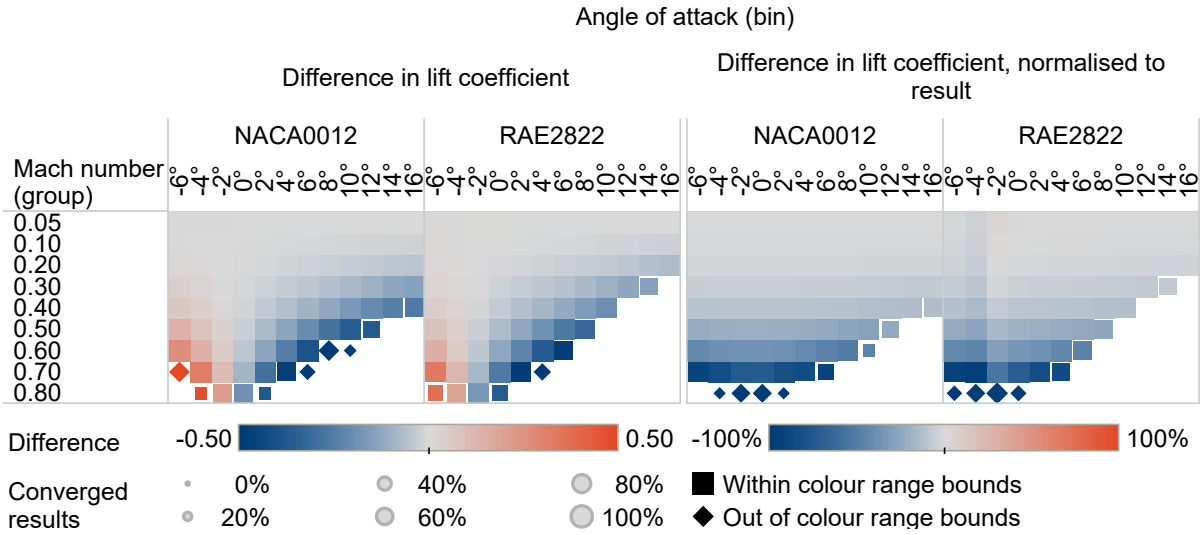
(b) With Prandtl-Glauert compressibility (XFOIL-PG)



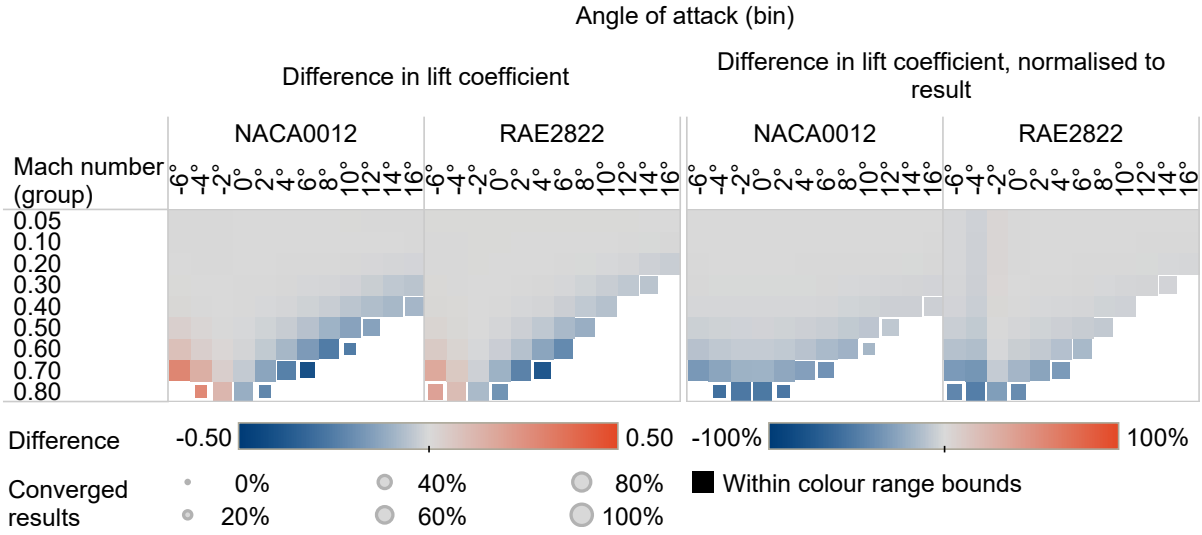
(c) With Karman-Tsien compressibility correction (XFOIL-KT)

Figure F.34: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) chordwise location of minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

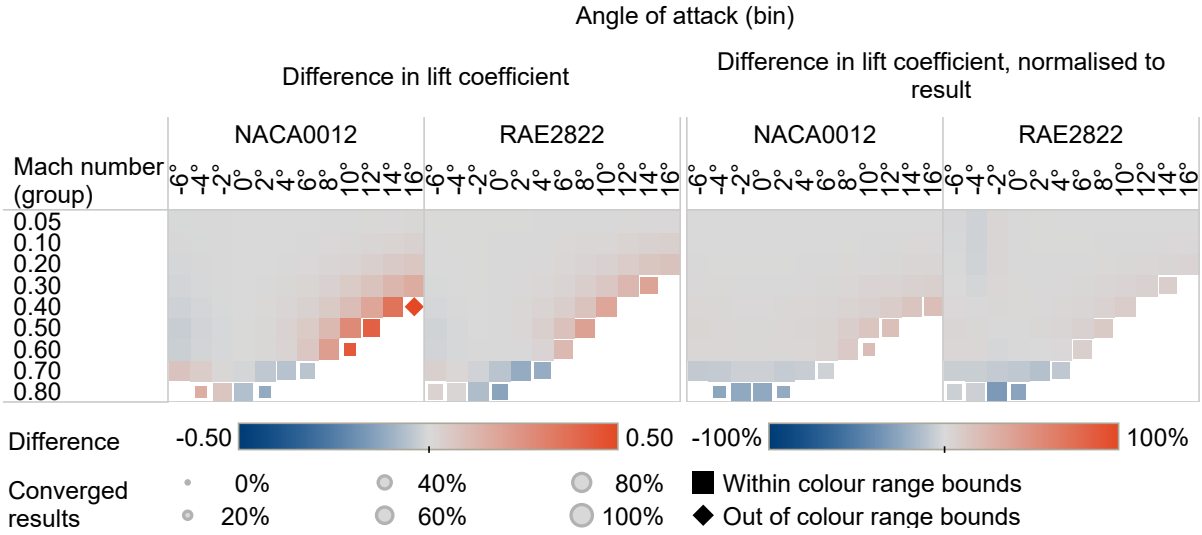
Normalised to result



(a) Without compressibility correction (XFOIL-U)

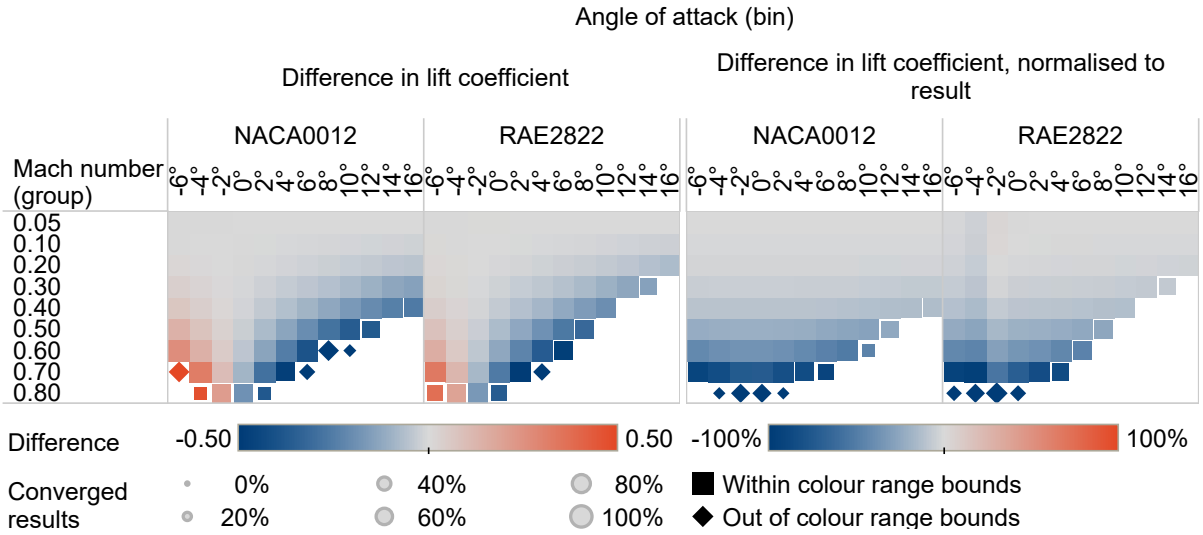


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

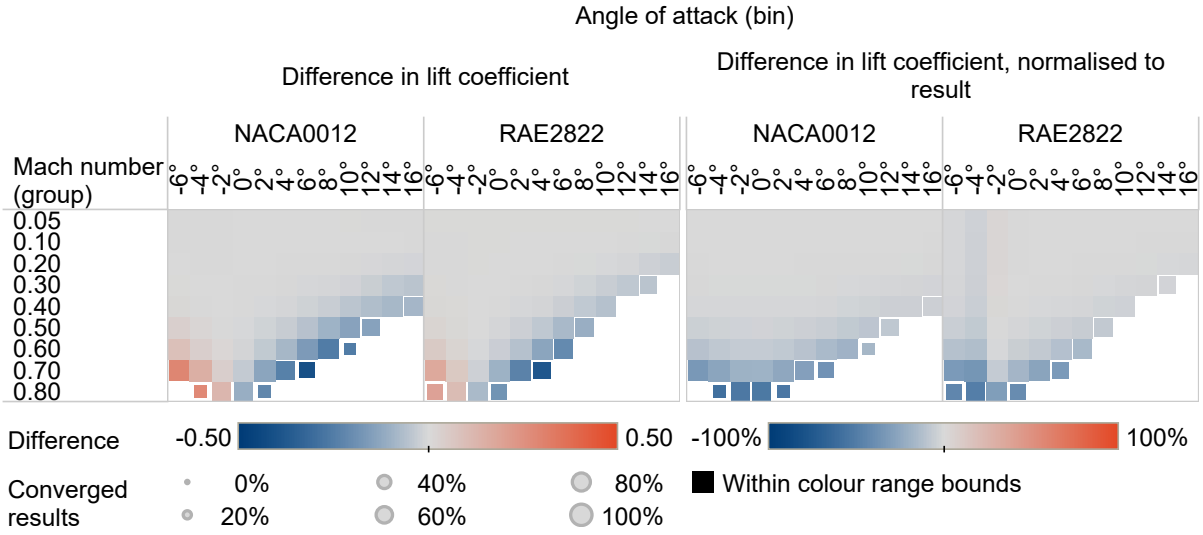


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

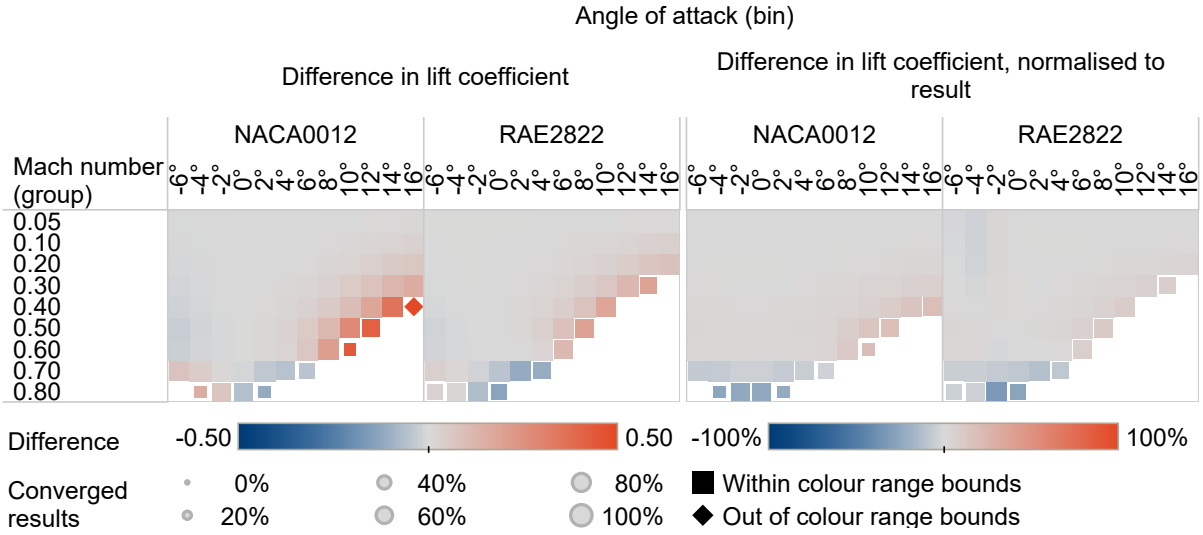
Figure F.35: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) lift coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

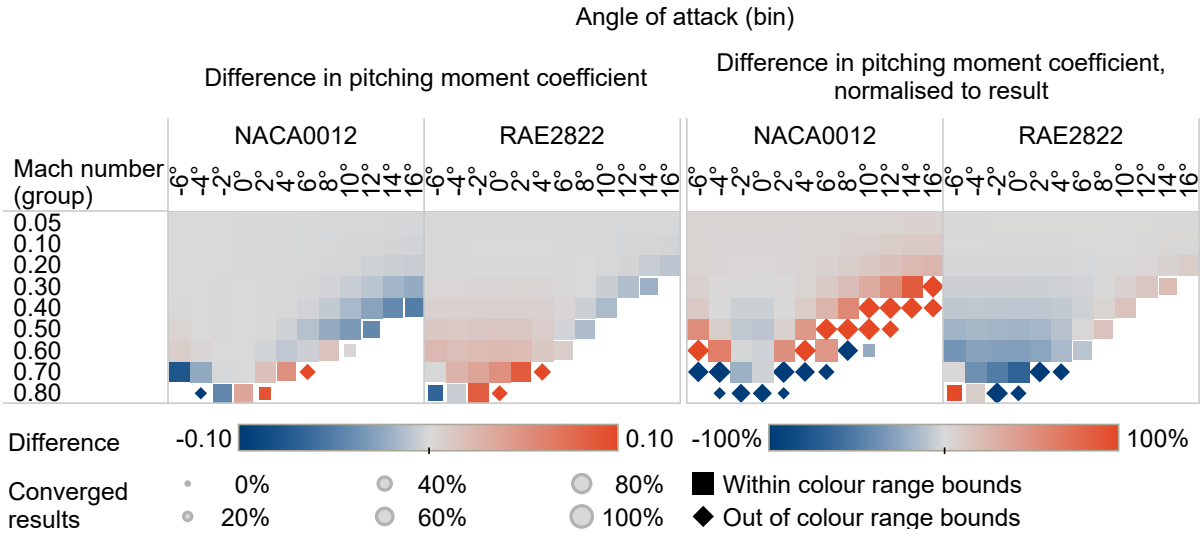


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

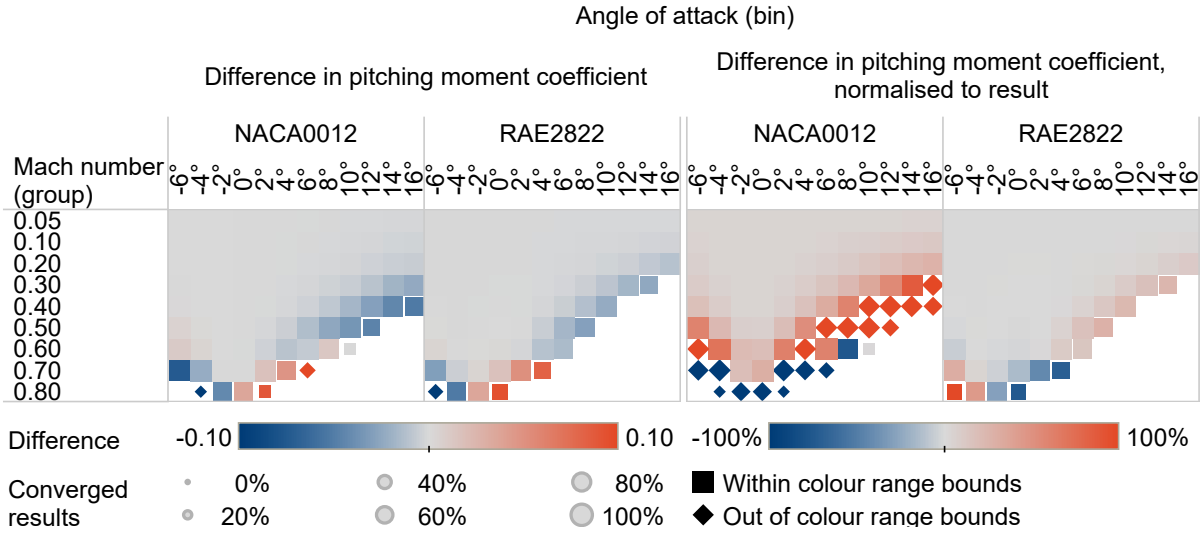


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

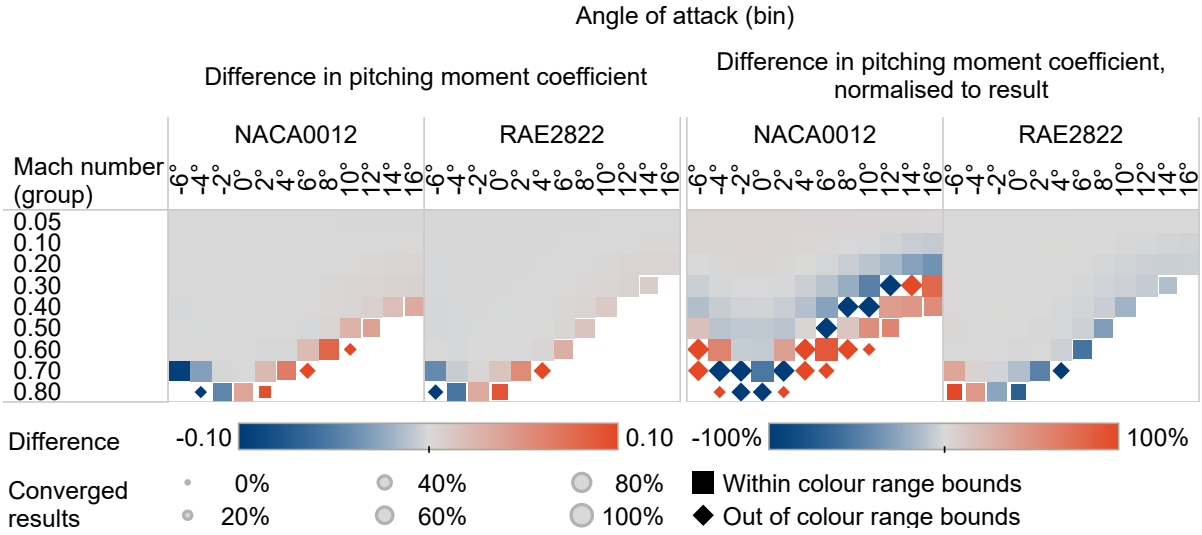
Figure F.36: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) lift coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

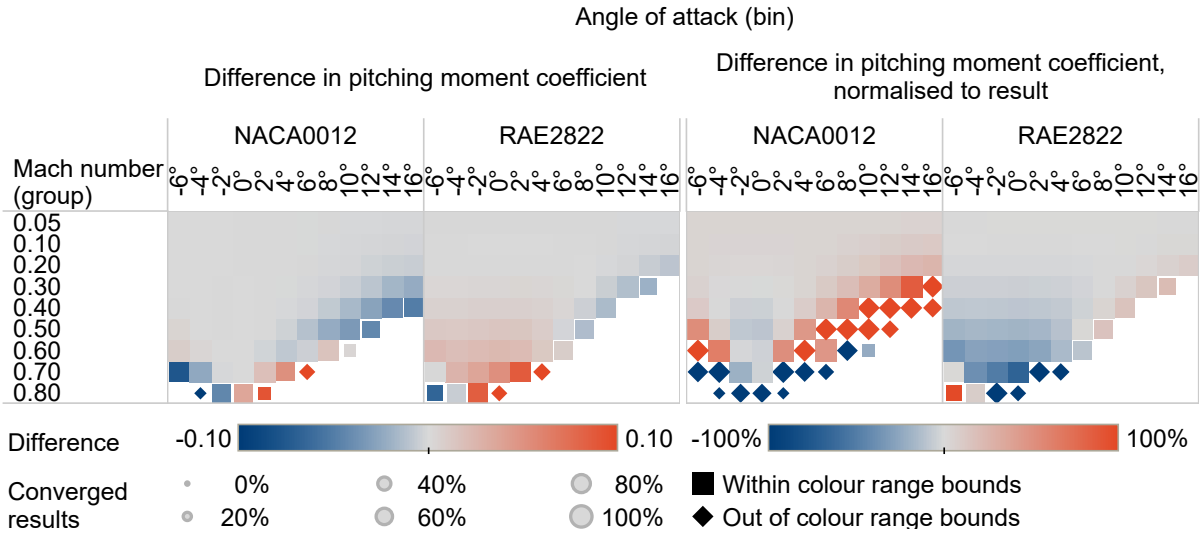


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

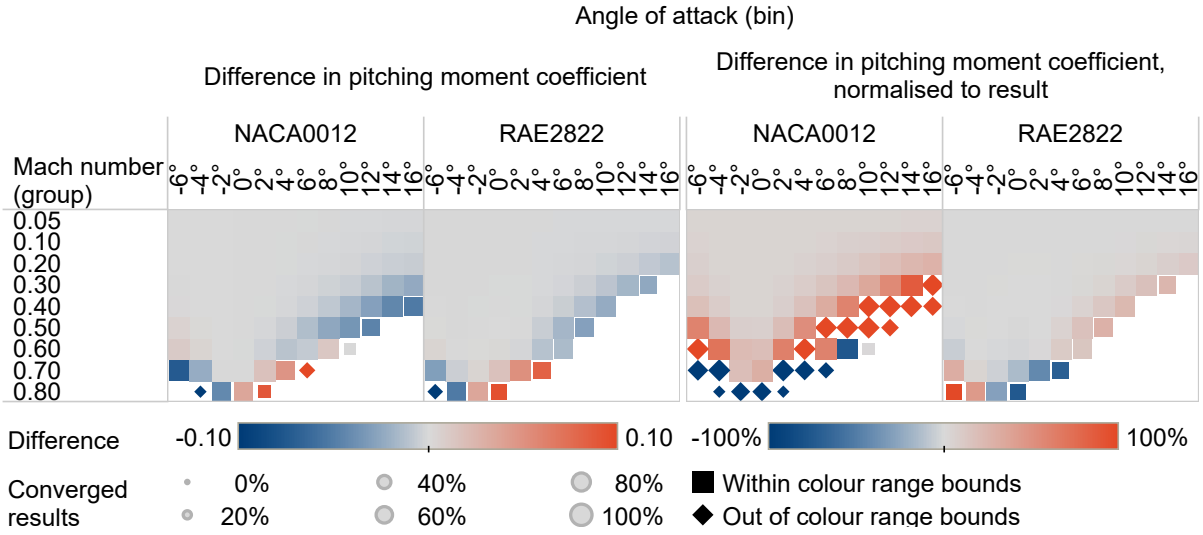


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

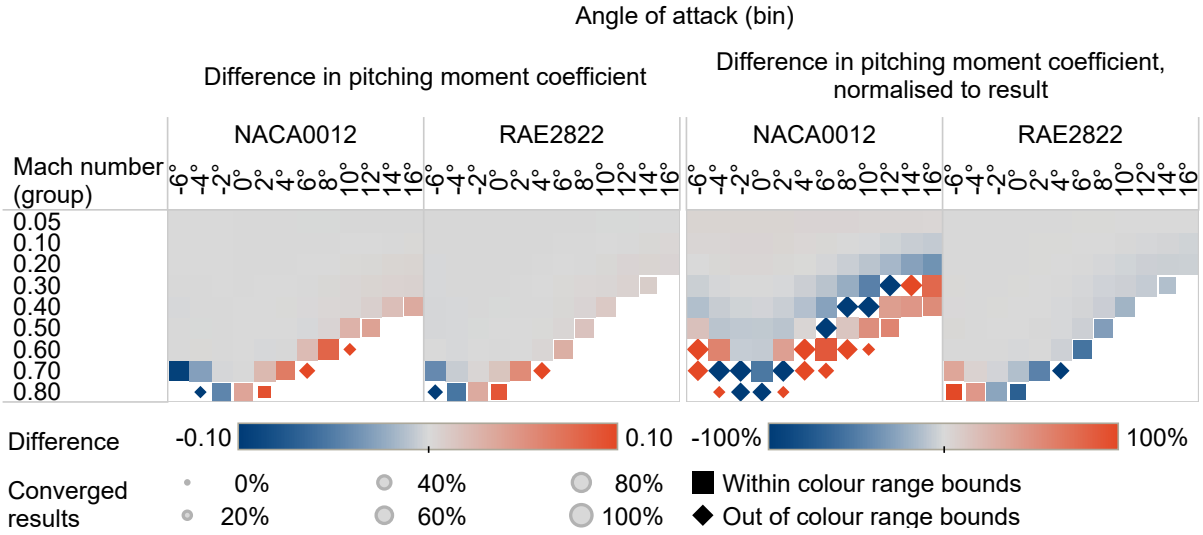
Figure F.37: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) pitching moment coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

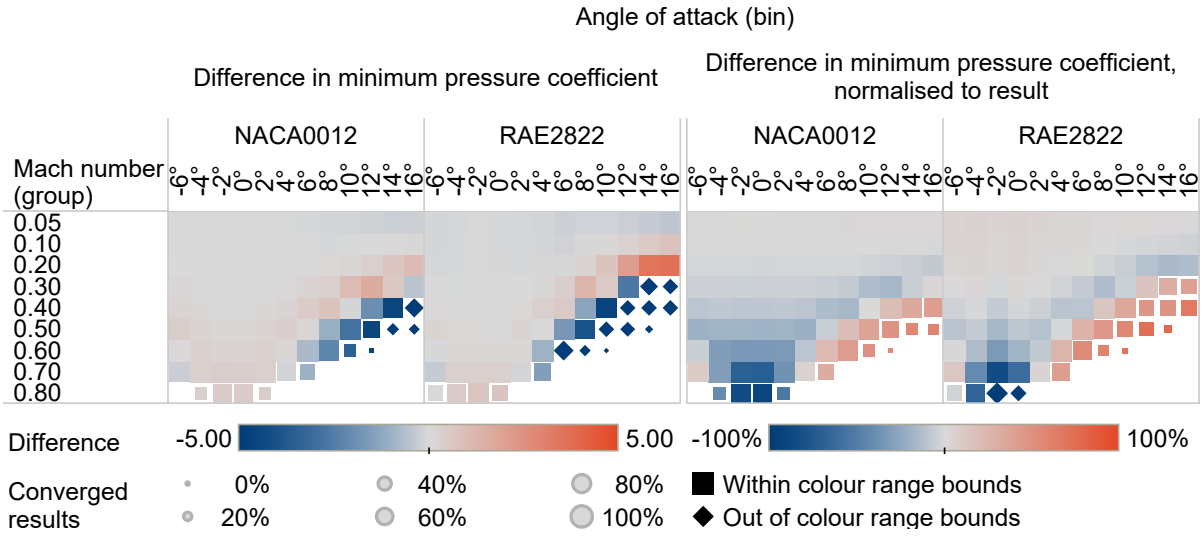


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

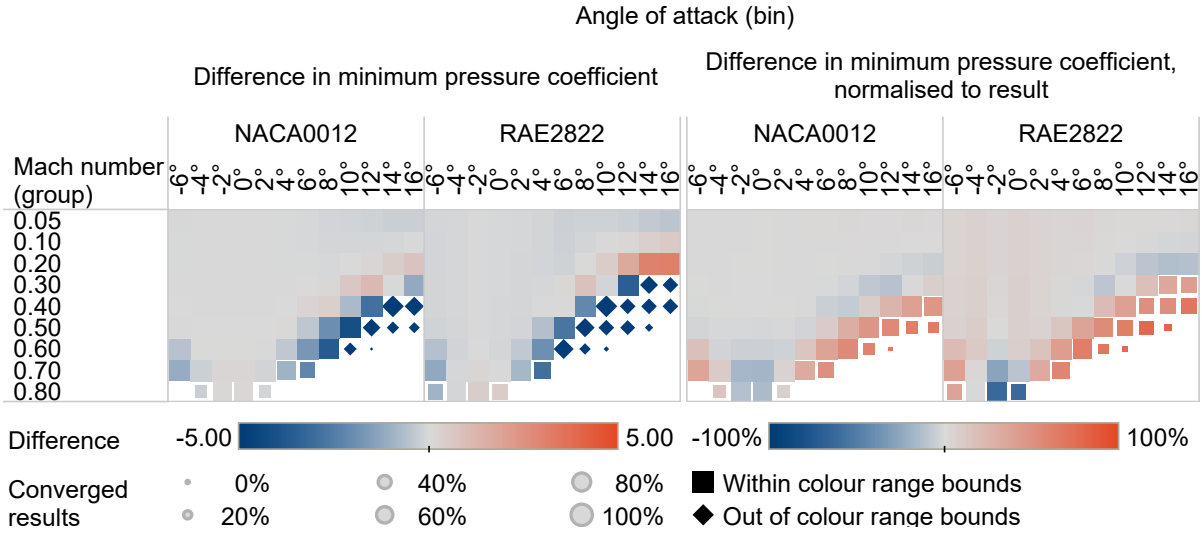


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

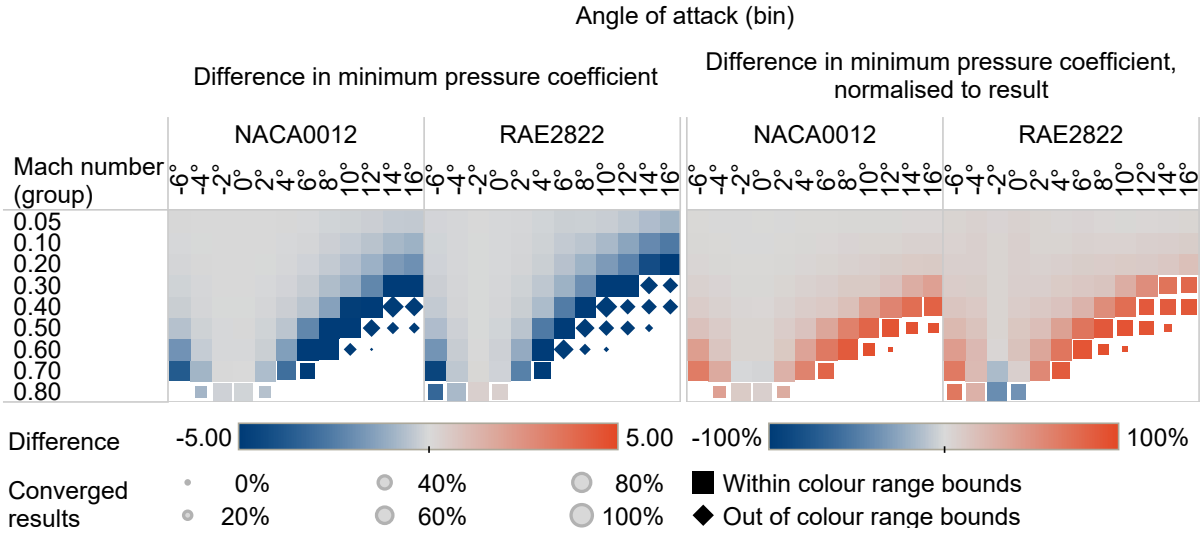
Figure F.38: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) pitching moment coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

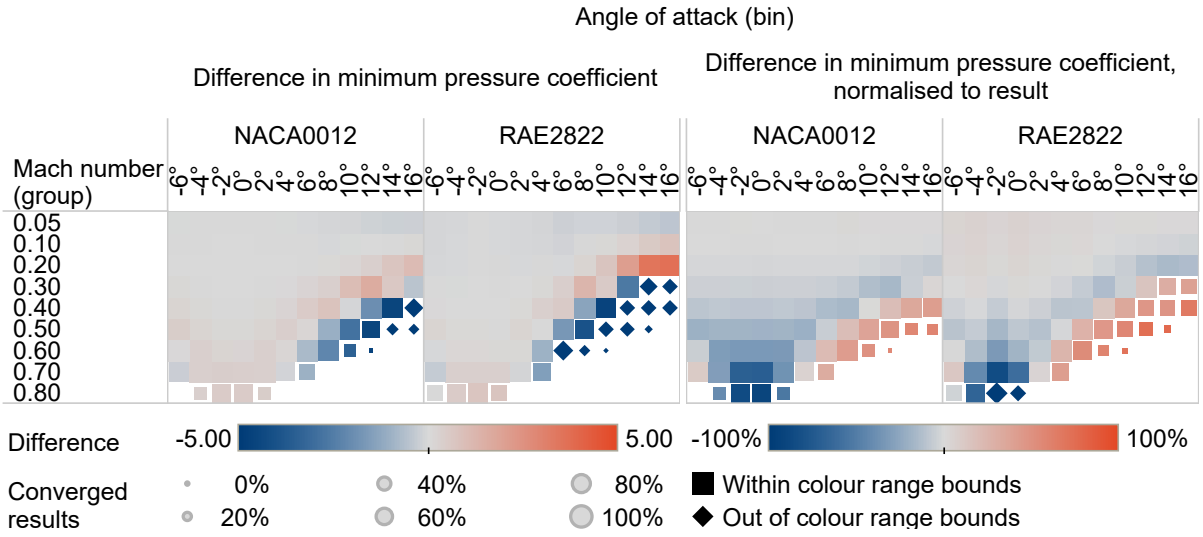


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

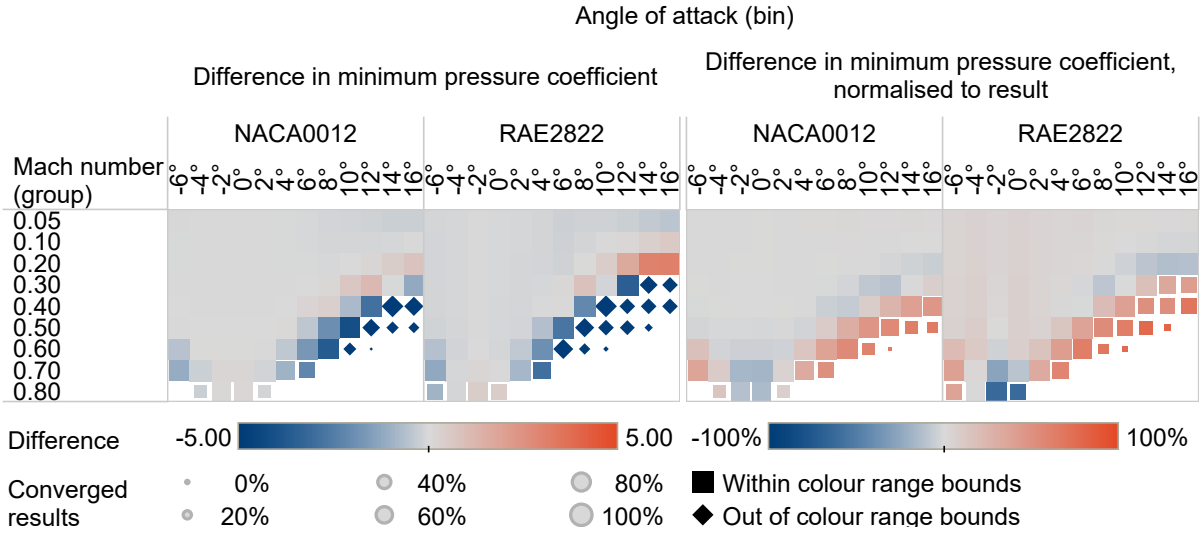


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

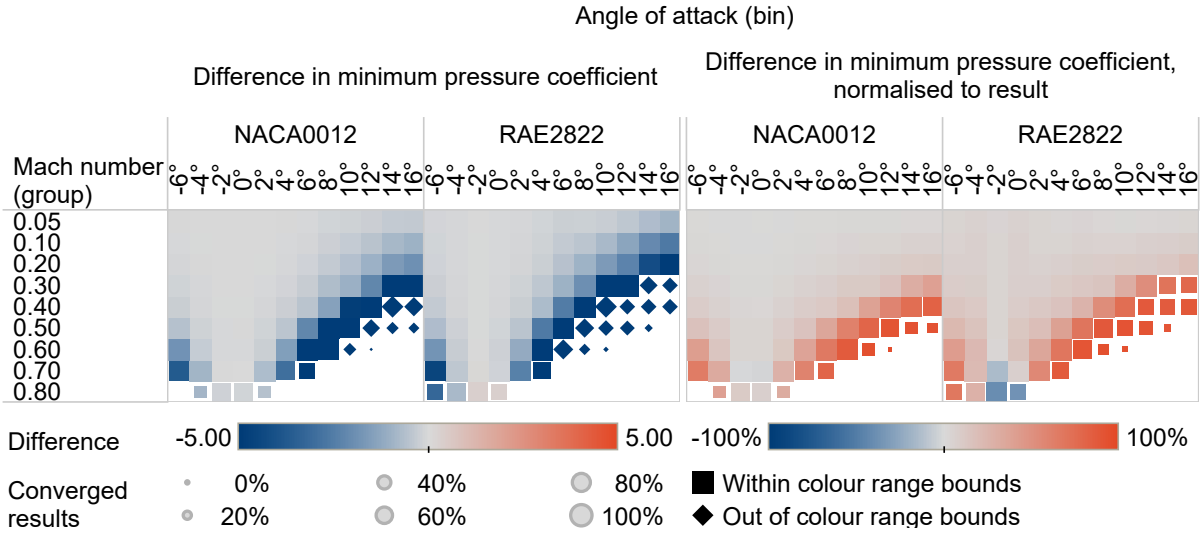
Figure F.39: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

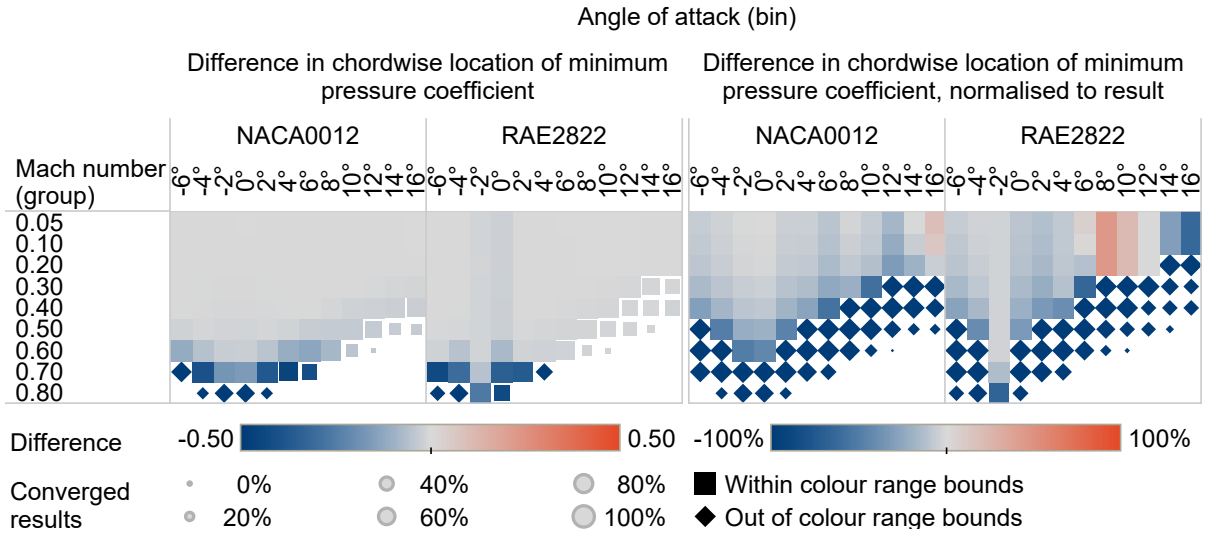


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

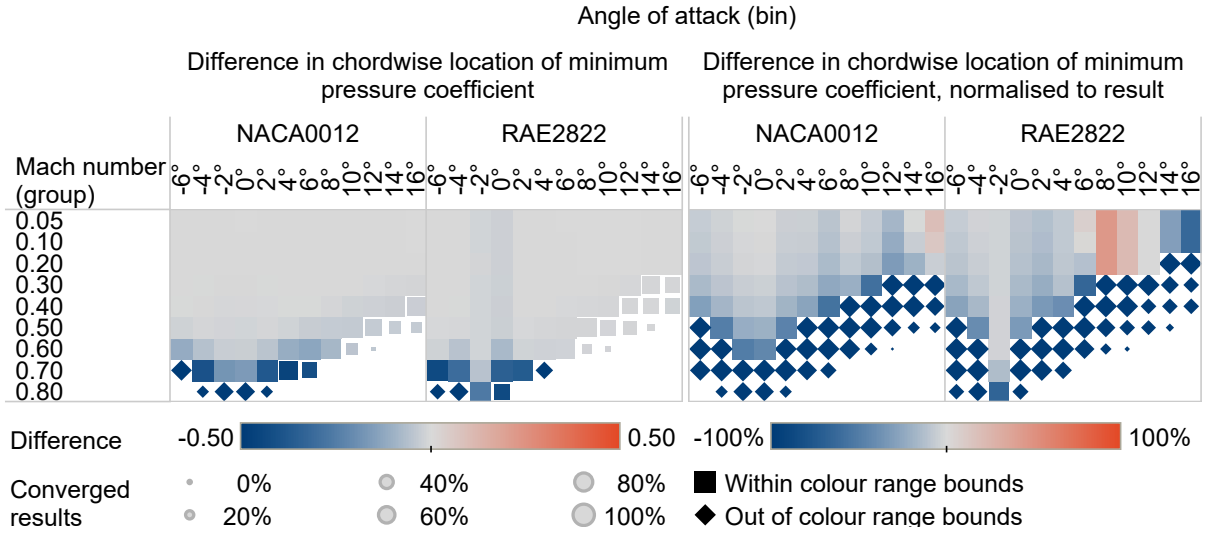


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

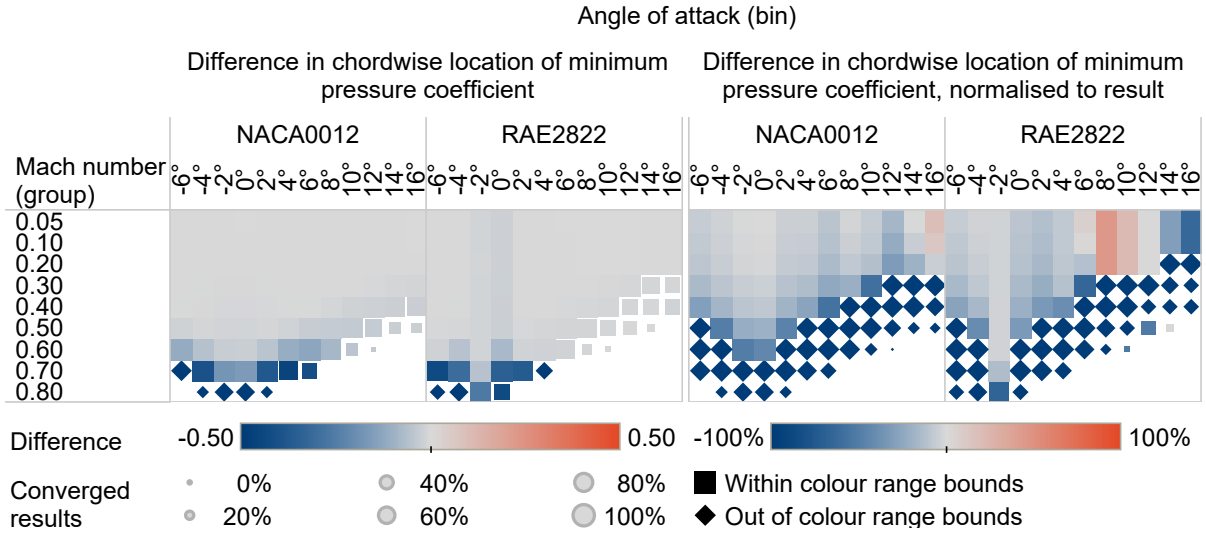
Figure F.40: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)

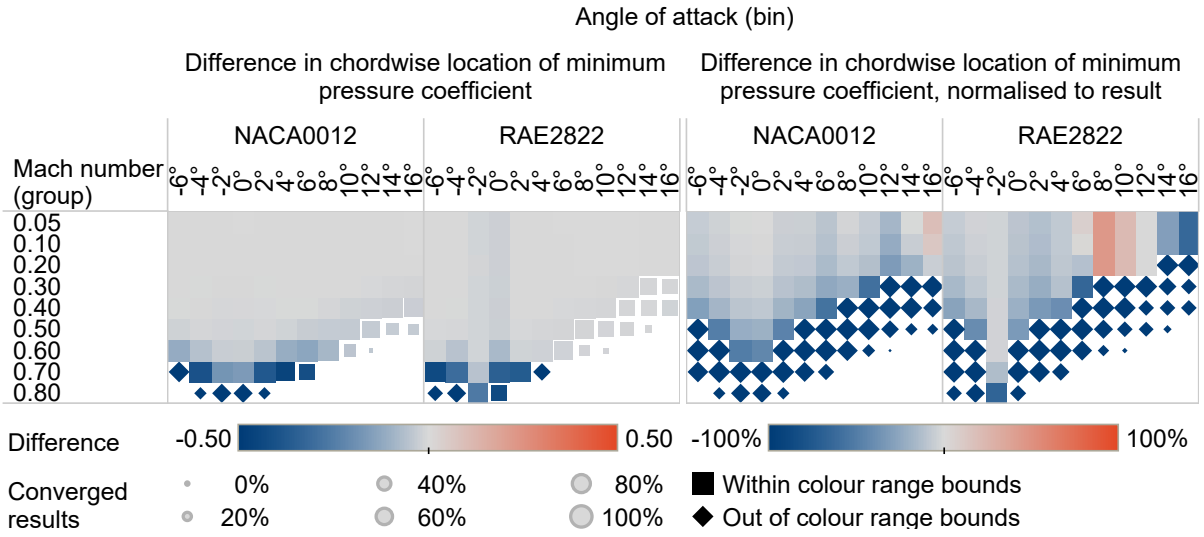


(b) With Prandtl-Glauert compressibility (XFOIL-PG)

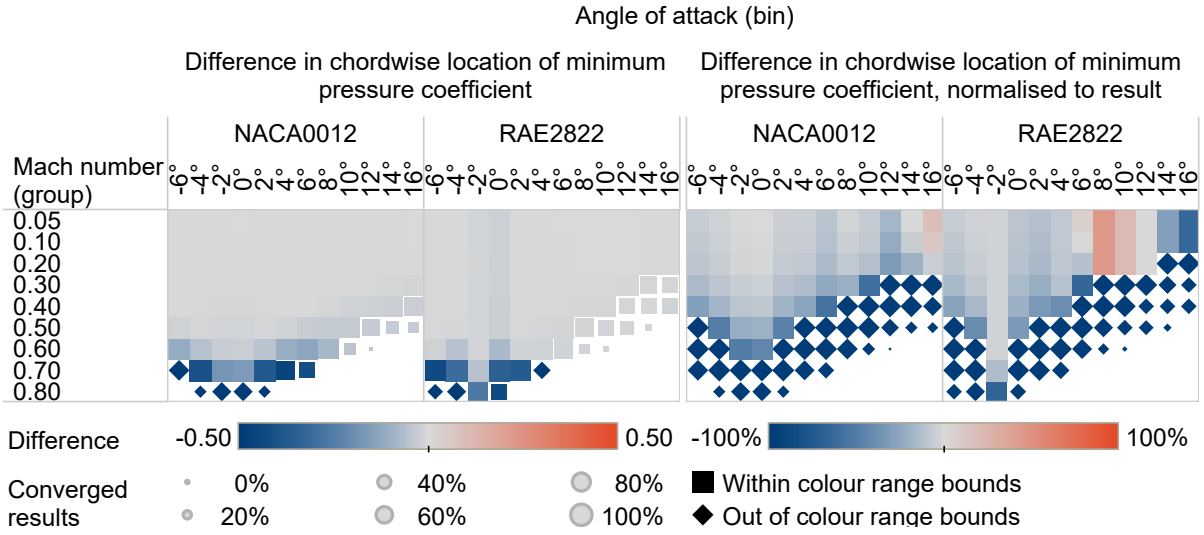


(c) With Karman-Tsien compressibility correction (XFOIL-KT)

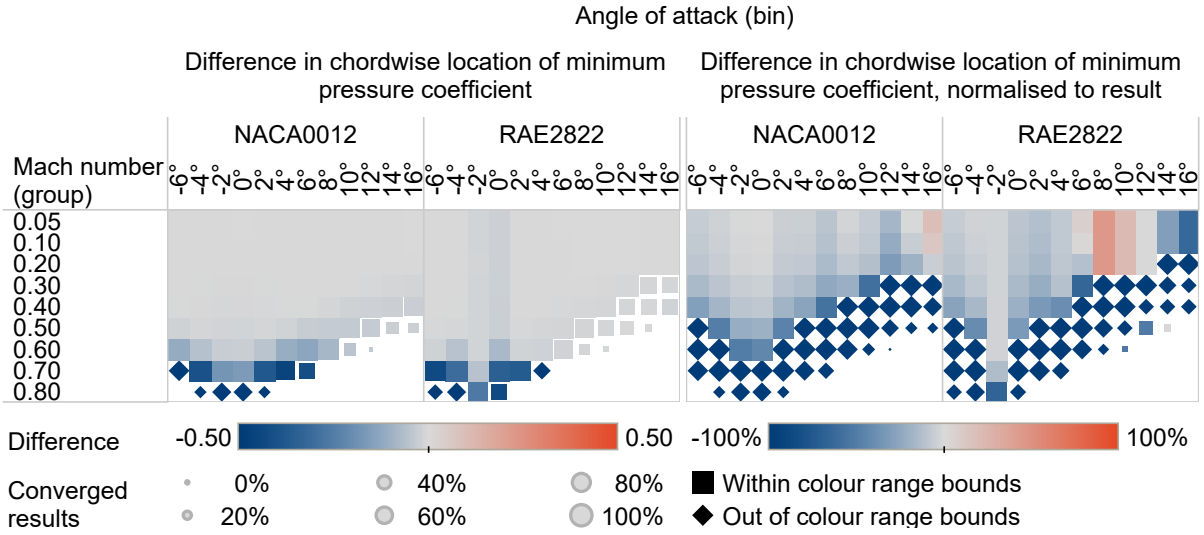
Figure F.41: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK) chordwise location of minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Without compressibility correction (XFOIL-U)



(b) With Prandtl-Glauert compressibility (XFOIL-PG)



(c) With Karman-Tsien compressibility correction (XFOIL-KT)

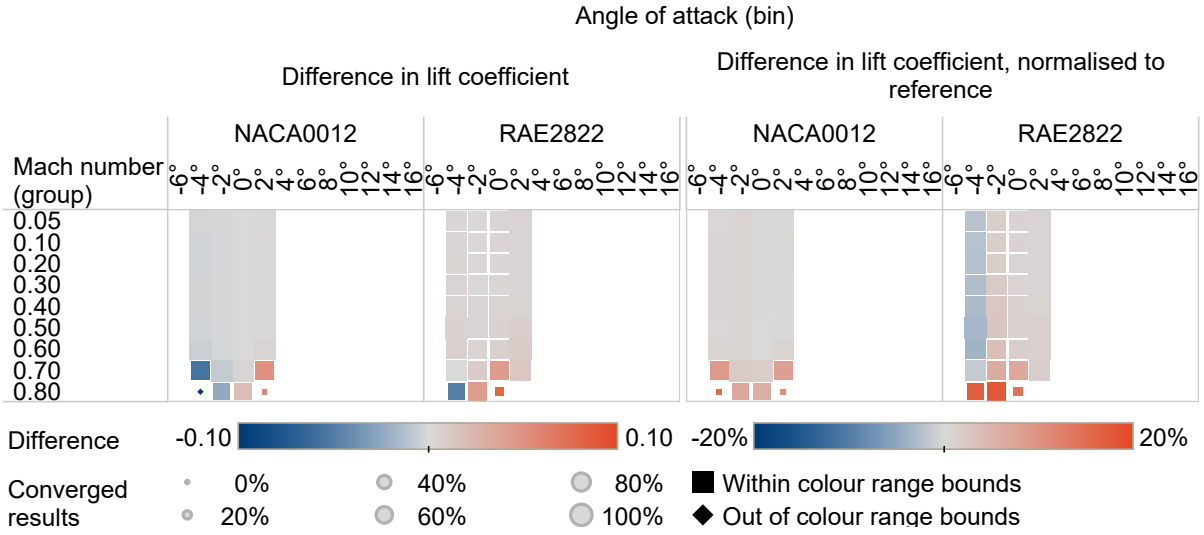
Figure F.42: Difference between corrected and uncorrected incompressible (XFOIL-U, XFOIL-PG and XFOIL-KT) and partially-conservative compressible (VGK-NC) chordwise location of minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack

F.1.4. Influence of flow model: irrotational flow assumption

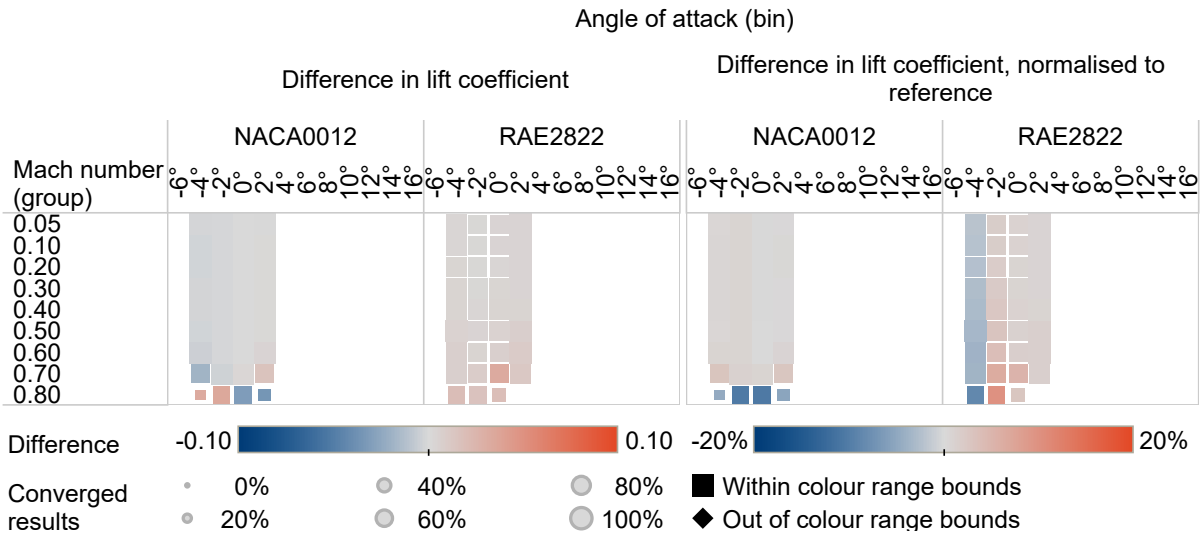
This section contains additional results showing the influence of the irrotational flow assumption on lift coefficient, pitching moment coefficient, minimum pressure coefficient and the chordwise location at which the minimum pressure coefficient is found, represented using the heat maps used in Section 6.3.3. Identical to Appendix F.1.3, the results normalised to the reference value are shown first. Figures in which the difference is normalised with respect to the 'lower order' model follow. These can be used to find a correction factor for the lower order output in order to arrive at the higher order result.

The results shown compare the results from both the partially-conservative (VGK) and non-conservative (VGK-NC) irrotational model to the rotational model (MSES).

Normalised to reference

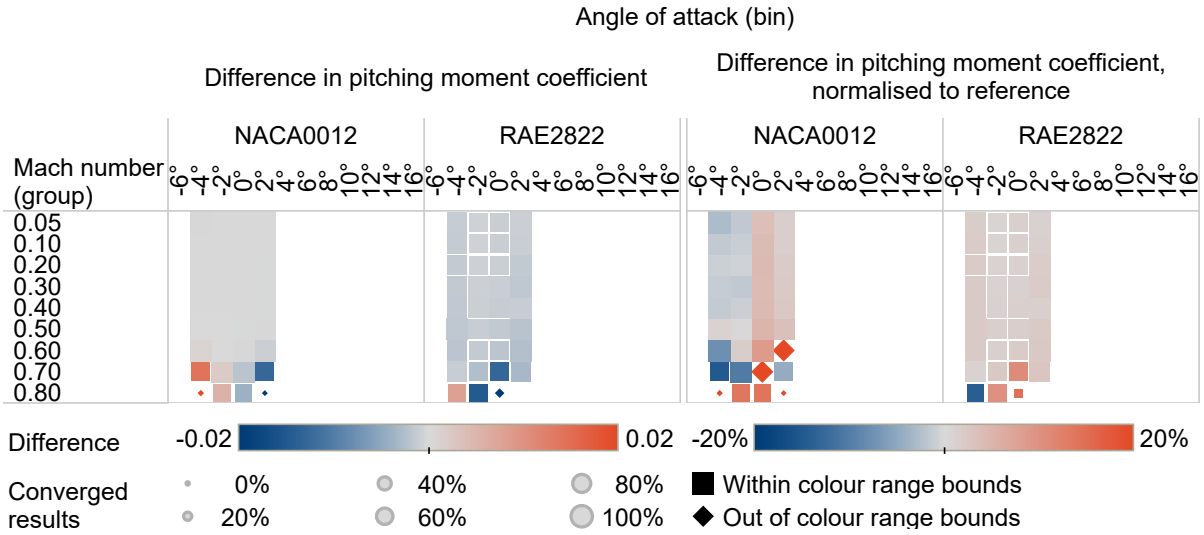


(a) Partially-conservative (VGK)

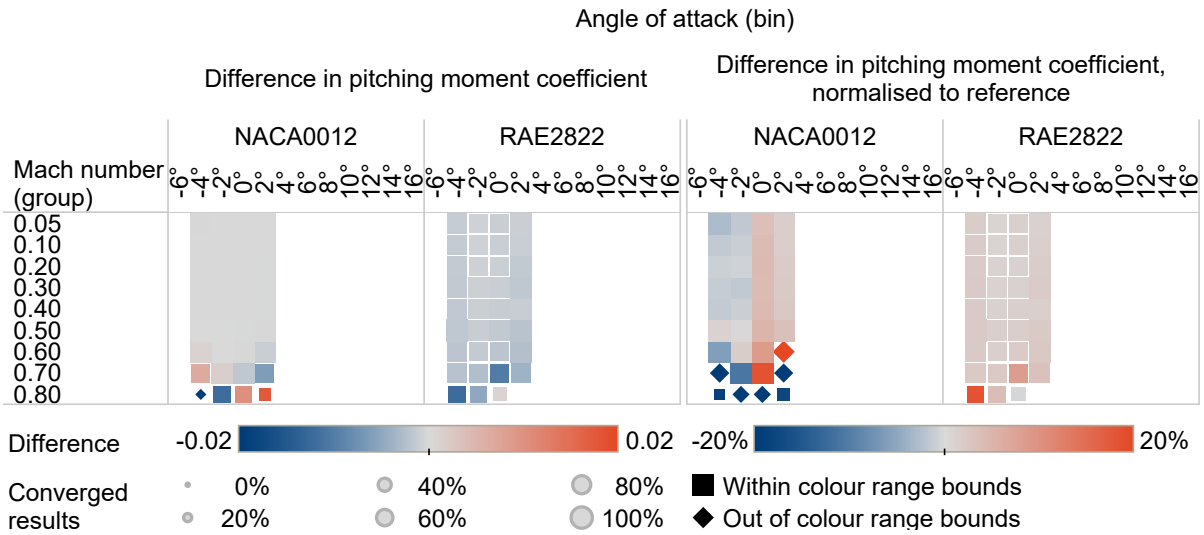


(b) Non-conservative (VGK-NC)

Figure F.43: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) lift coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

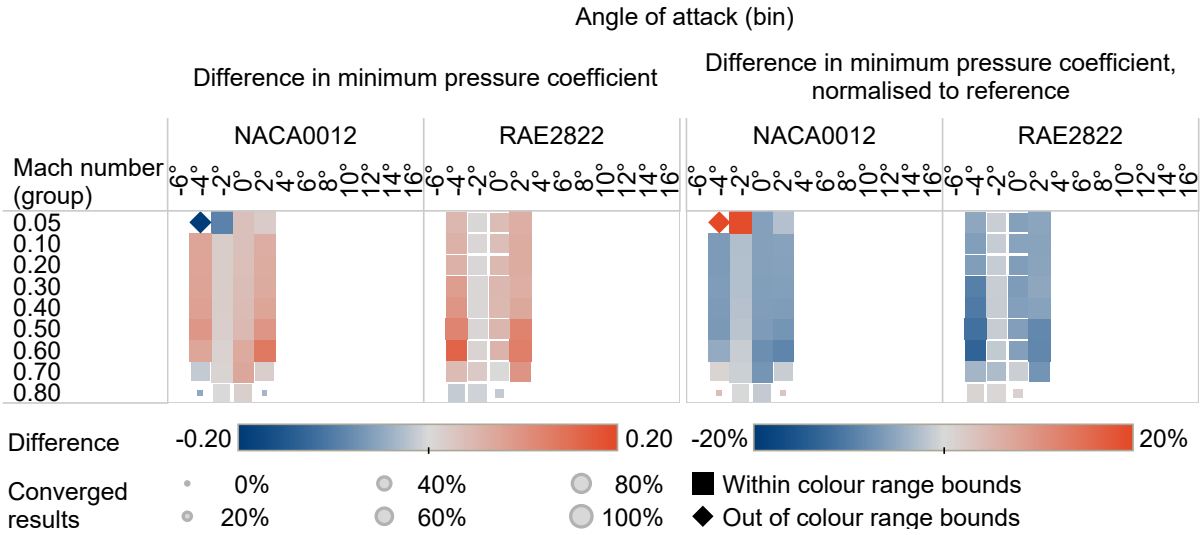


(a) Partially-conservative (VGK)

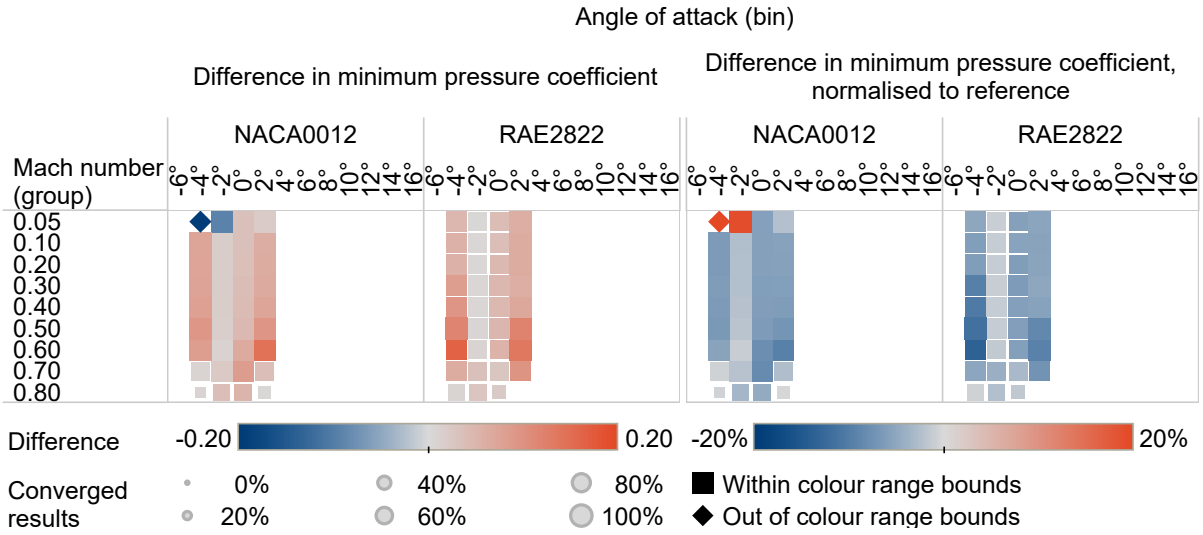


(b) Non-conservative (VGK-NC)

Figure F.44: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) pitching moment coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

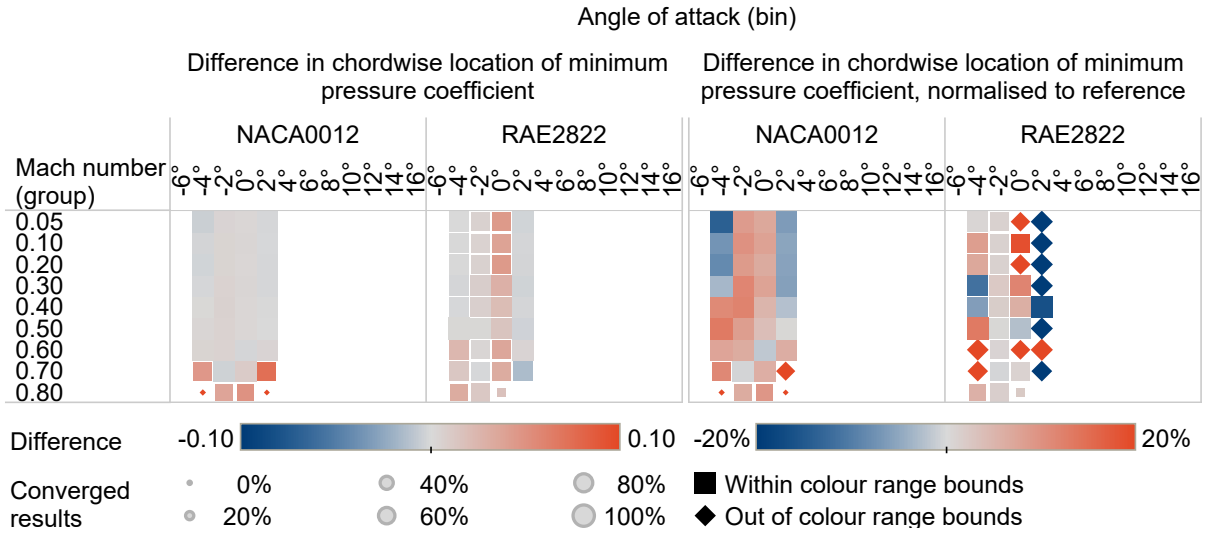


(a) Partially-conservative (VGK)

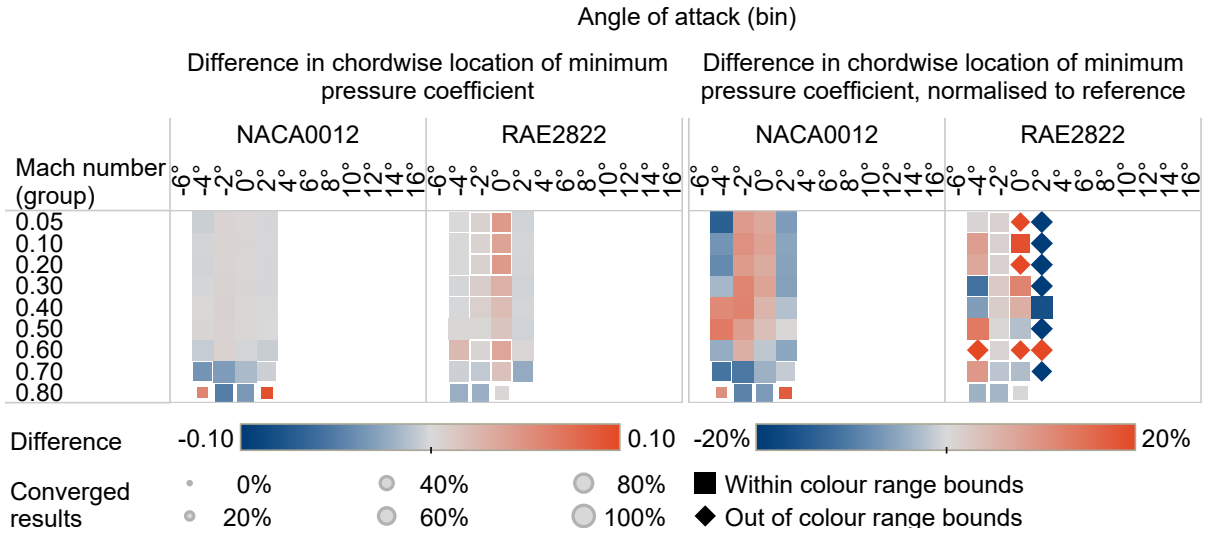


(b) Non-conservative (VGK-NC)

Figure F.45: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack



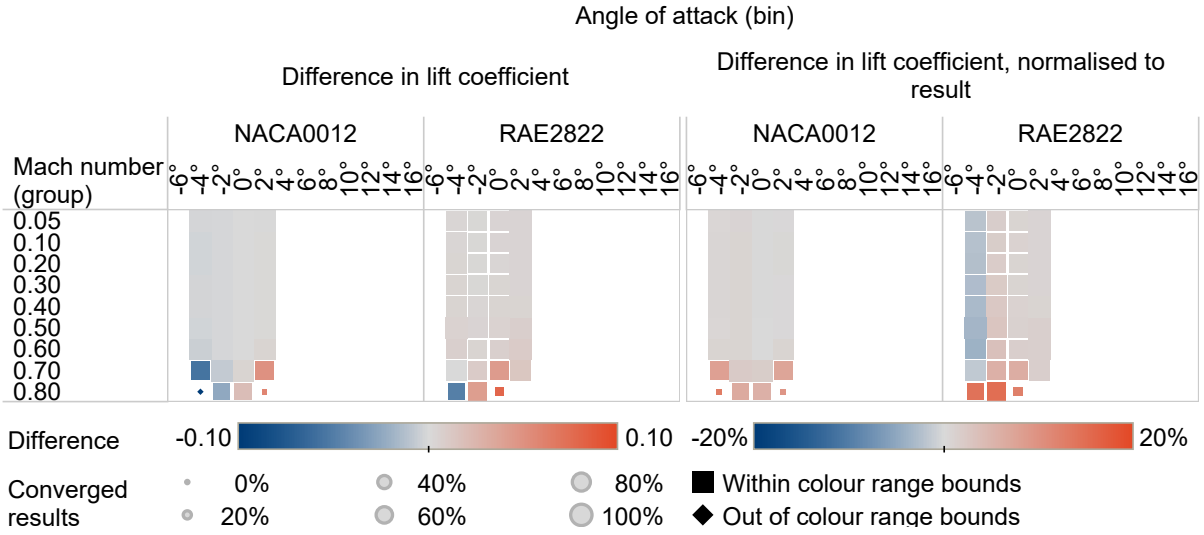
(a) Partially-conservative (VGK)



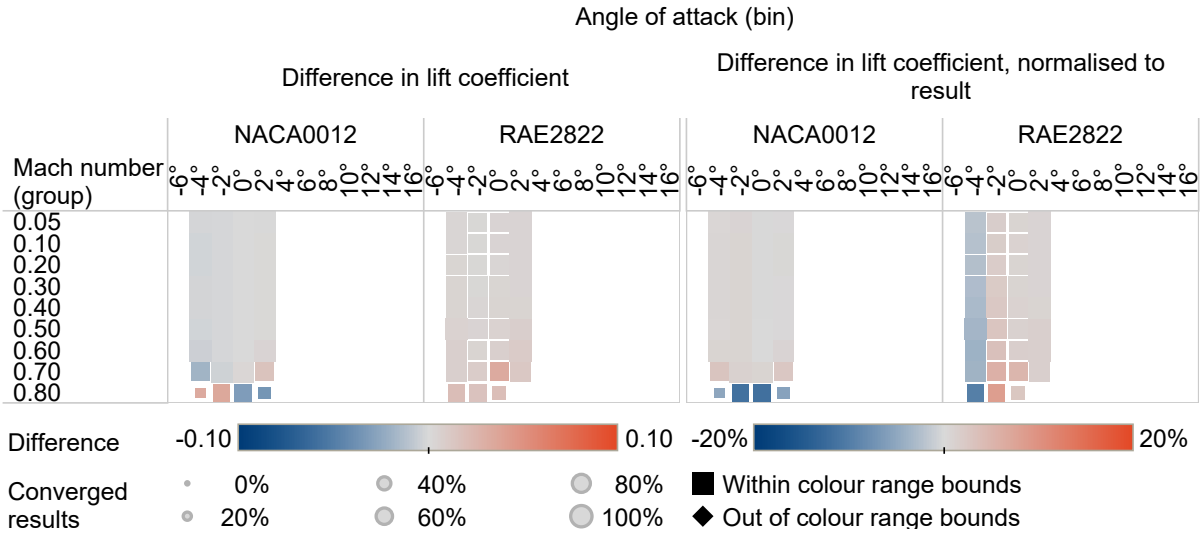
(b) Non-conservative (VGK-NC)

Figure F.46: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) chordwise location of minimum pressure coefficient (true and normalised w.r.t. reference) for different geometries, Mach numbers and (binned) angles of attack

Normalised to result

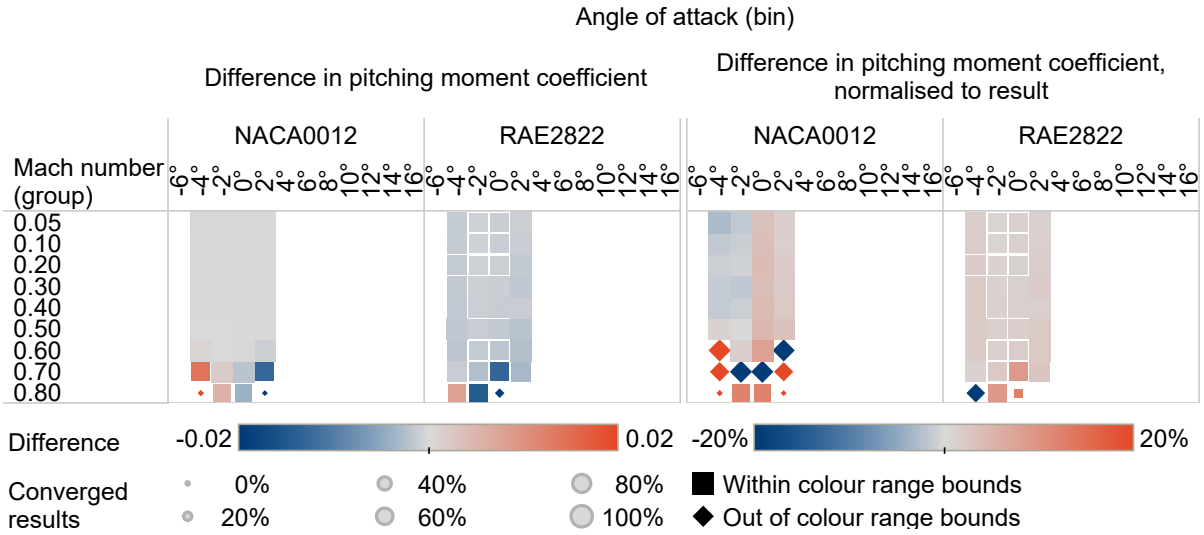


(a) Partially-conservative (VGK)

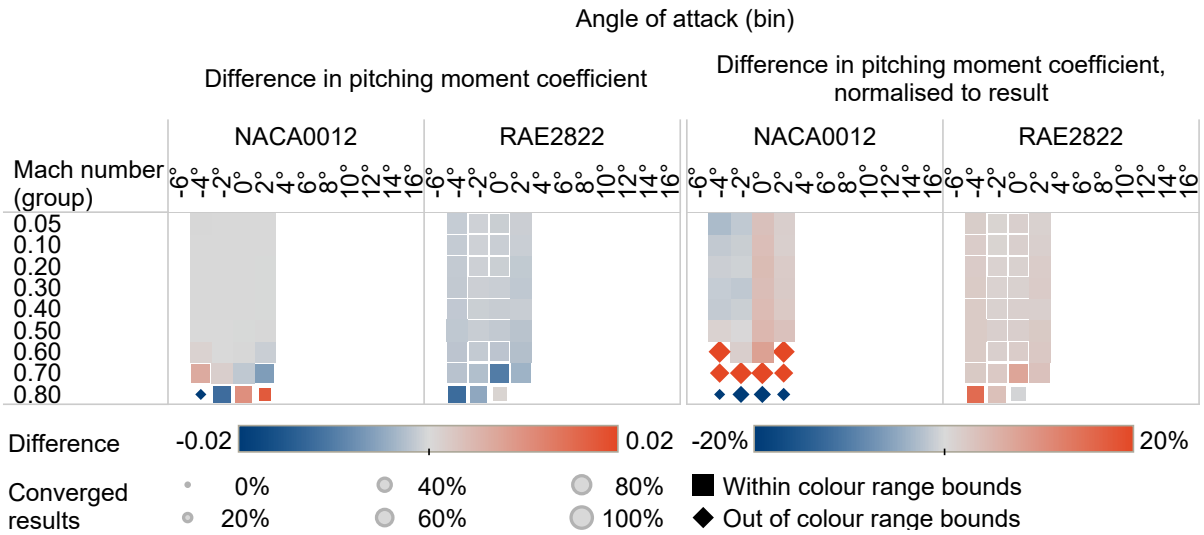


(b) Non-conservative (VGK-NC)

Figure F.47: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) lift coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack

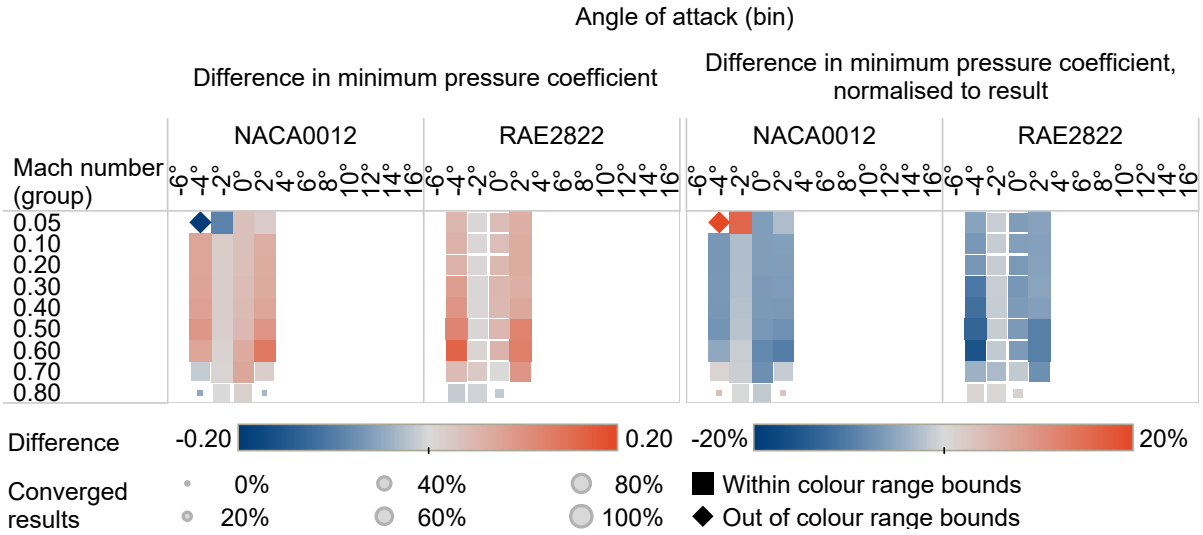


(a) Partially-conservative (VGK)

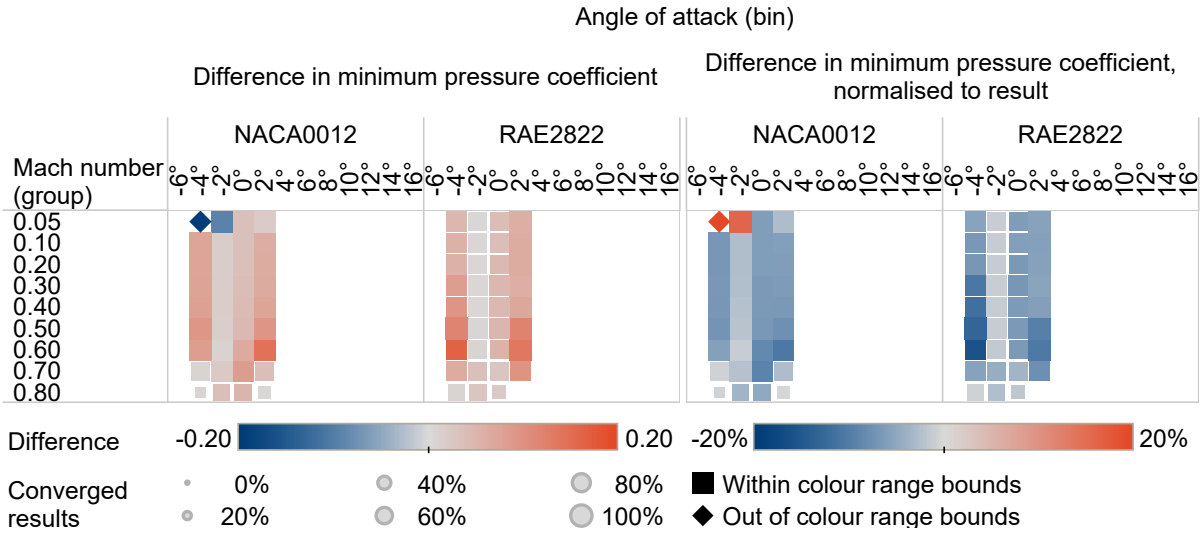


(b) Non-conservative (VGK-NC)

Figure F.48: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) pitching moment coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack

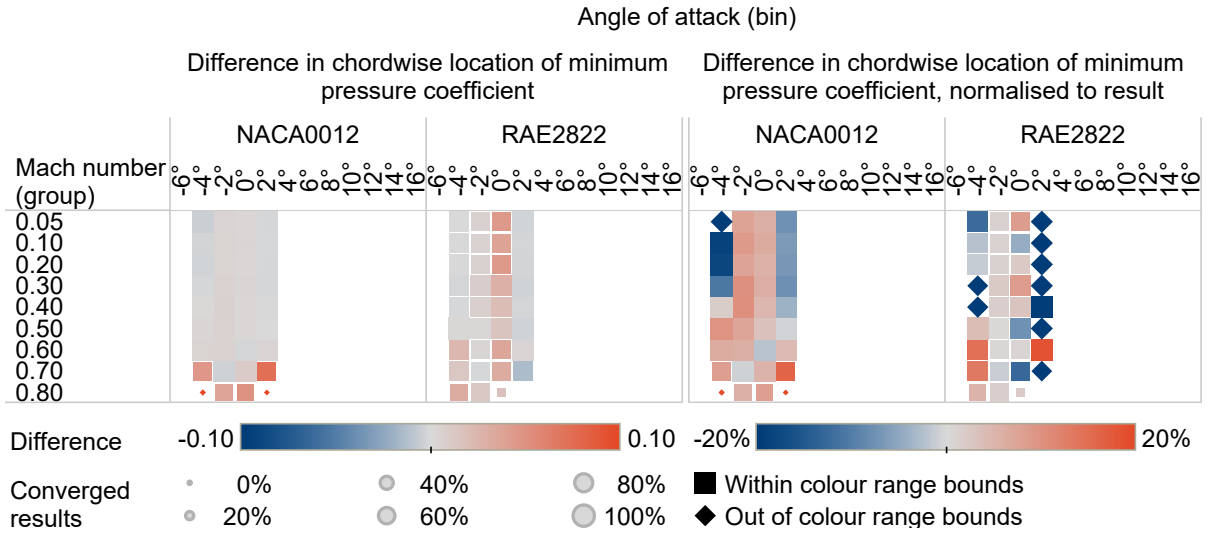


(a) Partially-conservative (VGK)

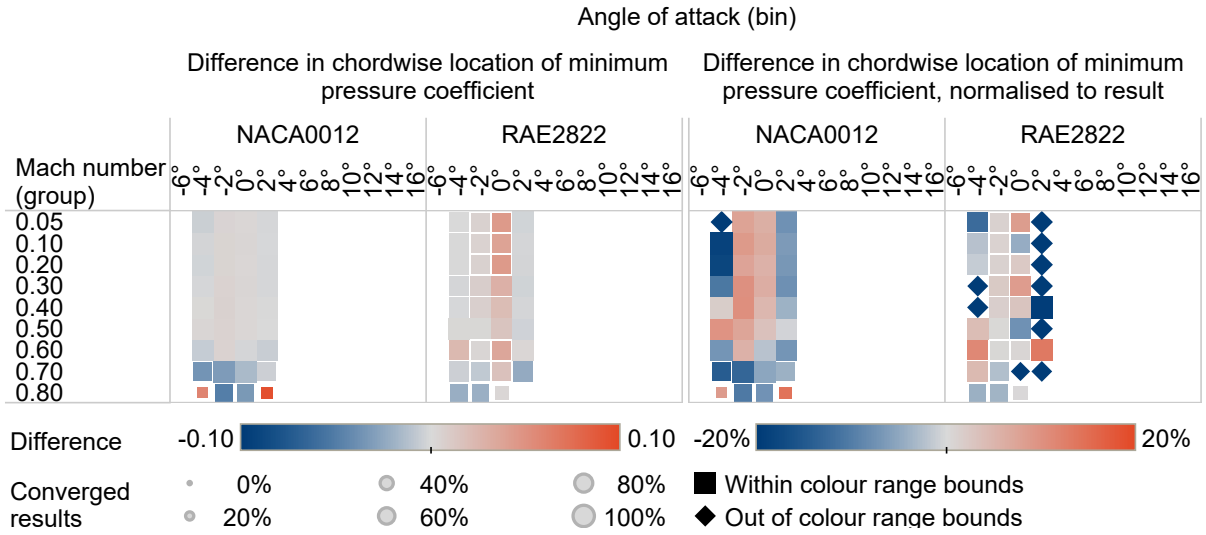


(b) Non-conservative (VGK-NC)

Figure F.49: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack



(a) Partially-conservative (VGK)



(b) Non-conservative (VGK-NC)

Figure F.50: Difference between partially- and non-conservative irrotational (VGK and VGK-NC) and rotational (MSES) chordwise location of minimum pressure coefficient (true and normalised w.r.t. result) for different geometries, Mach numbers and (binned) angles of attack

F.2. Uncertainty propagation

This section shows the full set of results regarding uncertainty propagation, presented in Chapter 7. Although most figures included here have only briefly been discussed (and not shown) in Chapter 6, a number of figures is repeated here to simplify comparisons. The figures are first shown as true and normalised difference with respect to the reference (i.e., the higher-fidelity flow model of the pair), before being presented as true and normalised difference with respect to the result (i.e., the lower-fidelity flow model of the pair). These last results can be used as a rudimentary correction factor.

F.2.1. Normalised to reference

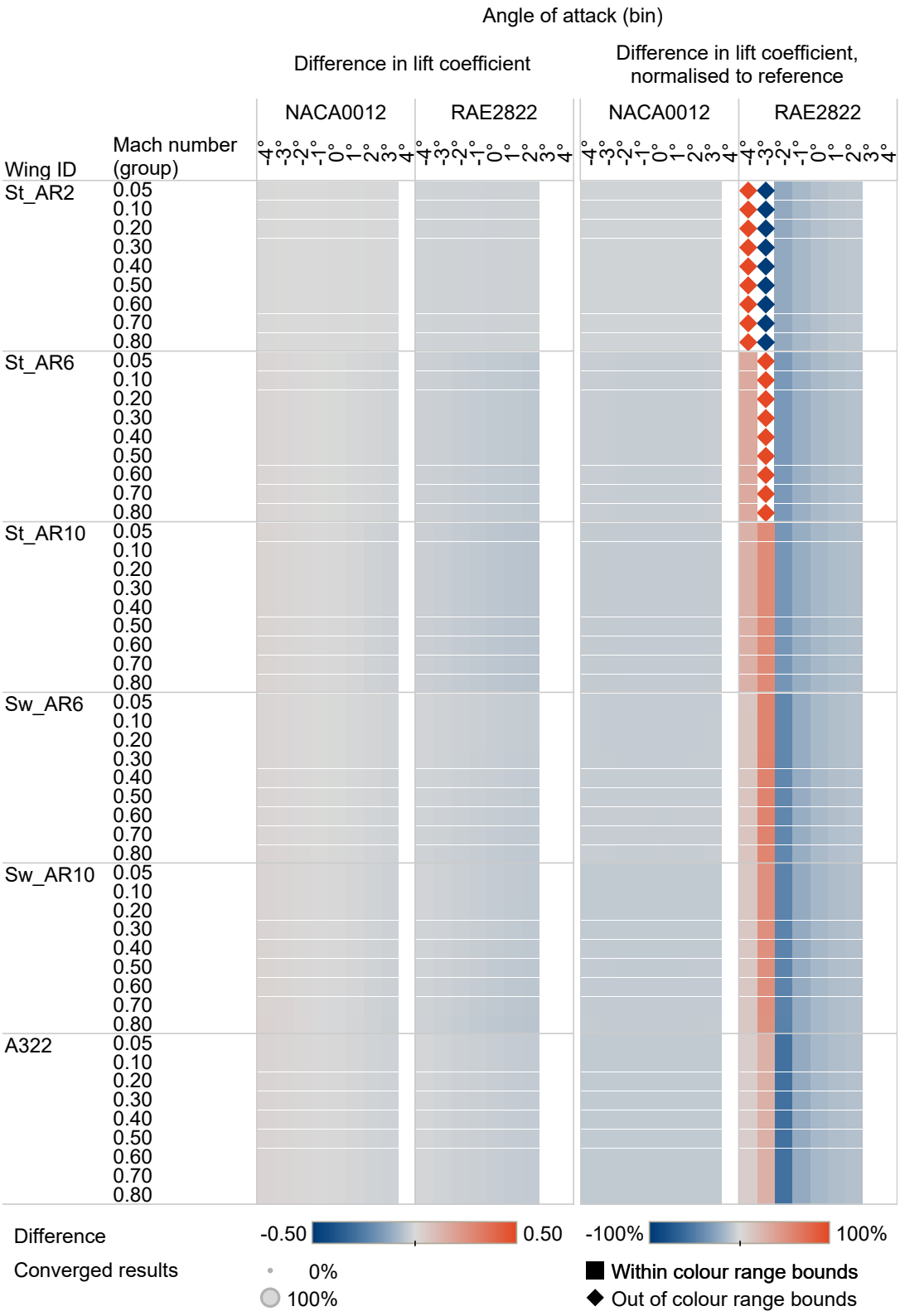


Figure F.51: Difference in lift coefficient (true and normalised w.r.t. reference) between thin airfoil theory (AVL) and incompressible flow (AVL + XFOIL-U) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

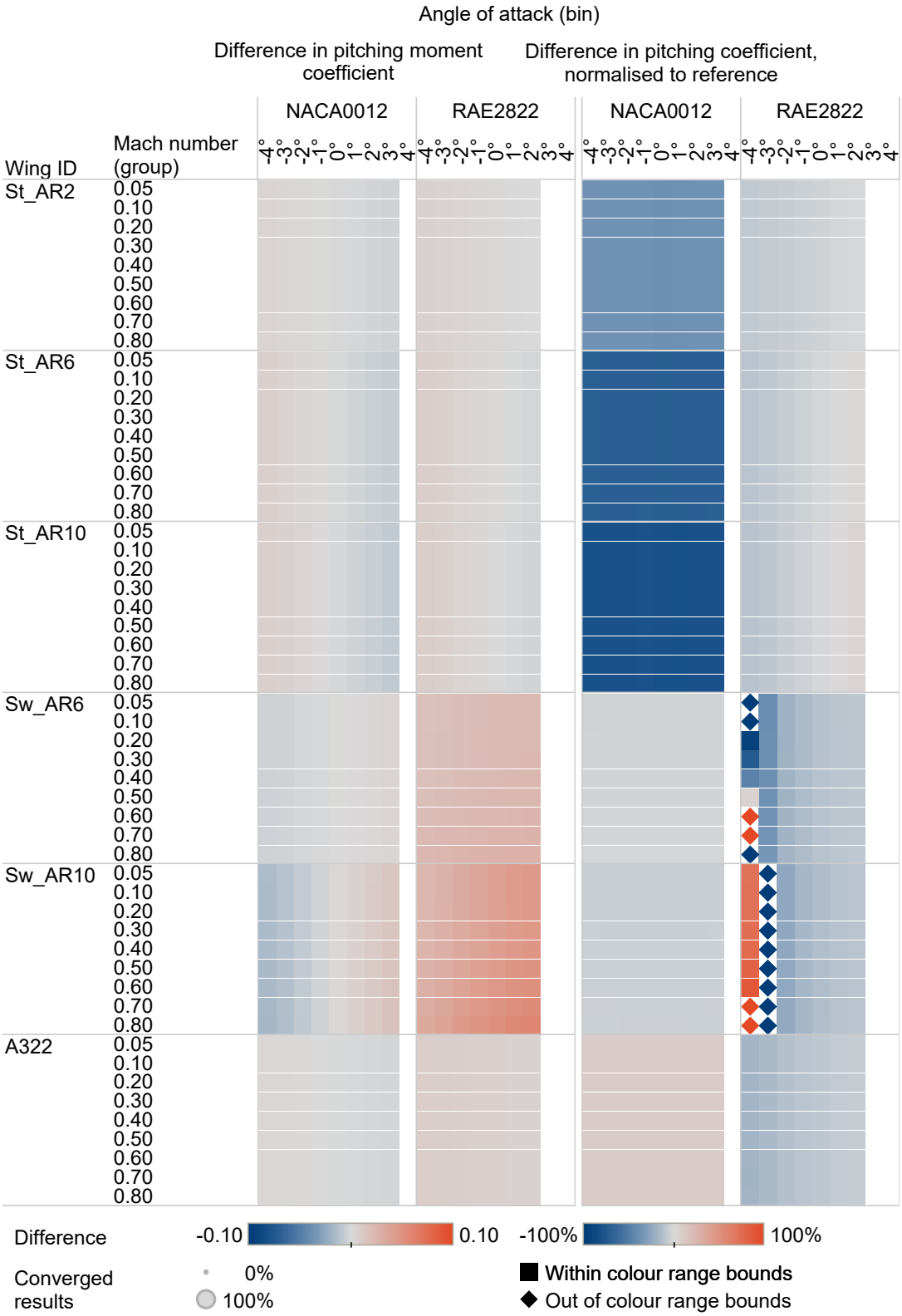


Figure F.52: Difference in pitching moment coefficient (true and normalised w.r.t. reference) between thin airfoil theory (AVL) and incompressible flow (AVL + XFOIL-U) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

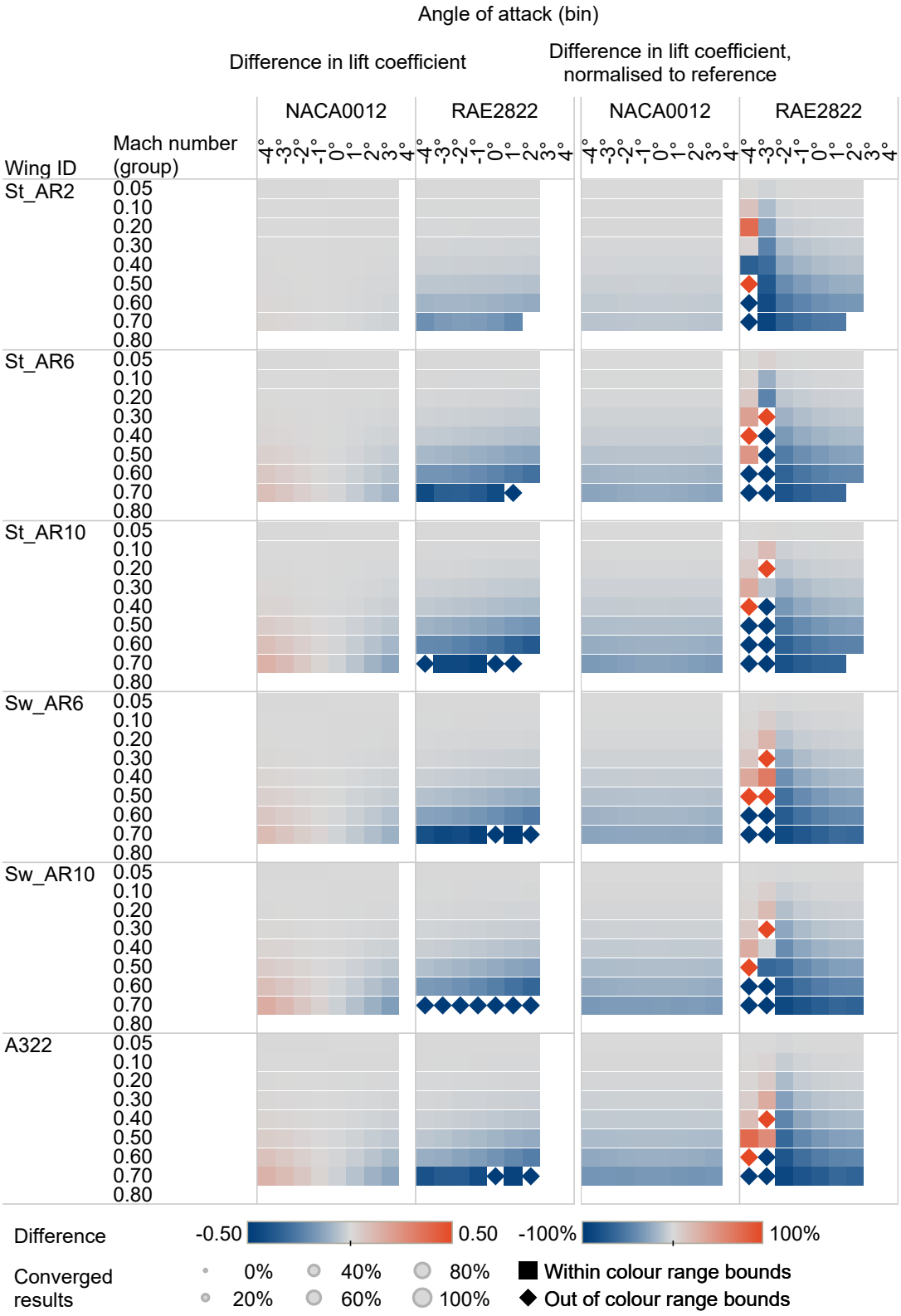


Figure F.53: Difference between incompressible (XFOIL-U + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

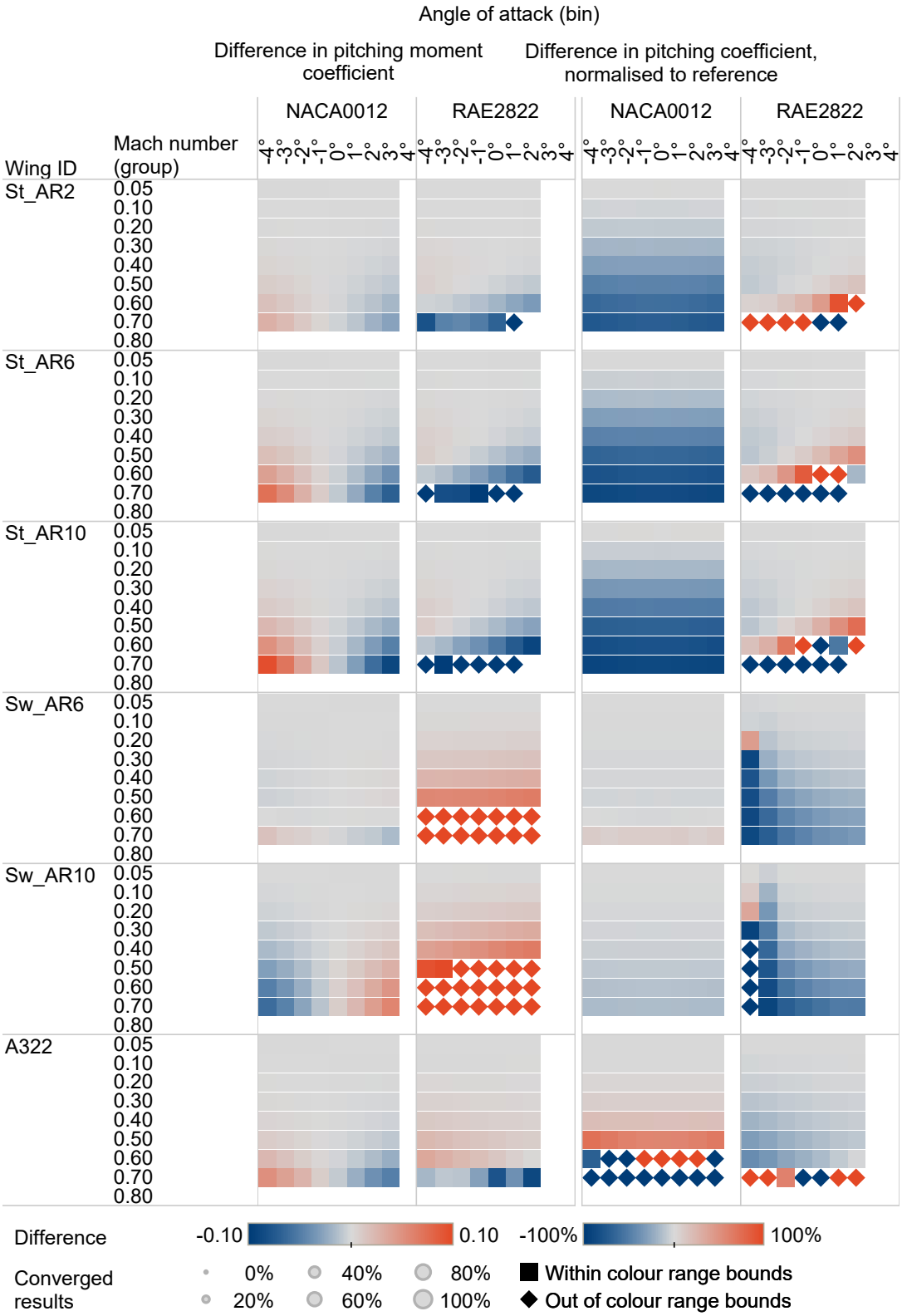


Figure F.54: Difference between incompressible (XFOIL-U + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

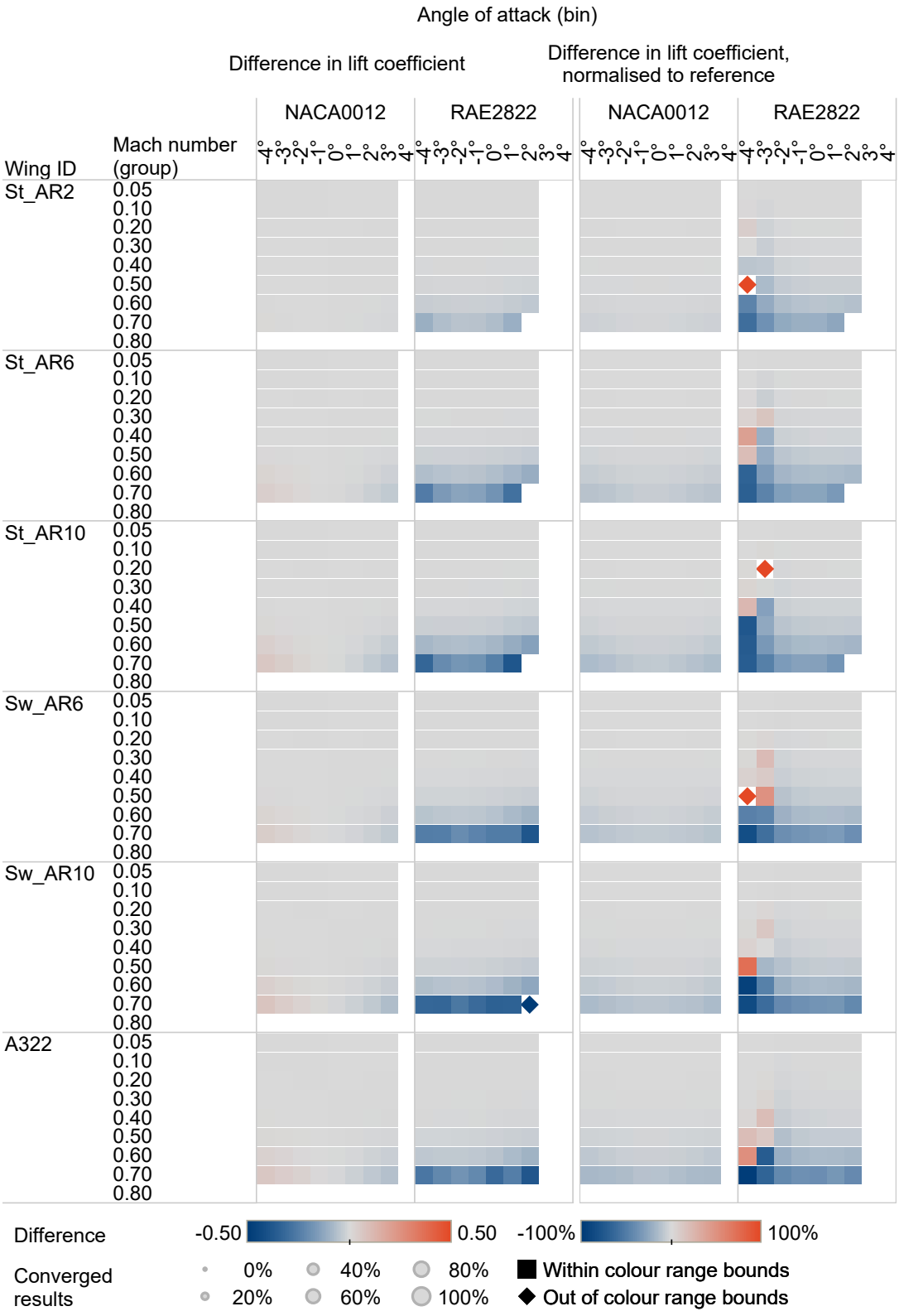


Figure F.55: Difference between Prandtl-Glauert corrected incompressible (XFOIL-PG + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

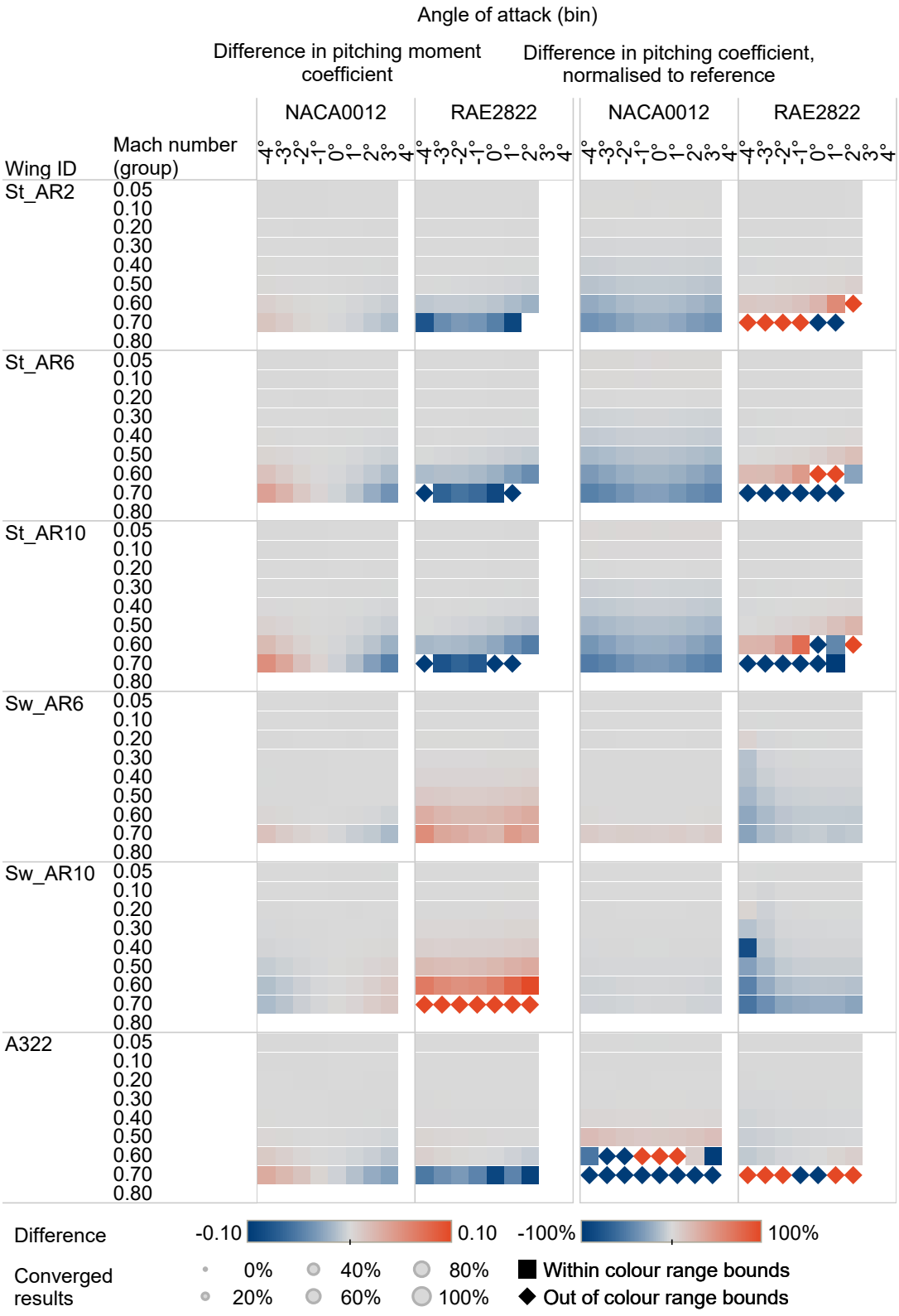


Figure F.56: Difference between Prandtl-Glauert corrected incompressible (XFOIL-PG + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

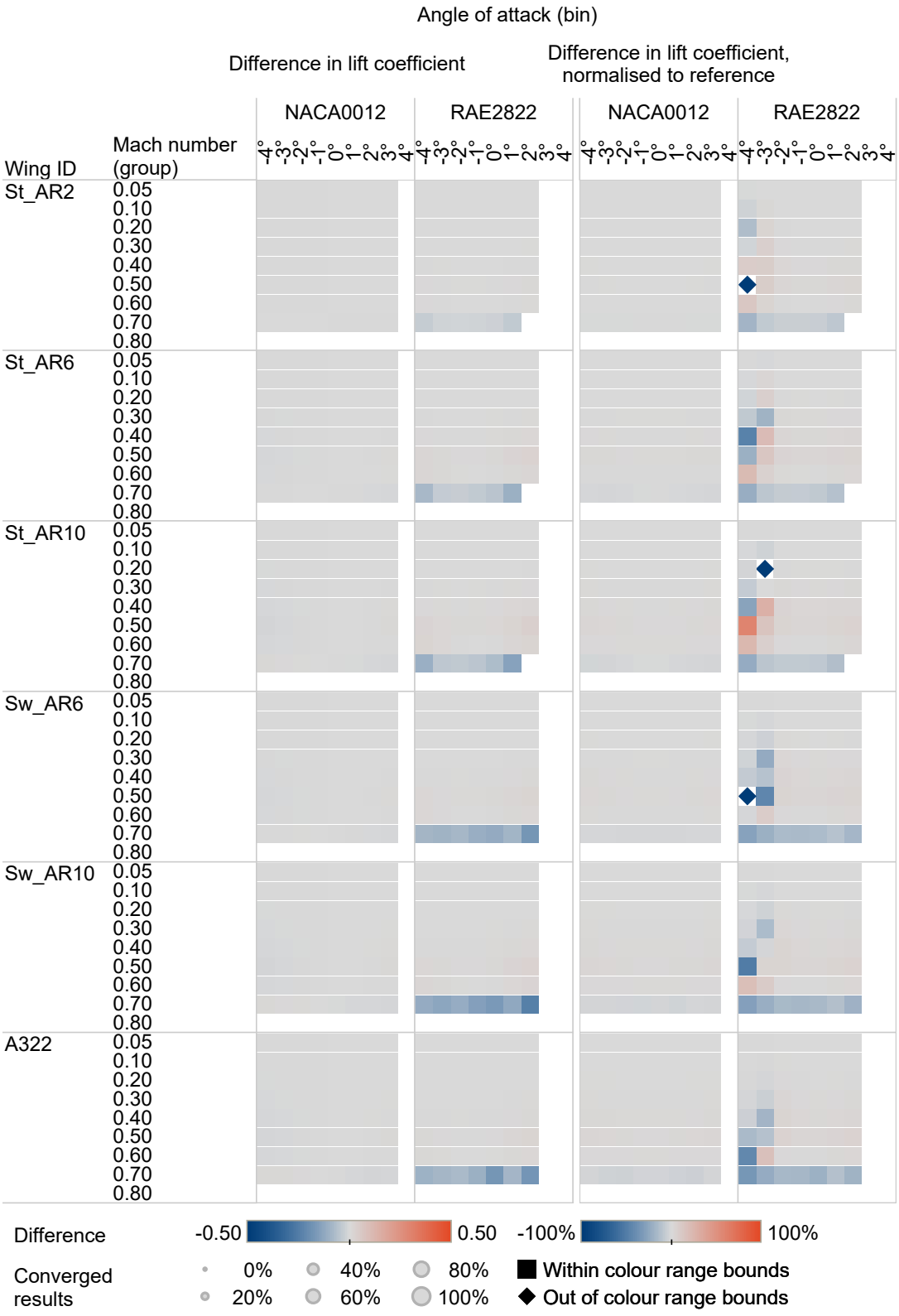


Figure F.57: Difference between Karman-Tsien corrected incompressible (XFOIL-KT + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

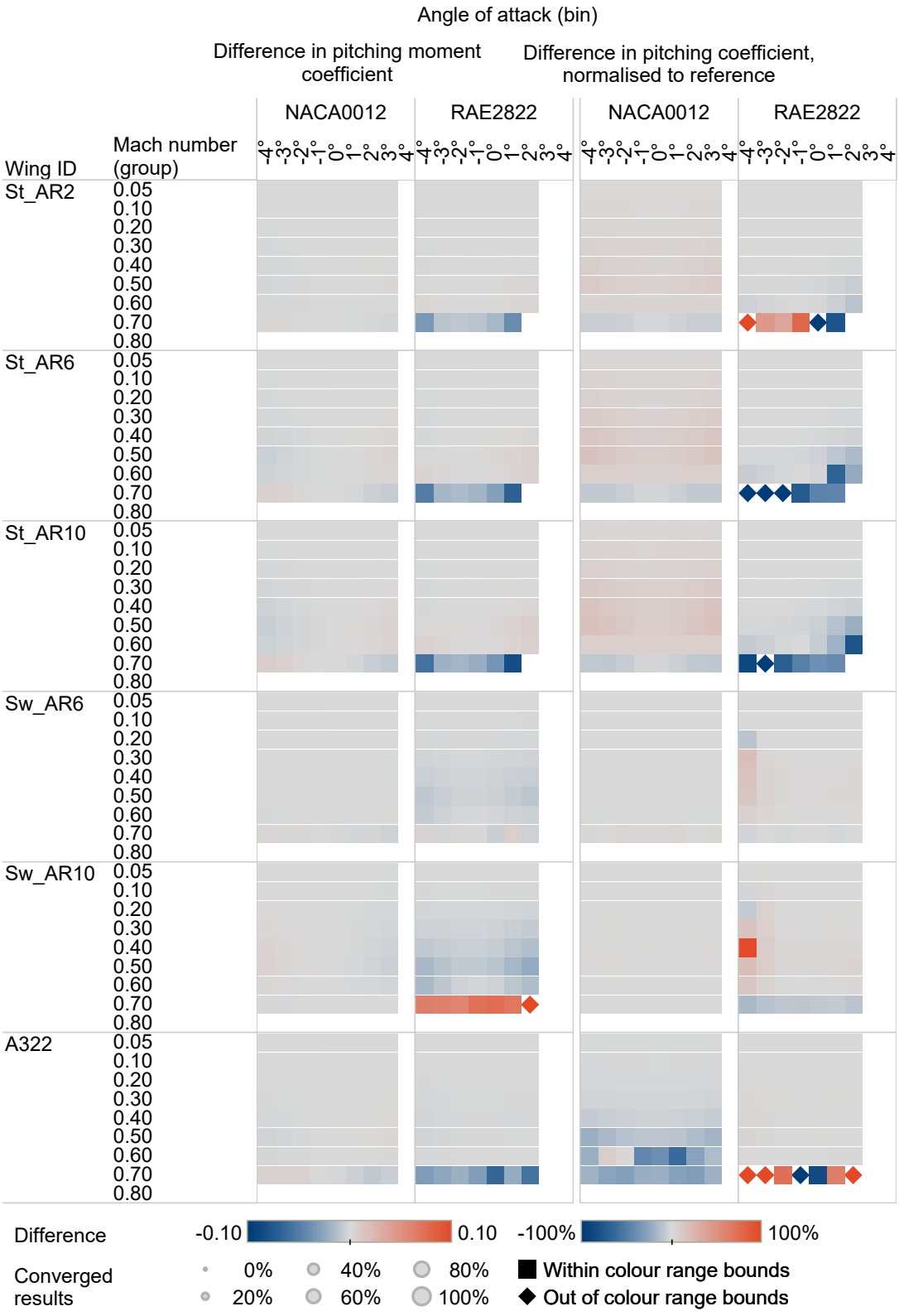


Figure F.58: Difference between Karman-Tsien corrected incompressible (XFOIL-KT + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

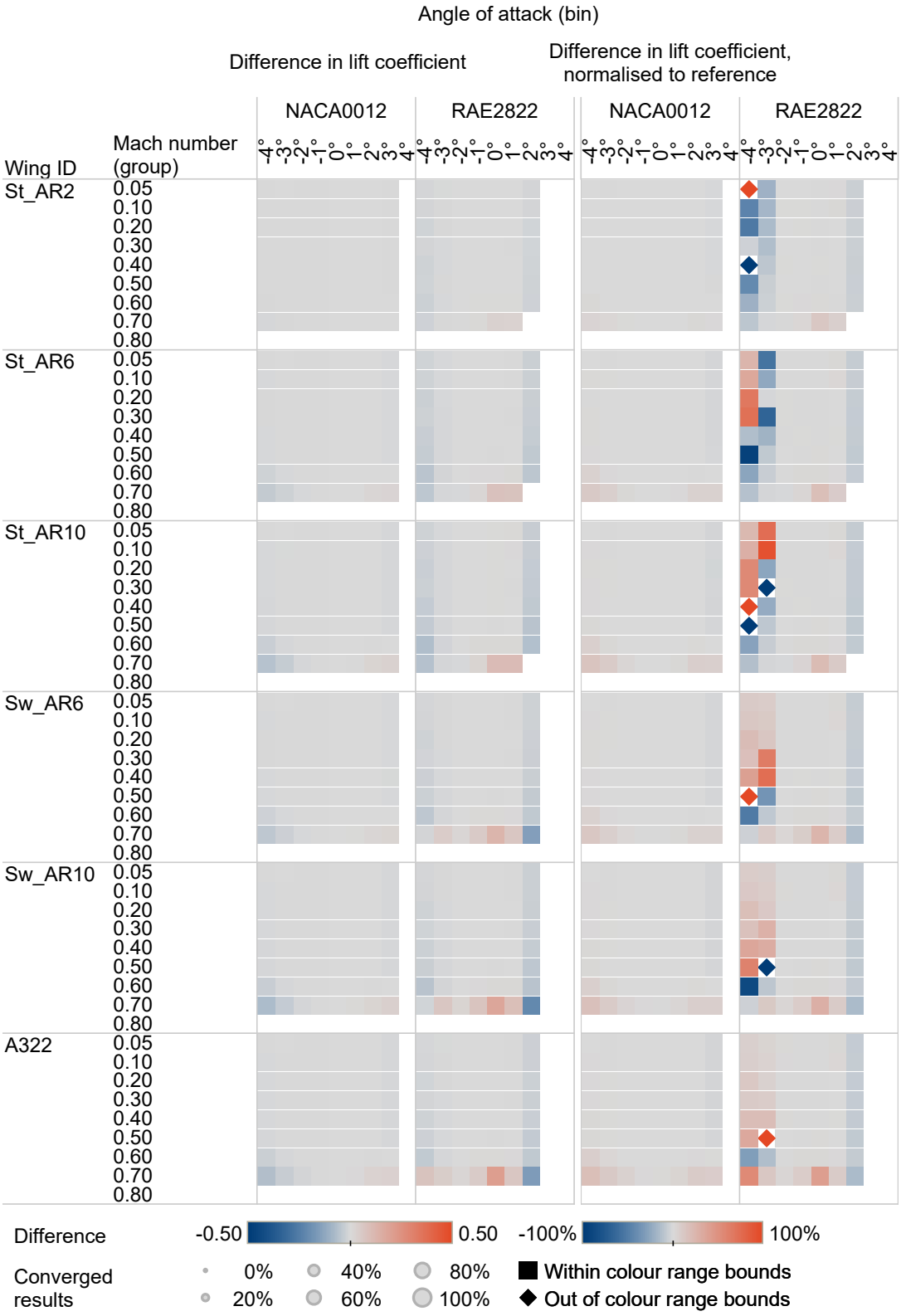


Figure F.59: Difference between irrotational (VGK + AVL) and rotational (MSES + AVL) lift coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

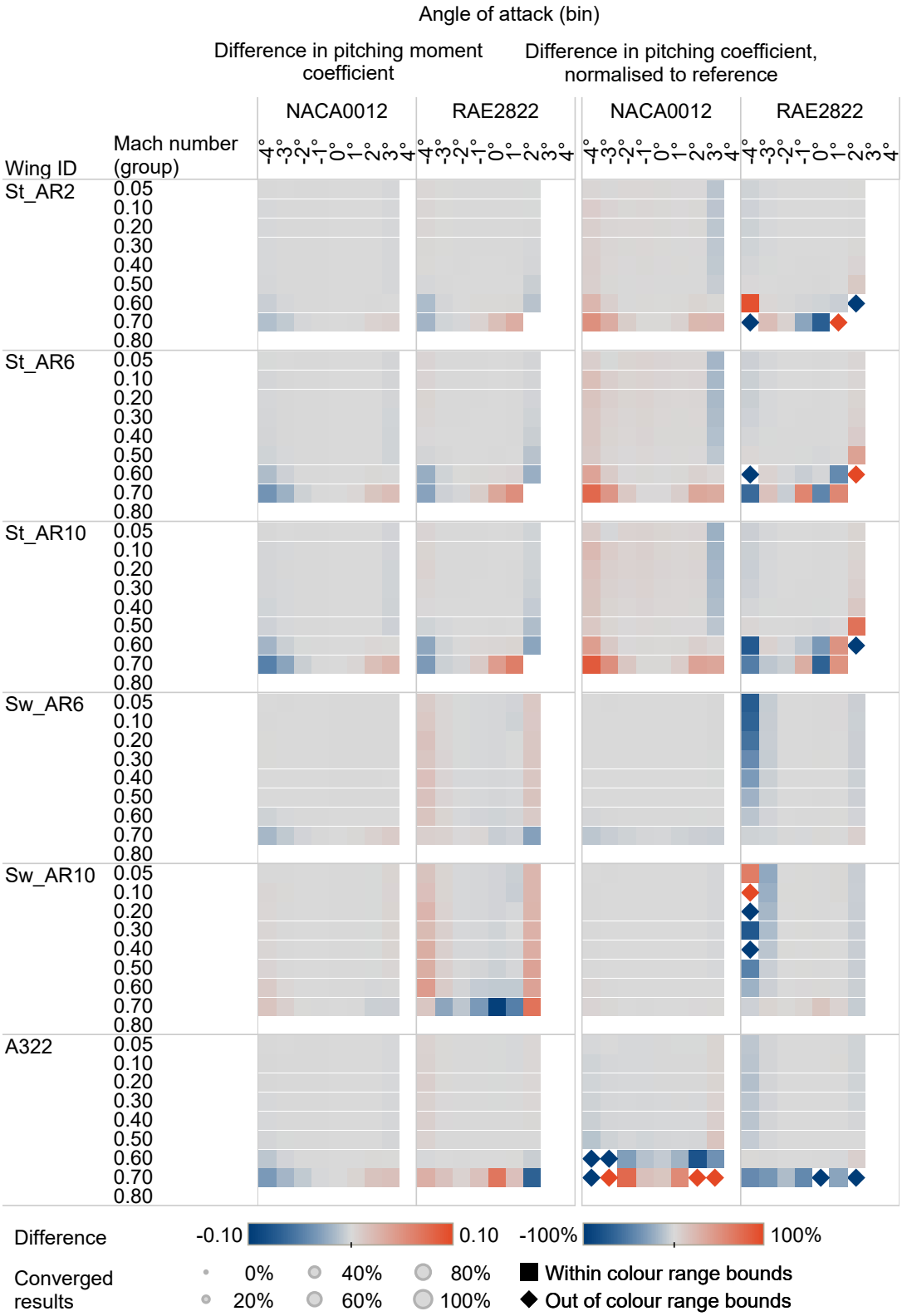


Figure F.60: Difference between irrotational (VGK + AVL) and rotational (MSES + AVL) pitching moment coefficient (true and normalised w.r.t. reference) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

F.2.2. Normalised to result

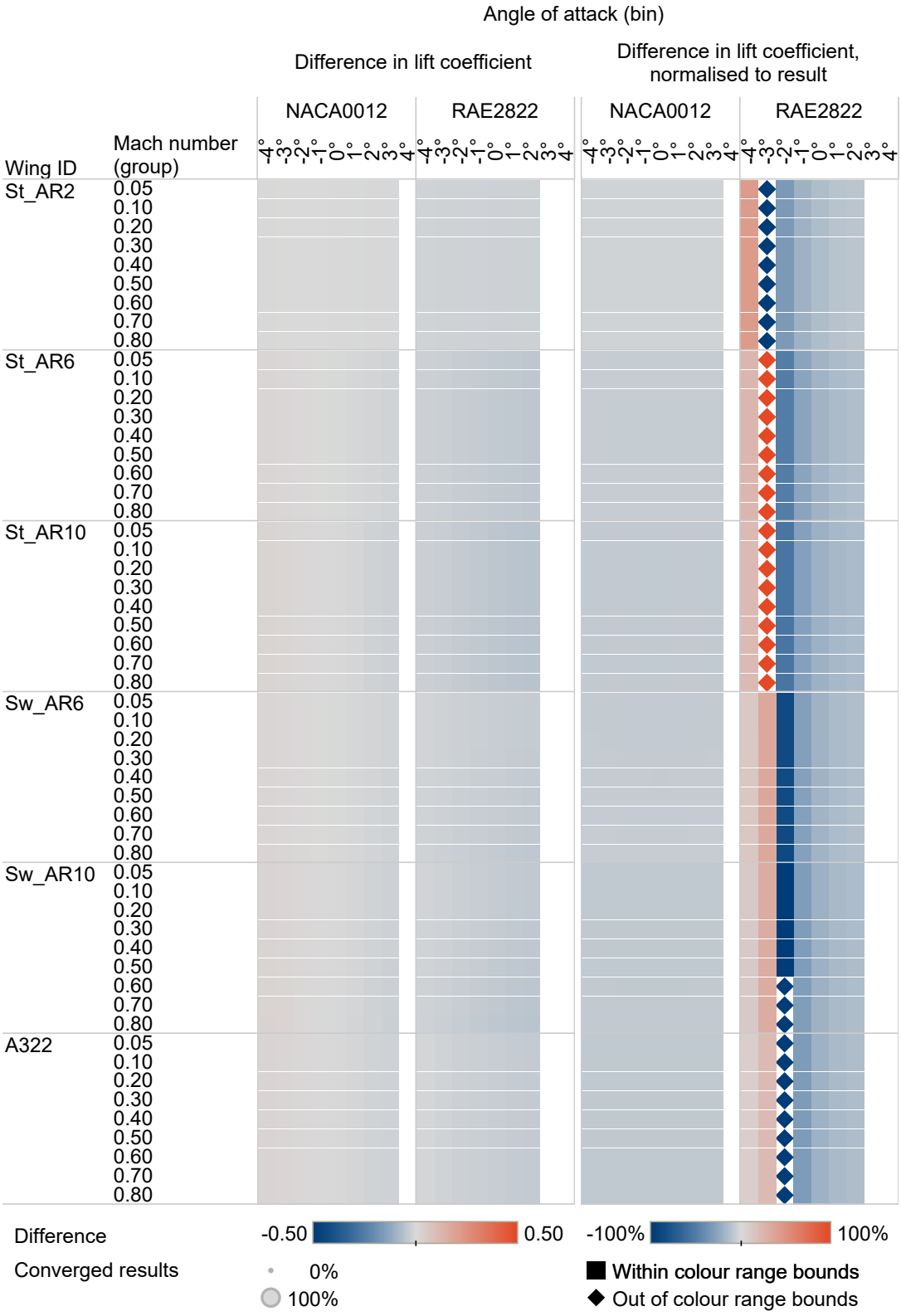


Figure F.61: Difference in lift coefficient (true and normalised w.r.t. result) between thin airfoil theory (AVL) and incompressible flow (AVL + XFOIL-U) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

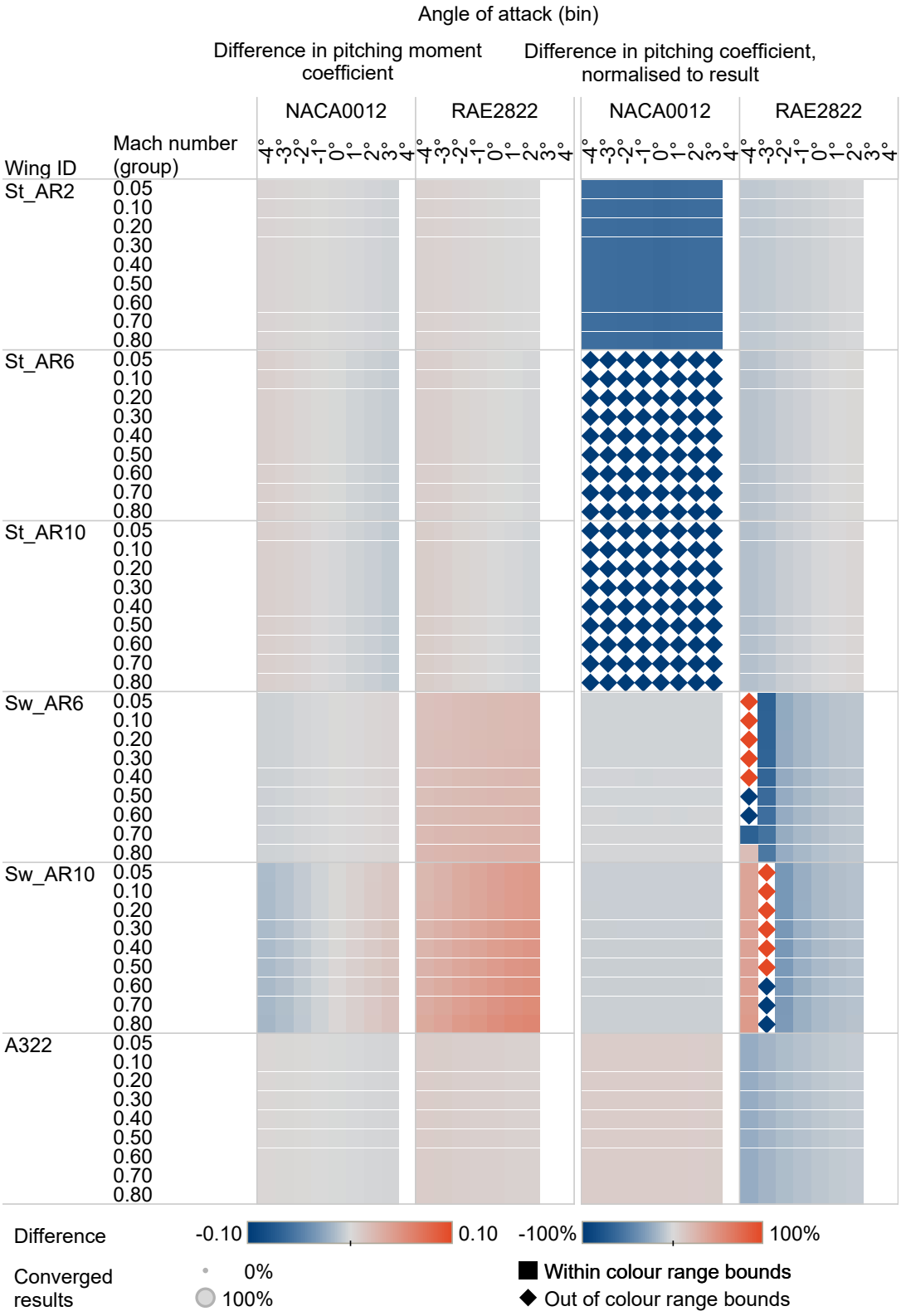


Figure F.62: Difference in pitching moment coefficient (true and normalised w.r.t. result) between thin airfoil theory (AVL) and incompressible flow (AVL + XFOIL-U) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

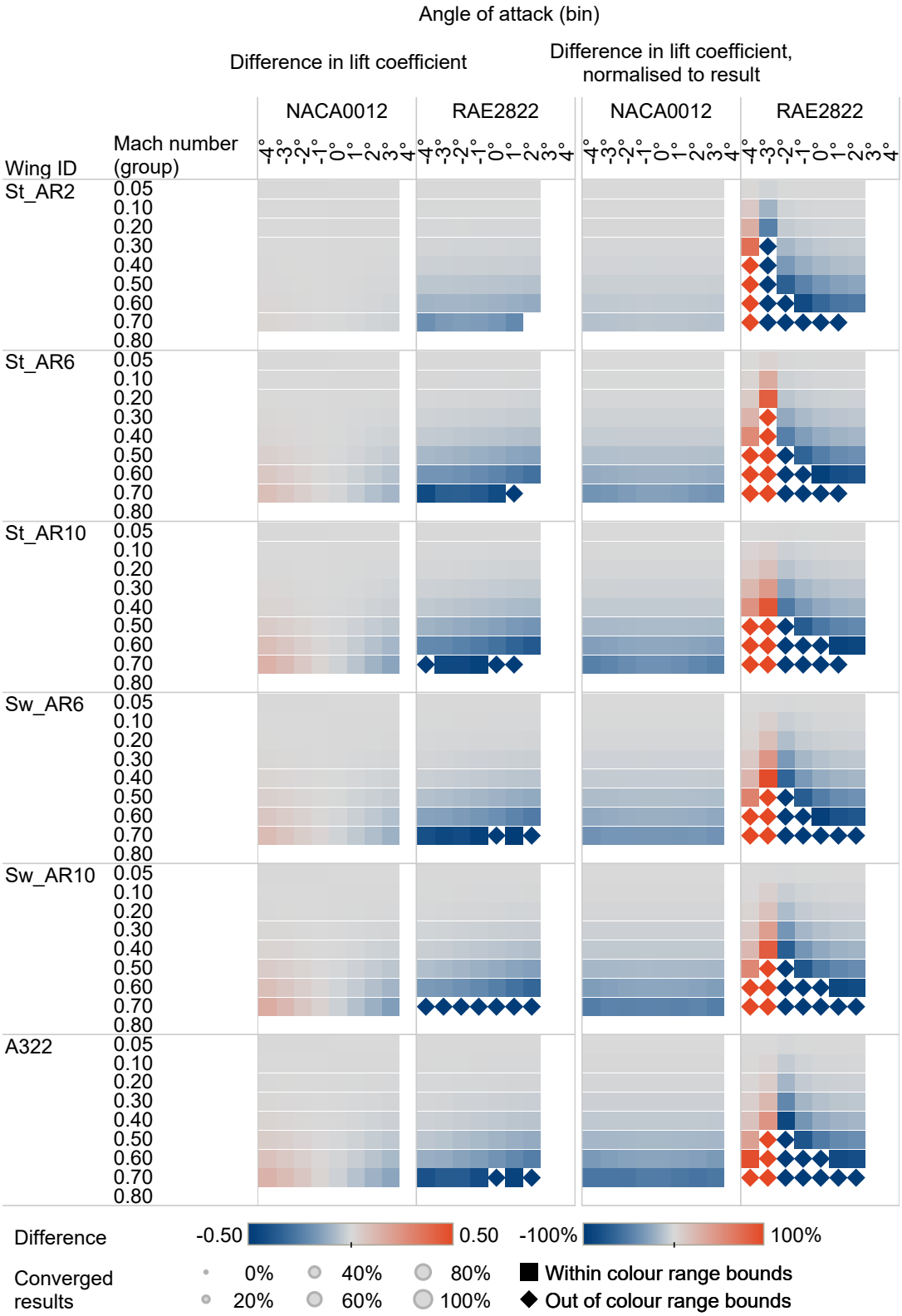


Figure F.63: Difference between incompressible (XFOIL-U + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

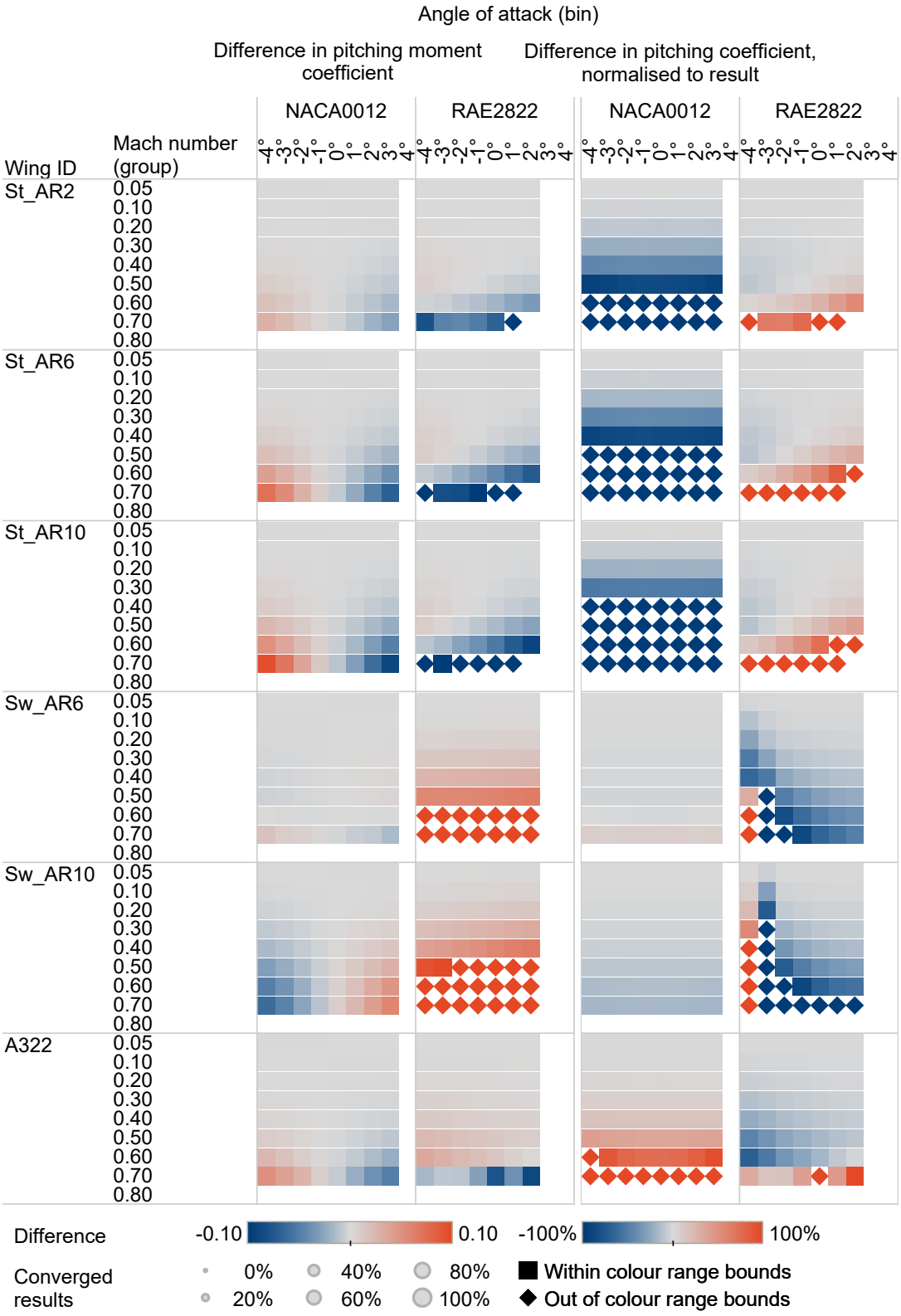


Figure F.64: Difference between incompressible (XFOIL-U + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

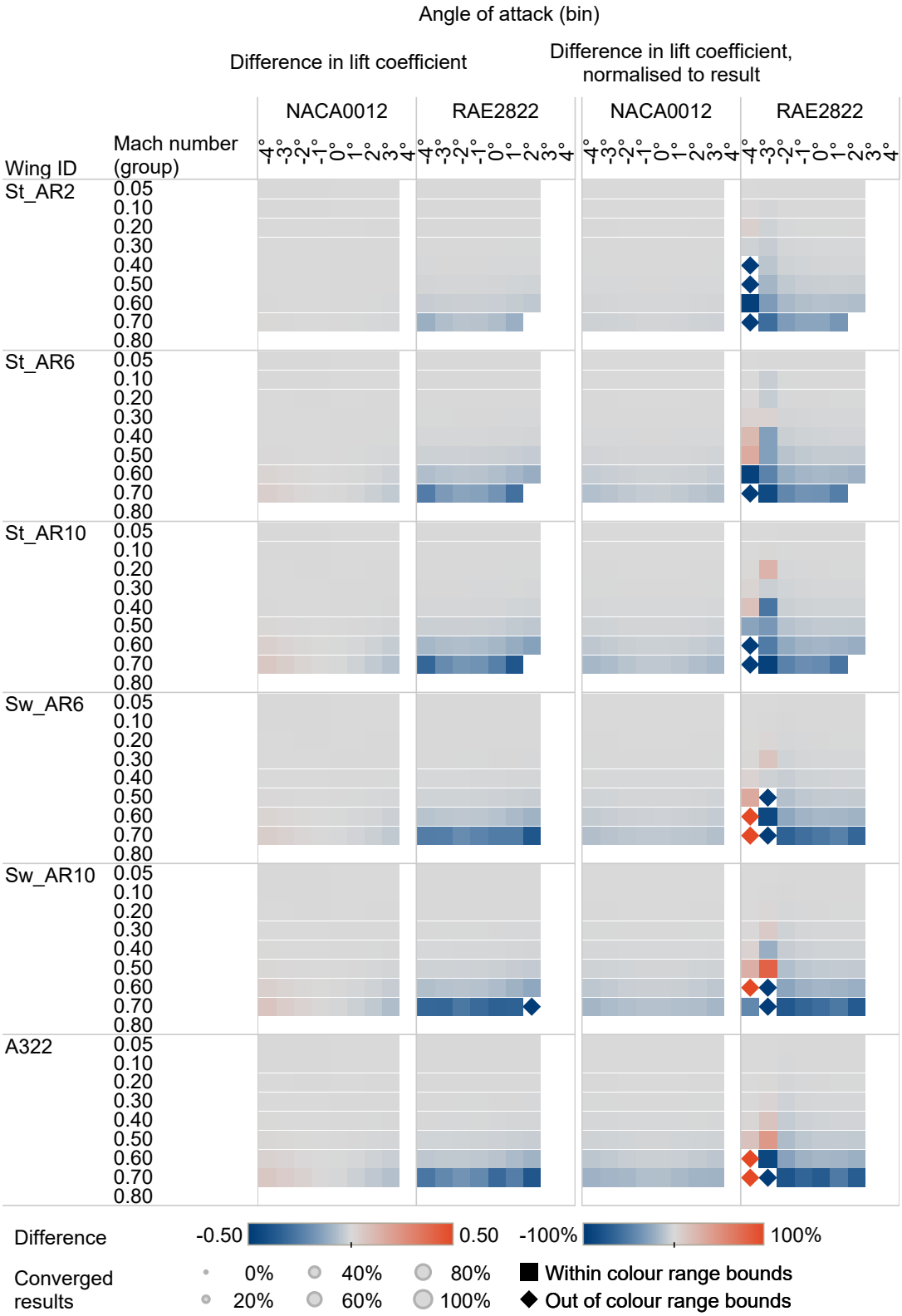


Figure F.65: Difference between Prandtl-Glauert corrected incompressible (XFOIL-PG + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

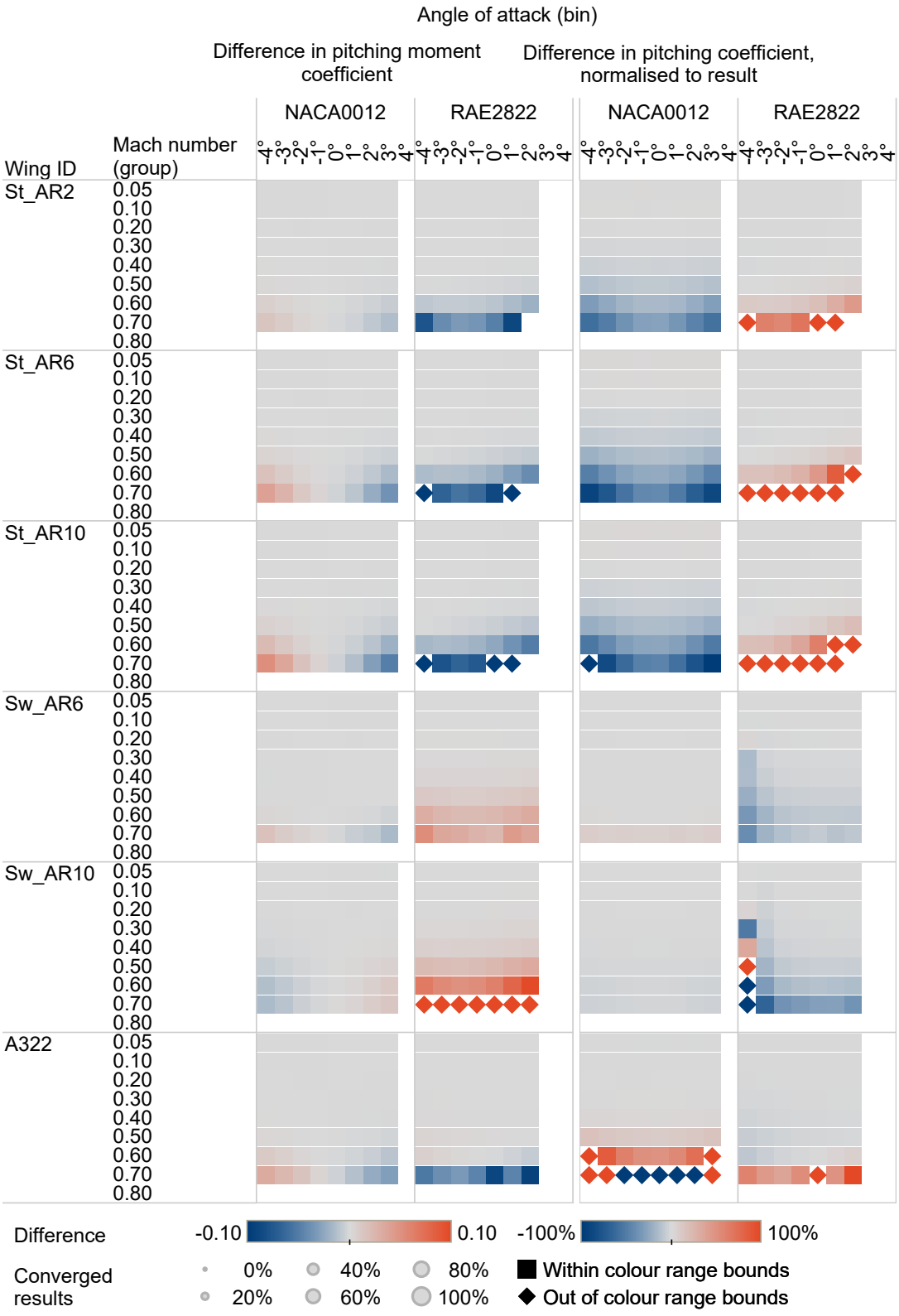


Figure F.66: Difference between Prandtl-Glauert corrected incompressible (XFOIL-PG + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

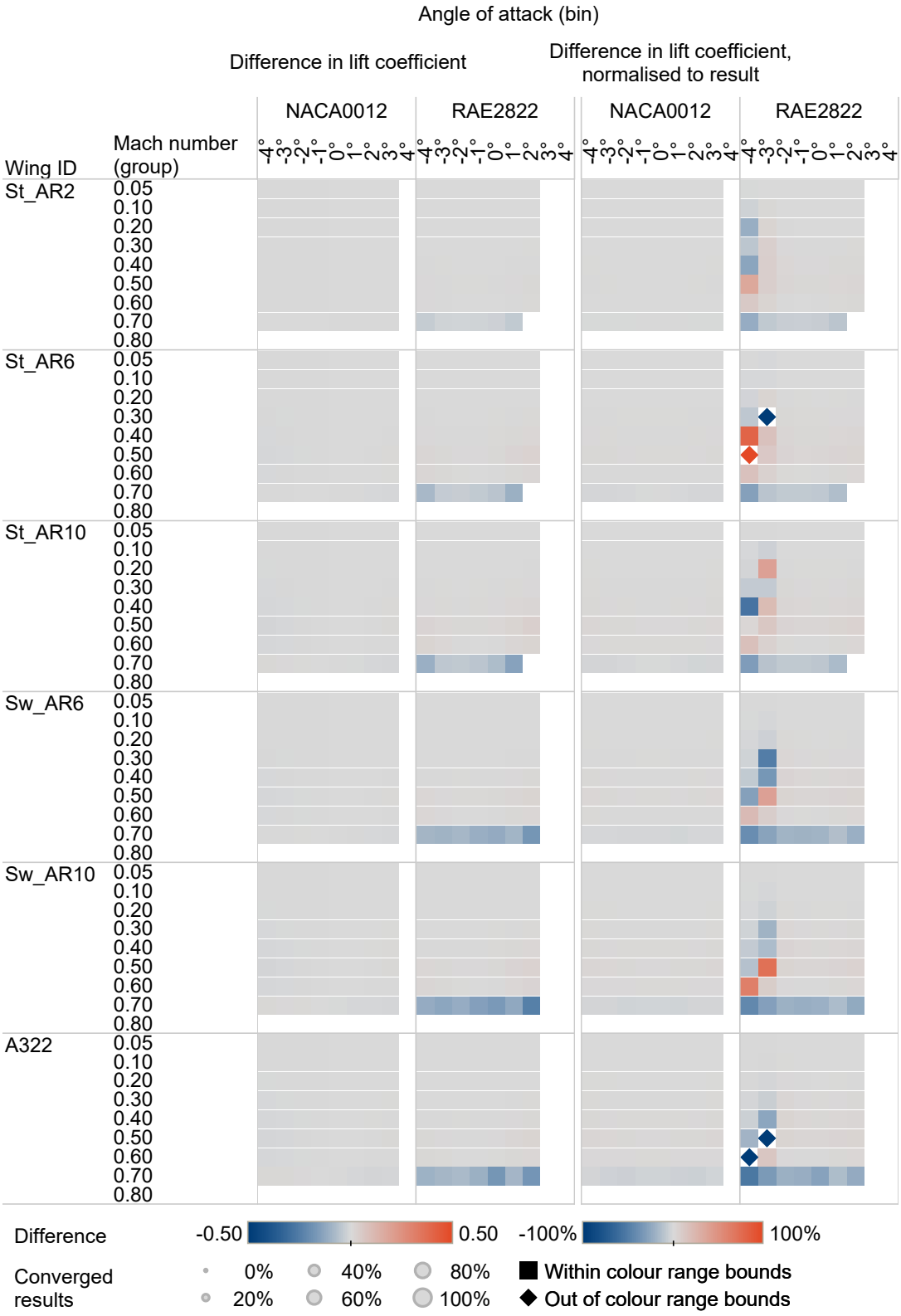


Figure F.67: Difference between Karman-Tsien corrected incompressible (XFOIL-KT + AVL) and compressible (VGK + AVL) lift coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

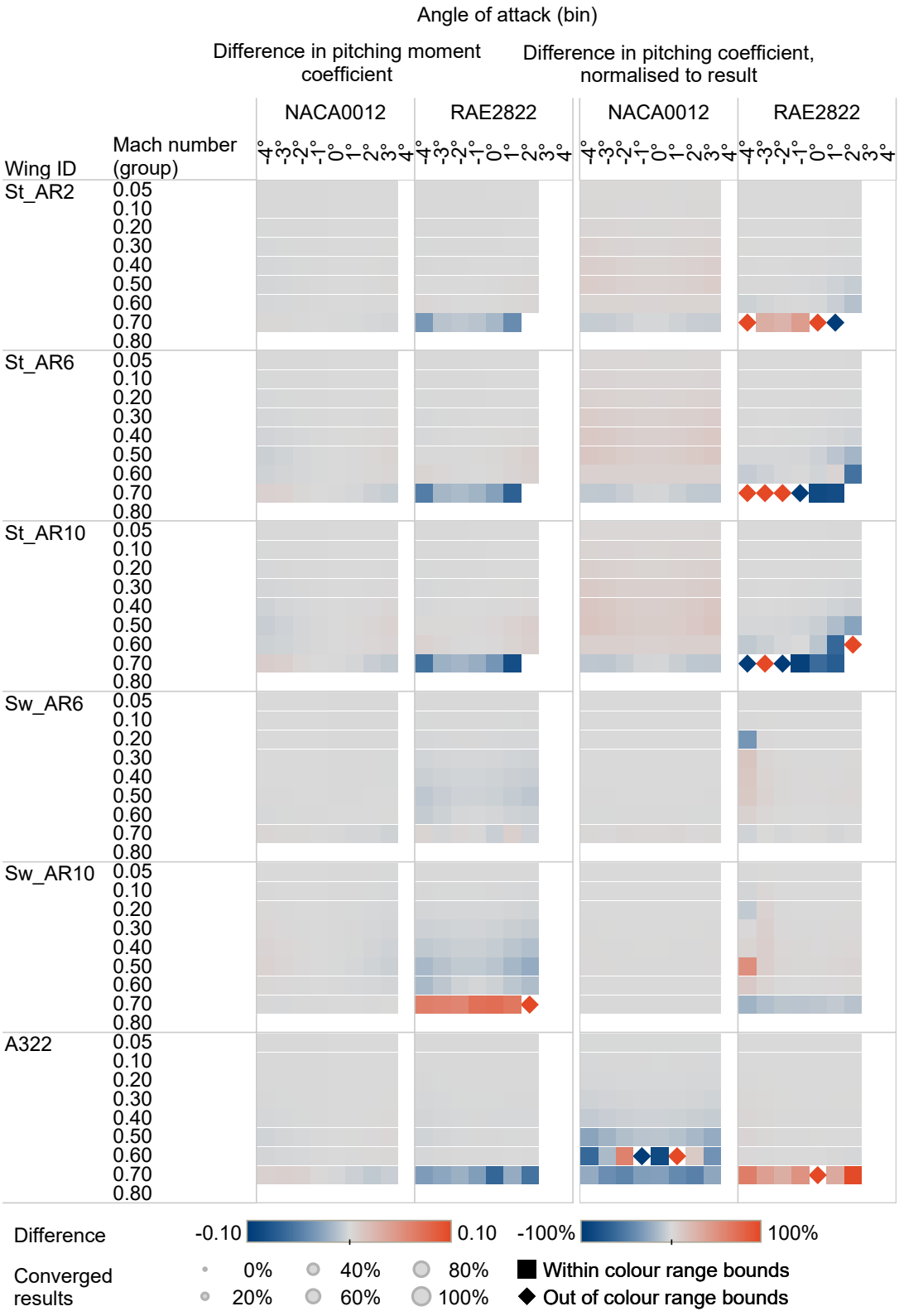


Figure F.68: Difference between Karman-Tsien corrected incompressible (XFOIL-KT + AVL) and compressible (VGK + AVL) pitching moment coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

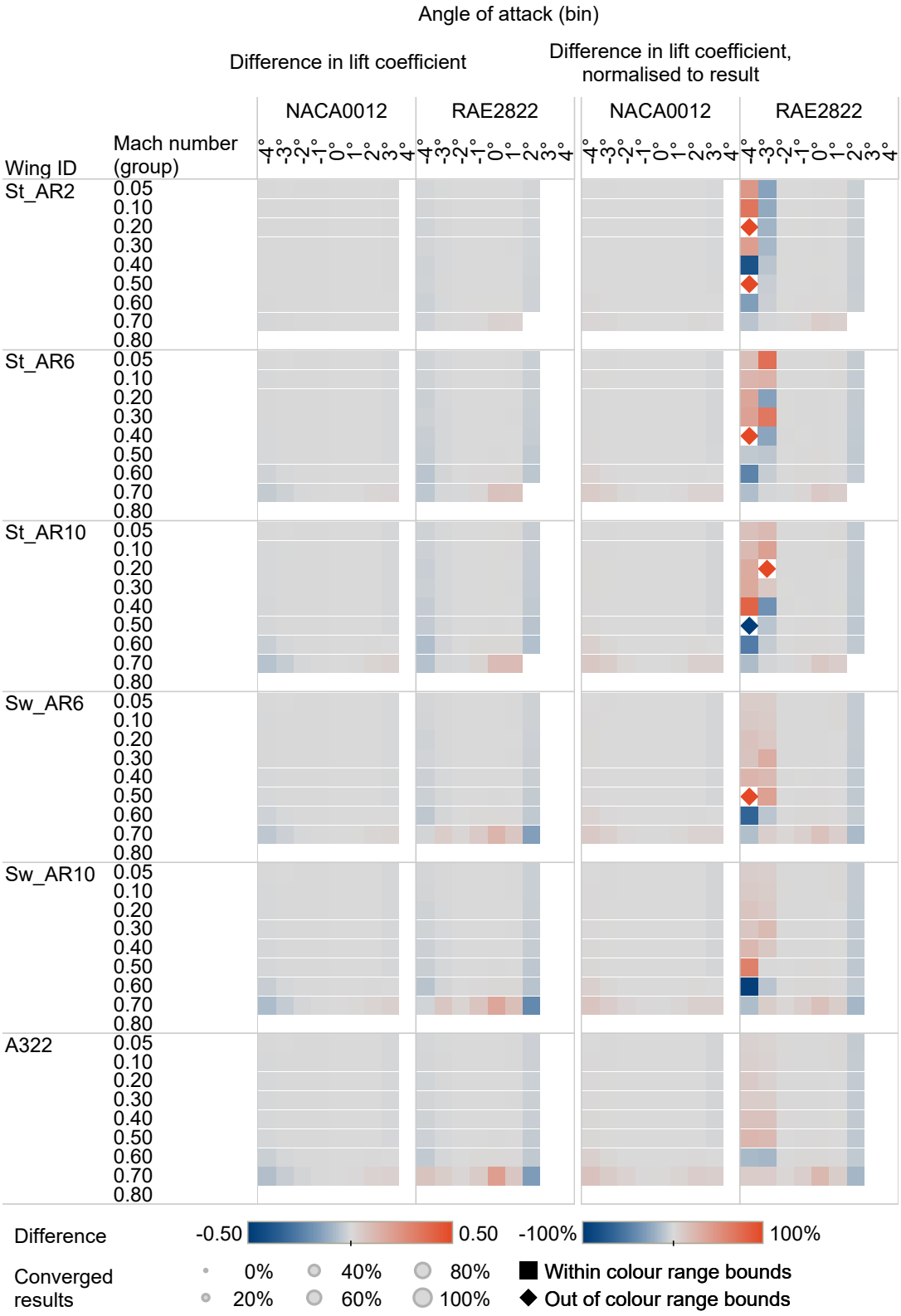


Figure F.69: Difference between irrotational (VGK + AVL) and rotational (MSES + AVL) lift coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

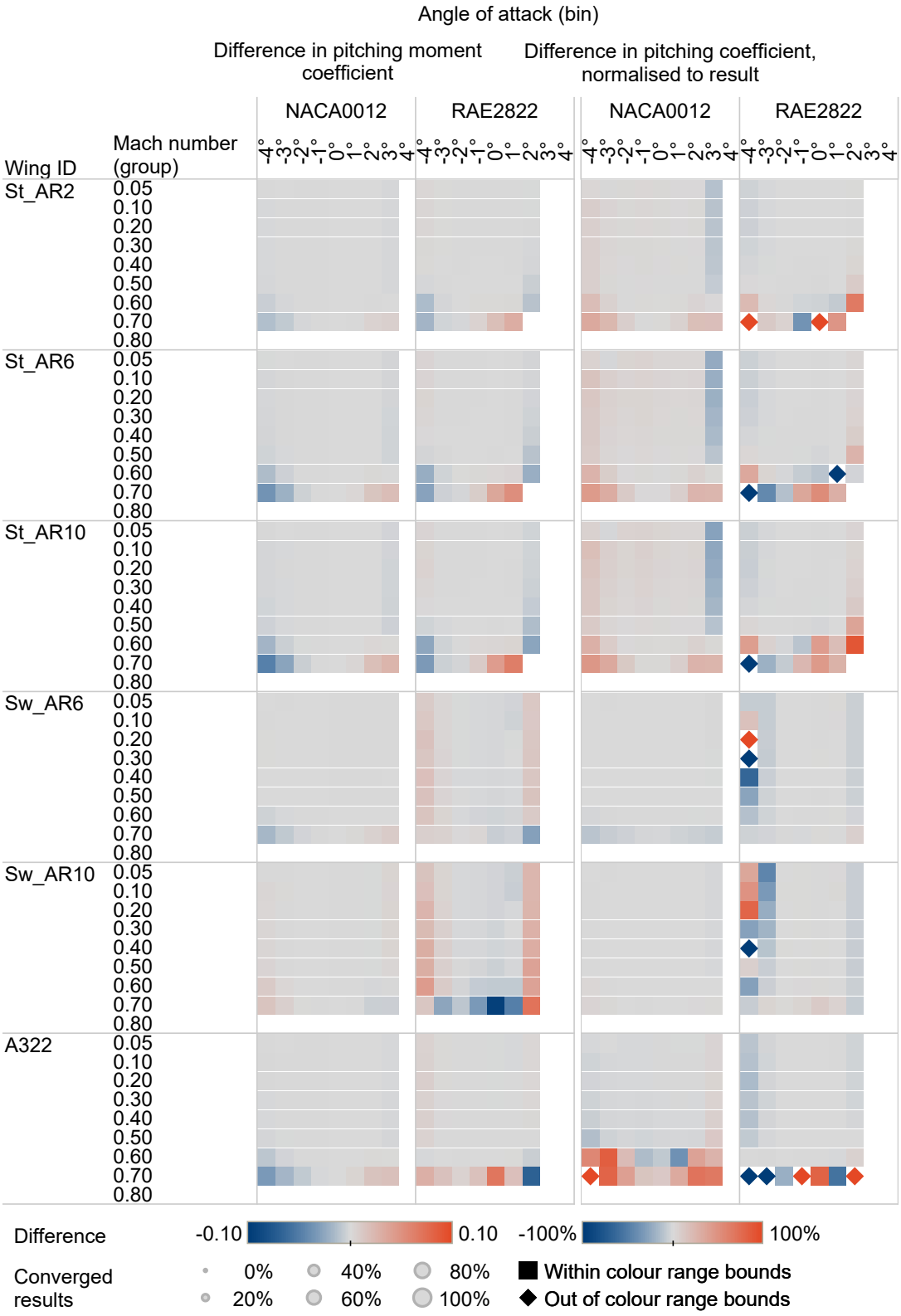


Figure F.70: Difference between irrotational (VGK + AVL) and rotational (MSES + AVL) pitching moment coefficient (true and normalised w.r.t. result) for different wing and airfoil geometries, Mach numbers and (binned) angles of attack

G

Technology readiness levels

Table G.1 provides the definition of technology readiness levels (TRLs) adhered to in this report. It has been quoted from European Space Agency (2008, p. 3) and as such is applied to space technology. For aero-applications, a relevant “space environment” is, for example, a flight test. A wind tunnel would be a relevant “ground environment”.

Table G.1: Technology readiness level definitions and explanations (European Space Agency, 2008, p. 3)

Readiness level	Definition	Explanation
TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.
TRL 5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment.
TRL 7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system.
TRL 8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions.
TRL 9	Actual system 'flight proven' through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions.

H

Interviews

This appendix provides additional details about the interviews used to gain additional insight into the problem, the results of which have been documented in Section 9.3. Appendix H.1 shows the interview guide and Appendix H.2 shows the e-mail invitation used to solicit part of the interviewees. Appendix H.3 presents the coding tree used to analyse the interview transcripts. Finally, Appendix H.4 shows the e-mails used to confirm the used quotes with interviewees.

H.1. Guide

This section shows the interview guide used to conduct interviews. As follows from the guide and as discussed in Section 9.3, these are semi-structured interviews involving five topics: project goals, collaboration, uncertainty, decision making and impact. The topics were discussed in the presented order, following an introduction.

Introduction

In the introduction, the research project was briefly described, as well as the goal of the interview: gain an inside perspective into project MANTA, and the various processes going on in the project. Furthermore, it was stressed that there were no right or wrong answers. Also, the introduction was used to make agreements (or confirm ones made prior to the interview, using e-mail, discussed in Appendix H.2) about recording the interview, anonymity and verification of the interview transcript and conclusions. Last, the introduction was used to gain understanding of the background and role of the participant in the context, by asking to elaborate on these items.

Goals

The questions below are related to goals of the project.

Dutch	English
Wat is, volgens jou, het hoofddoel van het project?	What is, from your perspective, the main goal of the project?
Waar komt de onderzoeksscope vandaan? Met andere woorden: hoezo focust MANTA waar het op focust?	What drives the research scope? Stated differently: why does MANTA focus on what it is focusing on?
Hebben de verschillende betrokkenen ook nog andere doelen – individueel, of in subgroepen?	Do the various participants have their own goals – individually, or in smaller groups?

Dutch	English
Wat vind je daar van?	How do you feel about that?
Wat zijn die doelen?	What are those goals?
Waar baseer je dat op?	On what do you base this?
Zie je (potentiële) conflicten tussen die doelen onderling, of tussen losse doelen en het hoofddoel?	Do you see any (potential) conflicts between those individual goals, or between those goals and the main goal?

Uncertainty

The questions below are related to uncertainty. In some interviews, it was discussed prior to the collaboration, whereas in other interviews, this was reversed.

Dutch	English
Welke (technische, sociale, ...) onzekerheden zie je binnen dit project?	What (technological, social, ...) uncertainties can you identify in this project?
In hoeverre is dit besproken? Hoe vaak? Met wie? In wat voor meetings?	To what extent is this discussed? How often? With whom? In which / what kind of meetings?
Hoe ga je om met onzekerheid?	How do you deal with uncertainty?

Collaboration

The questions below are related to collaboration within the project.

Dutch	English
Hoe goed ken je de mensen met wie je samenwerkt?	How well do you know the people you work with?
Hoe vind je dat de samenwerking verloopt?	What is your opinion on the quality of the collaboration?
Zijn je hierin wel eens dingen opgevallen? Zo ja, welke?	Did anything ever strike you in any way? If so, what?
Geldt dat voor alle verbanden, of slechts voor een aantal partijen?	Is that the case for all collaborations, or only for a few parties?
Is het duidelijk wie waar expertise in heeft?	Is it clear what is everybody's expertise?
Heb je het gevoel dat er een collectief beeld is van wat jullie aan het doen zijn / wat jullie doel is?	Do you feel there is a shared understanding of what it is you are doing / what your goal is?
Zou je de mensen die samenwerken eerder omschrijven als een groep (collectie individuen) of als een team (geolide machine)? Waarom?	Would you rather characterise the people that collaborate as a group (assortment of individuals) or as a team (well-oiled machine)? Why?
Is er sprake van hiërarchie? Hoe ziet die eruit? Hoe is dat van invloed op je (werk, motivatie, ...)?	Does the project have a hierarchy? What does it look like? How does it influence you, and your work, motivation, ...?

Decision making

The questions below deal with decision making in project MANTA.

Dutch	English
Hoe vind je dat de besluitvorming verloopt?	How do you think the decision making goes?
Zijn je hierin wel eens dingen opgevallen? Zo ja, welke?	Did anything ever strike you in any way? If so, what?
Wie maakt de besluiten?	Who makes the decisions?
In hoeverre wordt de stem van anderen daarin meegewogen, voor zover jij weet?	To what extent are other opinions weighed into that, as far as you know?
Is er iemand / zijn er mensen wiens mening zwaarder wordt gewogen dan die van anderen?	Is there somebody / are there people whose opinion is weighted heavier than those of others?
Hoe worden besluiten gemaakt? Voorkeur van de meerderheid, consensus, een andere vorm?	How are decisions made? Majority rule, consensus, another way?
Is er naar jouw mening voldoende tijd voor informatieuitwisseling, besluitvorming, delen van argumenten, voor iedereen om zijn / haar bijdrage te leveren, ...?	Is there in your opinion enough time for information exchange, decision making, discussion, for everybody do contribute?
Is er ooit sprake van ‘conflict’?	Is there ever a ‘conflict’?
Zo ja, is dat ‘georganiseerd’ (advocaat van de duivel, bijvoorbeeld)?	If so, is that ‘organised’ (such as a Devil’s advocate)?
Zo ja, in hoeverre is dat op de inhoud en in hoeverre op de persoon?	If so, to what extent is that focused on content, and to what extent on persons?
Zo nee, heb je het gevoel dat het er eigenlijk wel is (onder de oppervlakte), maar het niet wordt uitgesproken?	If not, do you feel it does exist (below the surface), but just not shared openly?

Impact

The questions below are related to the impact of all the other topics on the interviewee.

Dutch	English
Wat merk je van dit alles?	To what extent do you notice all we have discussed in daily operations?
Hoe beïnvloed dat je werk?	How does it influence your work?
Hoe beïnvloed het jouzelf, op persoonlijk(er) vlak?	How does it influence you, on a (more) personal level?

H.2. Invitation

Two interviewees were approached directly. Others were solicited through e-mail, after being acquainted with them face-to-face. The first e-mail was mostly introductory, the second e-mail asks permission to record the conversation and shares further details on how the results will be processed.

Dutch	English
Naar aanleiding van de concept selection meeting eerder deze maand zou ik graag een telefonische/Skype-afspraak maken om je enkele vragen te kunnen stellen over project MANTA. In ongeveer 45 tot 60 minuten wil ik het hebben over de projectdoelen, (de rol van) onzekerheid, samenwerking, besluitvorming en wat de impact daarvan op jouw werk is.	Following the concept selection meeting earlier this month, I would like to schedule a telephone/Skype-interview with you to ask you some questions about project MANTA. In approximately 30 to 45 minutes, I would like to discuss project goals, uncertainty, collaboration, decision making and how all these impact your work.
Zou je één of twee momenten kunnen noemen die geschikt zouden zijn voor zo'n gesprek?	Could you please let me know what times suit you best for such an interview?

Dutch	English
Daarnaast wil ik je graag op voorhand om toestemming vragen om ons gesprek op te nemen, zodat ik dat waarheidsgetrouw kan uitwerken. De resultaten ervan die in mijn afstudeerverslag komen zullen uiteraard geanonimiseerd zijn. Waarschijnlijk blijft mijn rapport sowieso nog een aantal jaar onder embargo, in verband met de NDA van het project. Wél verwacht ik de uitkomst van het interview in wat meer detail met het Wetenschapscommunicatiedeel van mijn afstudeercommissie te bespreken. (Ook die zijn overigens werkzaam bij de TU Delft en vallen dus onder de NDA.) Roelof en Martijn blijven daar in principe buiten. Aan het begin van het interview zal ik je dit nogmaals vragen, maar mocht je voor die tijd vragen hebben of je toestemming op een bepaalde manier willen beperken, hoor ik dat graag van te voren. Zo hoeft dat de [datum] niet ten koste te gaan van onze gesprekstijd.	Having said that, I'd like to ask you beforehand for your permission to make an audio-recording of the interview, to allow me to truthfully transcribe and analyse the conversation we had. Any results I might use in my graduation thesis report are, of course, fully anonymous. That report will most likely remain confidential for the next few years anyway, in order to respect the NDA of the project. I do expect to share some more details about our interview with my graduation supervisors that support my Science Communication research. (They are, by the way, also staff members of TU Delft and hence covered by the MANTA-NDA.) These discussions will, in principle, not involve Roelof and/or Martijn. Starting our interview, we can quickly go over these points again, but in case you have any questions before that time (or would like to set any additional limitations or safeguards), please let me know.

H.3. Code tree

Interview transcripts were structurally coded using the following tree, that was largely generated prior to starting the coding process. Italicised items were added during coding, in order to capture additional detail. It bears great resemblance to the interview guide presented in Appendix H.1.

- Participants
  - Background
  - Role
- Goals
  - Project goals
    - *Derivative goals*
  - Sub-goals
    - *Consortium partners*
    - *Topic leaders*
    - *European Commission / PPP*
  - Conflict
- Uncertainty
  - Types
  - Discussion
  - Management
- Collaboration
  - Acquaintance
  - Impression
  - Expertise
  - Integration
    - Group
    - Team
  - Hierarchy
- Decision making
  - Impression
  - Dominance
  - Strategy
  - *Bases*
  - Information exchange
  - Conflict
    - Organised
    - Unorganised
  - *Facilities*
- Impact / problems
  - Personal
  - *Project*
  - Professional

H.4. Quotation review

The e-mail shown below (in two version) was used to confirm with interviewees the quotes used in the report. Interviewees were given 7 days to respond.

Dutch	English
Een aantal weken geleden hebben we het [aan de telefoon] gehad over project MANTA, onder andere op het gebied van samenwerking, besluitvorming en de rol van onzekerheid. In het uiteindelijke stuk heb ik een aantal citaten uit dat gesprek gebruikt. Via deze weg leg ik ze graag – ter goedkeuring – aan je voor. Jouw citaten staan in de tabel onderaan deze mail. In de bijlage vind je de delen van mijn uiteindelijke verslag waarin ze gebruikt worden. Jouw uitspraken zijn daarin geel gemarkeerd. De zwartgelakte stukken zijn citatities van andere interviewees die nog niet zijn goedgekeurd. Zoals eerder aangegeven zijn alle citaten geanonimiseerd. Eventuele bezwaren of opmerkingen hoor ik graag uiterlijk zondag 11 augustus. Indien ik dan niets heb vernomen, ga ik uit van je akkoord. Op 18 augustus lever ik mijn eindverslag digitaal in, 29 augustus is de verdediging. Uiteraard stuur ik je daarna met alle plezier mijn volledige verslag, mocht je daarin geïnteresseerd zijn.	Some weeks ago, we talked [on the phone] about project MANTA, discussing topics as collaboration, decision making and uncertainties. As I am almost at the end of my thesis, I'd like to check with you the elements that I have used. Your quotes are listed in the table at the end of this mail, as well as highlighted in the PDF-document attached. (The redacted parts are quotes from other interviewees, still under review.) As I have indicated previously, they are all anonymous. In case you have any problems with me using the quotes as currently formulated, please let me know no later than August 11th. If I haven't heard back from you by that time, I am assuming you have no objections. I am handing in my final report August 18th and defending it August 29th. Of course, I'll gladly supply you with a digital copy of my work if you're interested in the complete results.
Een aantal weken geleden hebben we het [aan de telefoon] gehad over project MANTA, onder andere op het gebied van samenwerking, besluitvorming en de rol van onzekerheid. Aangezien ik bijna aan het einde van mijn scriptie ben, wil ik de elementen die ik heb gebruikt graag ter goedkeuring aan je voorleggen. Omdat de opname van ons telefoongesprek vanwege een technisch probleem is gewist, heb ik geen directe citaten uit dat interview gebruikt. Wel heb ik een aantal opmerkingen die je hebt geuit tijdens de selectie-vergadering, waar we elkaar hebben ontmoet. Die staan onderaan deze mail, en zijn gemarkeerd in het bijgevoegde PDF-bestand. (De zwartgelakte stukken zijn citaties van andere interviewees die nog niet zjin goedgekeurd.) ZOals je in het document kunt zien, zijn alle uitspraken anoniem. Eventuele bezwaren of opmerkingen hoor ik graag uiterlijk zondag 11 augustus. Indien ik dan niets heb vernomen, ga ik uit van je akkoord. Op 18 augustus lever ik mijn eindverslag digitaal in, 29 augustus is de verdediging. Uiteraard stuur ik je daarna met alle plezier mijn volledige verslag, mocht je daarin geïnteresseerd zijn.	Some weeks ago, we talked [on the phone] about project MANTA, discussing topics as collaboration, decision making and uncertainties. As I am almost at the end of my thesis, I'd like to check with you the elements that I have used. As a technical problem erased the recording of our phone conversation, I haven't used any direct quotes from that discussion. I did, however, include a number of remarks you have made during the selection meeting where we met. They are listed at the end of this e-mail, as well as highlighted in the PDF-document attached. (The redacted parts are quotes from other interviewees, still under review.) As you can see in the document, they are all anonymous. In case you have any problems with me using the remarks as currently formulated, please let me know no later than August 11th. If I haven't heard back from you by that time, I am assuming you have no objections. I am handing in my final report August 18th and defending it August 29th. Of course, I'll gladly supply you with a digital copy of my work if you're interested in the complete results.

A few minor revisions to the text were made based on interviewee feedback, mostly to further reduce traceability to particular participants.

TARE-model development iterations

This appendix shows various iterations working to extend the basic TARE-model shown in Section 11.2. The attempts shown here mostly aimed to include a dimension indicating the (potential) difference between individual and group goals.

The variant shown in Figure I.1 is essentially comprised of two instances of the basic model, shown beneath each other. The top half shows the task-relationship-balance at group level; the bottom half shows it at individual level. The distance between the two horizontal lines that form the basis of each half-diagram represents the alignment between group and individual objectives. The iteration was eventually discarded as too complicated. Especially when alignment is high, many lines intersect, cluttering the diagram.

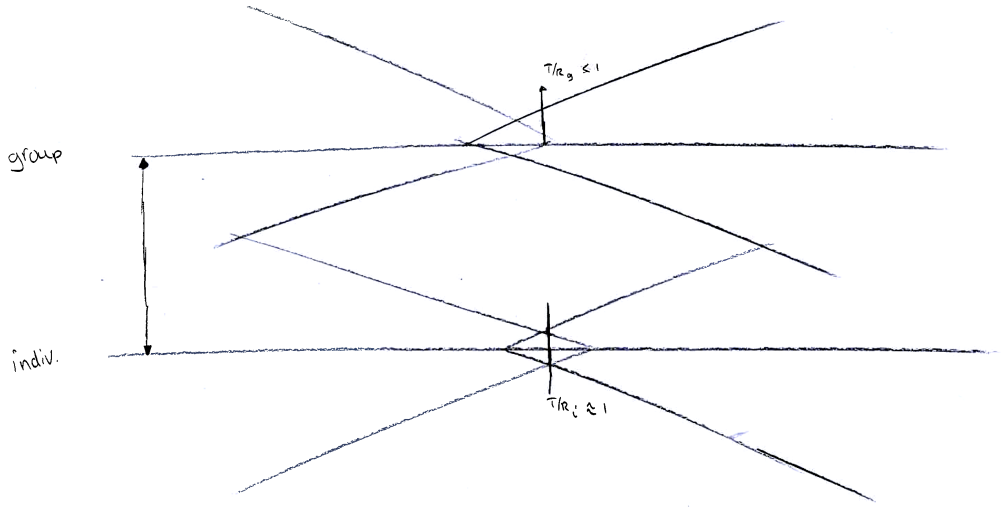


Figure I.1: First model iteration

The second variant, shown in Figure I.2, set out to solve that problem by combining the two instances in a stacked fashion, rather than placed beneath each other. In the figure, the inner arrows correspond to the individual perspective, whereas the outer lines represent the group-level. However, in this case, the current and desired balance between task-attention and relationship-attention at the group level, also defines that balance at the individual level. That need not be the case, thereby invalidating this version.

Figure I.3 shows the third iteration, which still has the same problem, as does Figure I.4. Both were used

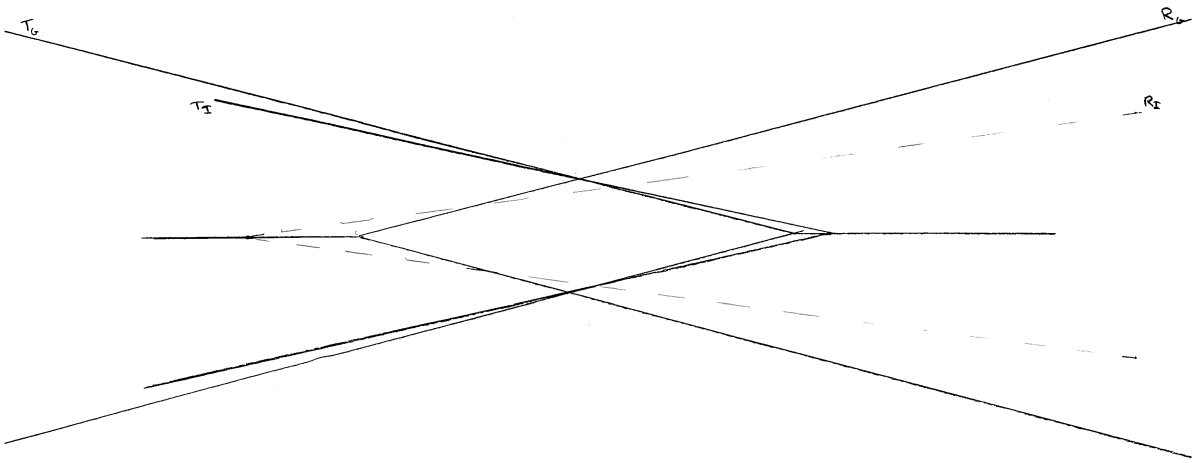


Figure I.2: Second model iteration

to explore whether the individual and group (or, as it is shown in the sketch: *project*) lines emanate from the same point on the vertical line, or not (as was the case in Figure I.2).

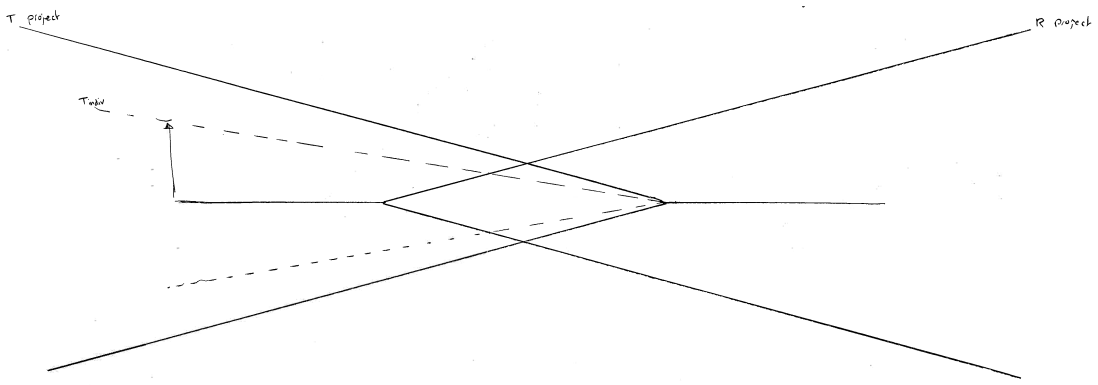


Figure I.3: Third model iteration

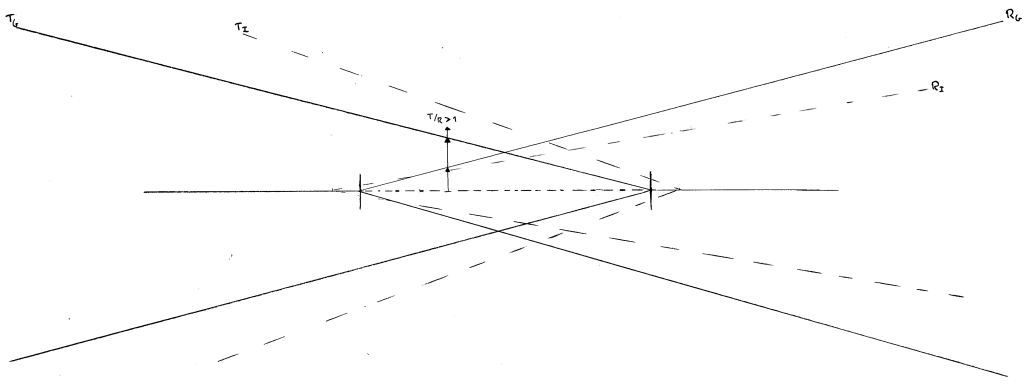


Figure I.4: Fourth model iteration

The conclusion that both options are possible formed the basis of a fourth idea, of which a sketch is shown in Figure I.5. This removes the symmetry in the horizontal axis and instead uses the upper lines to indicate the group perspective and the lower lines to visualise the individual perspective. As indicated by the black triangles, it is possible for these lines to intersect the horizontal at different points, but only

the most inward points are relevant. Beyond that, either the group does not exist anymore, or no single individual goal is met – leaving the project members without a reason to participate.

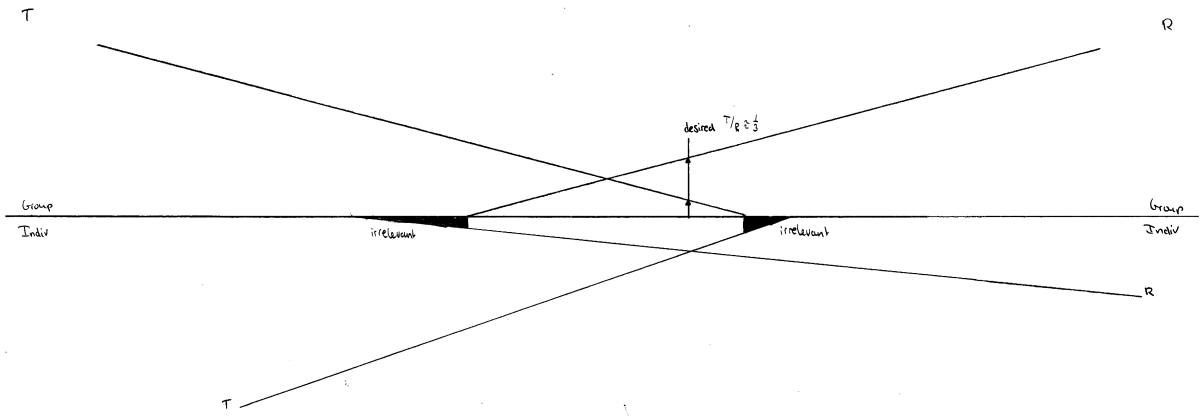


Figure I.5: Fifth model iteration

Last, a sixth version was made, which is shown in Figure I.6. In this iteration, a third spatial dimension was added to incorporate a new group-individual-balance at each ends (i.e., task and relationship) of the main diagram. Although this is not shown on the image, the two arrows on the main diagram would thereby take the shape of cones. Not long after starting construction of the sketch presented, it was concluded that such a model would be too complicated.

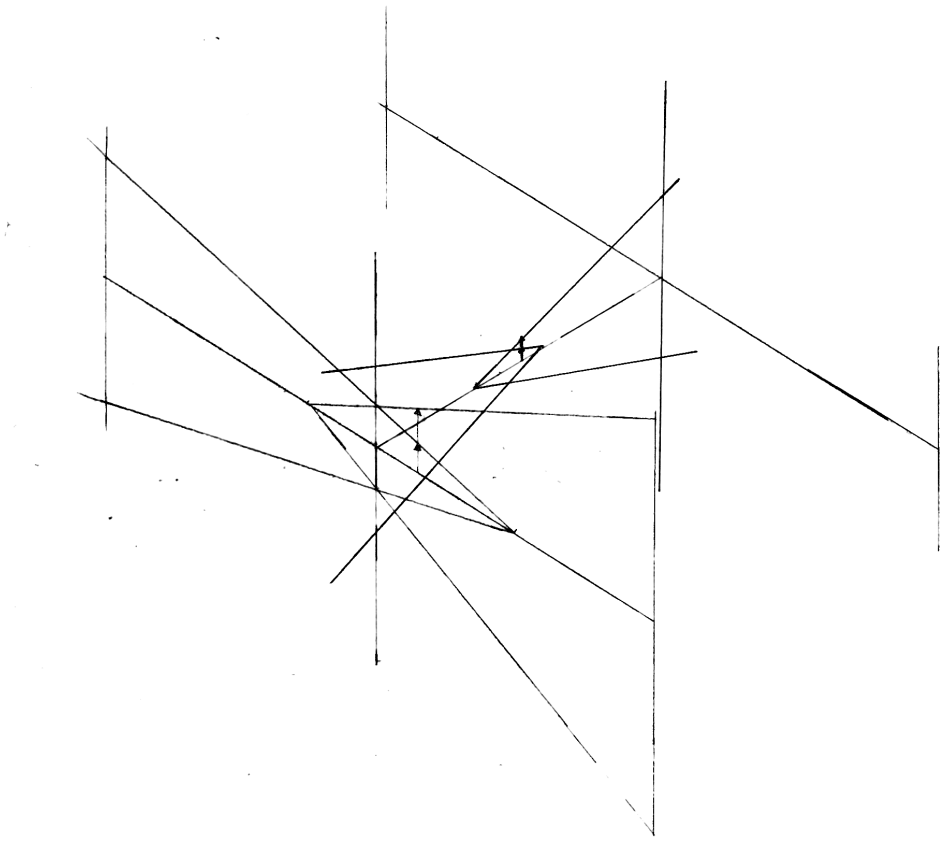


Figure I.6: Sixth model iteration

J

Research data

Due to reasons of confidentiality and anonymity as well as the sheer volume of items, not all research data is included as appendix to this report. It is, nevertheless, available upon request, in order to facilitate further scrutinising this research project, or building up on it. This section lists all data that is available.

Data listed in Appendix J.1 (Influences on decision quality) and Appendix J.3 (Socio-psychological perspective) can be requested from the Science Communication / Communication Design for Innovation department at the Faculty of Applied Sciences at Delft University of Technology[1]. The data listed in Appendix J.2 (Technical perspective) is kept by the department of Flight Performance & Propulsion at the Faculty of Aerospace Engineering at Delft University of Technology[2]. Both departments hold a copy of the data listed in Appendix J.4.

J.1. Influences on decision quality

- Cited publications, insofar as digitally available, including coding / annotations
- Analysis file, indicating colour coding and exclusion reasons (as discussed in Appendix B.1)

J.2. Technical perspective

J.2.1. Model and criteria selection and description

The chapters *Model and criteria selection* (Chapter 4) and *Solver description* (Chapter 5) are largely based on Peerlings (2018).

J.2.2. Uncertainty quantification

- Software and code listings of the programs discussed in Appendix C
  - Run-programs (code listing, MATLAB)
  - Analysis-programs (code listing, MATLAB)
  - Helper programs (code listing, MATLAB)
  - Solver executables (XFOIL, VGK, MSES)
  - Analysis worksheets (Tableau)

[1] Lorentzweg 1, 2628CJ, Delft, The Netherlands.
[2] Kluyverwg 1, 2629HS, Delft, The Netherlands.

- Solver results (raw and processed data, including logs)
- Analysis results (processed data)

J.2.3. Uncertainty propagation

- Software and code listings of the programs discussed in Appendix C
  - Run-programs (code listing, MATLAB)
  - Analysis-programs (code listing, MATLAB)
  - Helper programs (code listing, MATLAB)
  - Solver executables (AVL)
  - Aircraft Design Initiator code
  - Analysis worksheets (Tableau)
- Solver results (raw and processed data, including logs)
- Aircraft Design Initiator results (Controller-object and *ReportWriter*-exports)
- Analysis results (processed data)

J.3. Socio-psychological perspective

- Initial impressions / document review
  - Documents, including coding / annotations
- Participants perspectives / interviews
  - Correspondence
  - Recordings
  - Transcripts and notes, including coding / annotations
- Decision making in action / observation
  - Field notes

J.4. Other

- Presentations used in progress meetings
- LaTeX-files (including images) of the current report

K

Word count

Table K.1 shows the (equivalent) word count of the text in the various chapters of the body of this report, determined using TeXcount web service[1]. The equivalent word count is computed by adding 200 words to the actual word count per figure contained in that chapter. Figures that are made up of sub-figures (a, b, ...) are counted as one.

[1] Version 3.1.1, available through https://app.uio.no/ifi/texcount/online.php

Table K.1: Thesis word count

Ch.	Title	AE	SC	Words	Figures	Eq. words
1	Introduction	✓	✓	2.409	1	2.609
2	Context	✓	✓	1.771	6	2.971
3	Decision quality	✓	✓	5.718	2	6.118
4	Model and criteria selection	✓		2.990	6	4.190
5	Solver description	✓		5.052	4	5.852
6	Uncertainty quantification	✓		9.175	32	15.575
7	Uncertainty propagation	✓		4.917	8	6.517
8	Closing	✓		1.156		1.156
	Total Part I, Technical perspective	✓		**23.593**	**50**	**33.593**
9	Project description and problem definition		✓	13.164	5	14.164
10	Theoretical framework		✓	3.956	2	4.356
11	Model development		✓	2.162	9	3.962
12	Model use		✓	1.725	5	2.725
13	Closing	✓		1.068		1.068
	Total Part II, Socio-psychological perspective		✓	**22.327**	**21**	**26.527**
14	Synthesis		✓	2.865	12	5.265
	Total Part III, Integrated perspective	✓	✓	**2.964**	**12**	**5.364**
15	Conclusions	✓	✓	1.076		1.076
16	Discussion	✓	✓	4.781	1	4.981
17	Reflection	✓	✓	2.324		2.324
		✓	✓	2.307		2.461
	Grand total	✓	✓	**69.270**	**93**	**87.870**

Bram Peerlings

Holistically improving screening decisions under uncertainty in aircraft conceptual design and technology assessment

TU Delft

