Conceptual Design of Fibre Metal Laminate Fuselage Panels

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Challenge the future

Conceptual Design of Fibre Metal Laminate Fuselage Panels

by

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PREFACE

The work presented in this thesis concludes my 2.5 years as master student, and represents the 1 year of efforts put into performing this research. The work presented, combines Knowledge Based Engineering Systems, and the method of design of experiment. In doing so it increases design process efficiency and verifies the effectiveness of automation and optimisation in laminate design of FML panels. This thesis project has been performed using the design process followed at Fokker Aerostructures as case study, and the tool made is a part of the bigger PANADEE project, aimed at fully automating panel design.

Goals of this thesis could not have been realised without the support and guidance of many. I would like to take this opportunity to express my gratitude to all those who have supported and guided me through this journey. Firstly I would like to thank Jacques Wildemast, my daily supervisor at Fokker. My first point of contact, he guided me with patience keeping my Student's outlook in perspective. I would also like to thank Jan Baan. His jovial nature and passion for codes has been a great support while I developed PANADEE-II.

My sincere gratitude to Gianfranco La Rocca, my supervisor at TU Delft, and Cees van Hengel and Hans van Goozen, design experts at Fokker. Despite their busy schedules, they have supported me throughout. Their opinions and advise as experts, always acted to better the standards of my work.

Many thanks to my friends and fellow interns at Fokker. Performing this thesis alongside them, greatly simplified the journey, and prepared me for the trials and tribulations that came on the way. I would like to thank all my friends and family for their unending support. In helping me prepare for the different milestones of this thesis, they infused me with confidence and improved my performance.

This accomplishment is a result of support from many more and I would like to thank them all for it.

S. Banerji
Delft, January 2018

SUMMARY

With improvements in aviation technology, design requirements to be full-filled have also increased exponentially. This in turn influences the complexity of design process, along with the time and effort required for it. The problem, for this research, has been set up with respect to challenges faced at Fokker Aerostructures, during in-proposal design of fuselage panels made from Fibre Metal Laminates (FML). FML technology allows material tailoring that offers substantial weight saving with bigger part dimensions. This trait of material tailoring poses a complex design challenge in the time constrained in-proposal design phase. The objective of this phase, is to explore the solution space in order to come up with a winning proposal at a profitable cost. To tackle the challenges experienced, this research work establishes phase-I of a three phased project, proposed for implementation of full scale optimisation. The first phase is concerned with formalising the product and process knowledge of the laminate design, and bringing out the benefits of automation in a process largely treated as creative. For this a KBE application, called the PANADEE-II is developed. This tool aims to isolate all creative tasks to be performed by experts, and automate all repetitive and non-creative tasks around it.

PANADEE-II is capable of quickly generating multiple designs while keeping the designer in-loop. Dividing the design challenges into smaller Constraint Satisfaction Problems(CSP), it uses heuristic techniques of trial and error to find solutions for individual problems. Further, by experimenting with designs adapted to different design trait combinations, it performs general solution space searches. In doing so, it quadruples the number of design points tested as compared to the original manual process. This, along with a 28% smaller lead time, and 18% reduction in required expert time, greatly increase opportunities for design studies and manual optimisation. For a part manufacturer like Fokker Aerostructure, this serves a competitive advantage, as the current design process allows study of limited designs(1 or 2), offering no feel of the actual available solution space or how the performance of selected design ranks in it. On the longer run, PANADEE-II has laid down a foundation for implementing a full scale design optimisation, including processes that have been currently isolated as creative for experts.

Contents

1
INTRODUCTION

Design of aircraft and its components pose a complex engineering problem, requiring a high level of interaction. This interaction may be among primary fields(aerodynamics, structures, propulsion, and control), departments of company (cost, weight, manufacturing, design, etc.), or even interaction of practical aspects(design skills and experience)[1]. While this level of interaction and exchange is essential for a sound design, it contributes to increasing the amount of changes, iteration and re-work, which in turn increases design lead time.

In recent decades, aviation has turned into a global business, greatly influenced by competition. For an aerospace equipment manufacturer, coping with competition and the new trends of "more affordable, cleaner, and quieter" technology[1], an increased design lead time is highly undesirable. Further, one of the goals assigned to the aeronautics industry as a part of European Aeronautics vision 2020 was to 'halve the time to market for new products'. For this it was proposed that companies progress to use of advanced electronic capabilities for their design and manufacturing processes[2]. Flightpath 2050 proceeds on similar lines by supporting high level integrated system design with multi-disciplinary design and development tools[3].

Another challenge that comes with limited time is of limited design space exploration. This directly impacts how a manufacturer performs in the face of competition. Creating a single or a pair of designs, offer no comparison as to how the proposed design ranks, or if it is indeed the best design to meet all requirements. This challenge can again be tackled by reducing lead time, to create multiple designs within the same time frame.

Research presented in this thesis, works towards managing the time challenge mentioned above. This is specifically done in context of tasks classified as 'creative'[1]. The solution has been proposed with respect to problems faced in the conceptual design phase of fuselage panels made from Fibre Metal Laminates (FML). In particular the focus is on the design process followed at Fokker Aerostructures.

1.1. IN-PROPOSAL DESIGN OF PANEL LAMINATES

The in-proposal design phase, for a part manufacturer such as Fokker Aerostructures, lies within the conceptual design phase of the global product i.e. the aircraft. Literature study performed on the in-proposal design phase and process, show the strong influence of decision made in this phase on the cost-weight performance of the final design[4]. Typically lasting 4 weeks, the objective of this phase is to study the design space in order to come up with a winning proposal(design that best meets customer requirements) at profitable costs[5]. With the current design process, it was found that the time available is just about sufficient to generate at best 2 designs per panel, for a total of 25-30 panels designed. While experience of the manufacturer might vouch for performance of the panels, 2 designs hardly give an indication of size of the design space and how the proposal ranks in it.

[1] Defined as those that are not yet, guided by a pre-defined set of knowledge rule

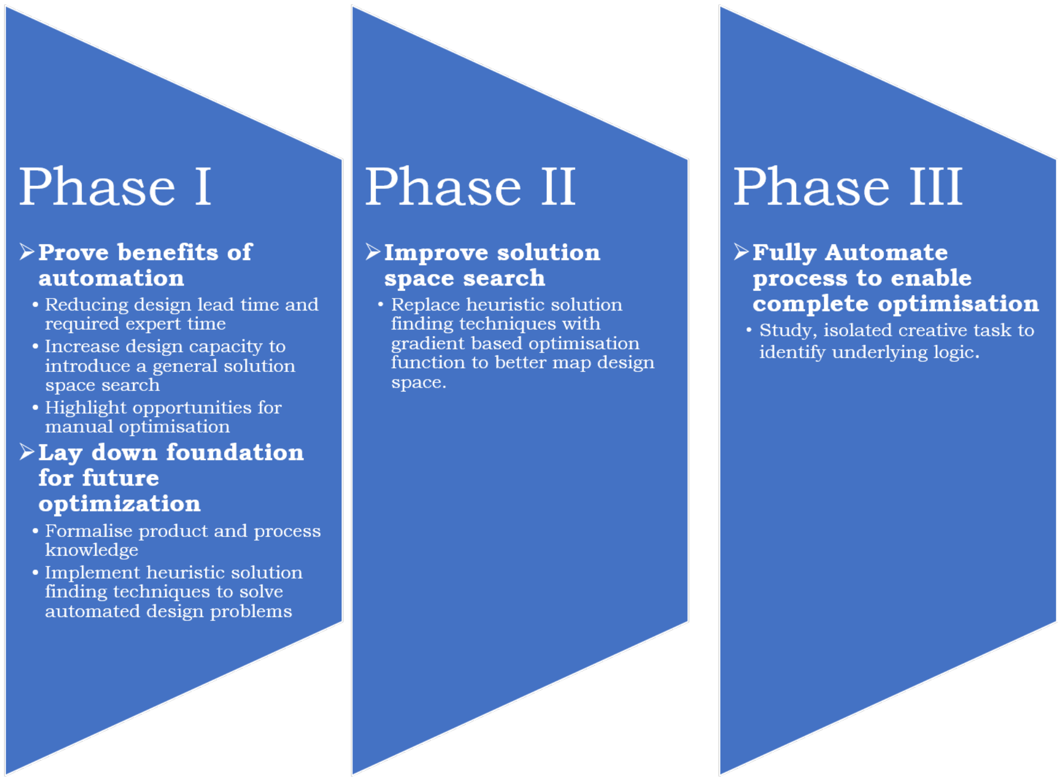


Figure 1.1: Proposed phases for implementing optimisation

The primary reason as to why automation had not been looked into earlier, for improving performance of this phase, is that the process is usually classified under creative. This is because a relevant portion of the tasks to be performed, may, but do not have to, conform to certain guidelines, which are often unclear in themselves. For these tasks, designers tend to draw from experience and look for new solutions only when these fail. It was also found that influence of certain decisions could not be specifically stated or quantified, as these varied from panel to panel. Faced with such uncertainties in performance, automation in this phase is seen with scepticism, particularly by creative experts. However, this uncertainty also supplies the primary benefits of solution space search through automation.

Figure 1.1, gives the three phases, that have been proposed for the gradual implementation of complete automation and optimisation. In a step by step manner, these three phases enable experts to discover the benefits of automation and optimisation, and its use in a manner complementary to their work.

Research presented in this thesis, performs exclusively in phase I. For FML panel design, a process extensively treated as creative, the challenge was to identify the underlying knowledge. Further this knowledge needed to be formalised in such a manner that it enables automation and supports future optimisation.

1.2. RESEARCH OBJECTIVES

Objective of the research is to develop a methodology that employs Knowledge Based Engineering(KBE) tools to increase design process efficiency[2] with comparable performance[3], while keeping the designer in loop. The hypothesis being that by generating more concepts, in the same time frame, and involving experts for strictly "creative" tasks, enables better proposals to be created while avoiding stagnation in design. Results from this research will quantitatively establish the influence of automation on creative tasks. Further, its learning points can be employed to structure such tools, in a manner more intuitive to the user i.e. design

[2]Defined number of designs created per hour

[3]Cost and weight should be comparable to those generated from a fully manual process performed by experts.

expert.

Keeping the above mentioned project goal in mind, the following research questions were formulated to serve as a guide to the research:

1. How do the designs for FMl fuselage panels, from the automated tool, improve the design space exploration, during the in-proposal phase?
   (a) What number of panels can be designed per hour, when aided by the tool?
   (b) What is the range of cost and weight that can be mapped using the new design process(aided by tool) as opposed to the original process?
2. What is the influence on the performance of final proposal when design is carried out with the aid of a tool dedicated to the design process?
   (a) What is the difference(if any) in the cost and weight of the final proposal, for the same panel, when created using the developed design methodology and the original manual design processes?
   (b) What is the average number of deviations (not tested and/or recommended design characteristics) from the design principles[4] that is seen per panel when the design is solely created without designer interference.

In an effort to answer the above posed research questions, further questions were developed that served to guide the choices made while using the tool.

1. What are the most time and/or effort consuming tasks? These highlight the aspects that would be most time saving if automated.
2. What are the tasks that are creative as per definition and thus do not, currently, show prospects of automation? How can this task be simplified through automation?
3. What are the main constraints that need to be satisfied for the designs to be classified as manufacturable?

1.3. STRUCTURE OF REPORT

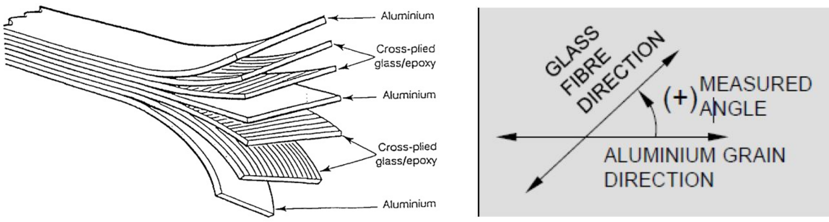
The paper henceforth is arranged as follows: Chapter 2 gives a brief introduction to FML and the challenges that arise when it is used for part manufacture, particularly for fuselage panels. Chapter 3 describes different design phases, establishing the process followed by part manufacturers, and how(and why) it differs from the standard design process. Chapter 4, deals specifically with the in-proposal phase of design. Examining the process flow, roots of the problem are identified and a solution is proposed. The solution finding process and the improvements it offers to the design process is elaborated in Chapter 5, followed by details on the implementation of solution algorithm in Chapter 6. Chapter 7 is dedicated to discussing the results and how they answer the research questions. Answers to the previously mentioned research questions, and a critical analysis of the proposed methodology is presented in Chapter 8, followed by conclusion and recommendation, in Chapter 9.

[4] Set of guidelines created after extensive testing, that ensure quality in the final manufactured part.

2

INTRODUCTION TO FIBRE METAL LAMINATES

FML is a hybrid material which is composed of alternately stacked metal and fibre-reinforced composite layers[6]. It combines the best traits of both while circumventing their disadvantages. ARALL (Aramid Reinforced Aluminium Laminate), GLARE (Glass Reinforced Aluminium Laminate), and CARALL (Carbon Reinforced Aluminium Laminate) are among the most commercially available FML. At the most abstract level, FML offers quick damage detection and durability of metals, along with superior fatigue and fracture characteristics of fibre-reinforced composite. All the while, it serves a 15%-30% weight saving relative to monolithic metal[6, 7].



(a)Schematic view. (b) Fibre Orientation.

Figure 2.1: Typical FML: GLARE.

GLARE is a variant of FML with high burn through resistance. Developed at TU Delft, it uses glass fibres embedded in an adhesive of rubber toughened epoxy[8]. Depending on fibre orientation (0°/90°) w.r.t. Aluminium grain direction(Figure 2.1), and prepreg[1] layup, 6 different GLARE grades have been commercialized. Each GLARE grade/type displays a set of unique properties beneficial for localised use. With regard to fuselage panels the following GLARE types are employed:

- GLARE 3: having fibre layup of 0°/90° or 90°/0°, displays better impact characteristics and is applied on upper parts of fuselage where prominence is on pressure loads and bending under weight[9].
- GLARE 4: with 0°/90°/0° or 90°/0°/90° layup, it has high directional strength and is best suited to cope with directional loads[10].
- GLARE 6: having +45°/−45° layup, it features exceptional shear and off axis properties. It is primarily used in door doublers [9].

Use of GLARE in large components, such as fuselage panels, offer significant weight savings. These manifest in the form of long term profit, greater payload capacity, and/or higher weight allowable for other components. FML application to Airbus A380 fuselage panels resulted in weight saving of 1000[Kg], while complying to higher fatigue allowable. Application on leading edge of horizontal and vertical empennage, also

[1] All layers of glass fibers, having same or different orientation, embedded in adhesive and sandwiched between two metal layers are collectively called prepreg

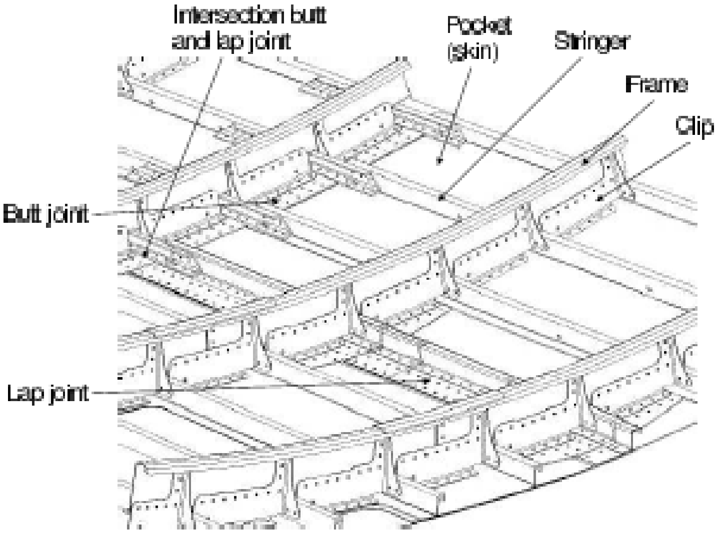


Figure 2.2: Typical Fuselage Structure [13].

saved 71[Kg] with much better impact strength[11]. As cost benefits are obtained only in the long run, application of GLARE has been largely constricted to aerospace components. Common applications of GLARE have been on fuselage skin, cargo floor, bulkheads and lower wing skin. Other spin-off applications include engine cowling and cargo containers (tested for blast resistance) which require reduction in material cost to become commercially viable.[8, 12].

2.1. FML FUSELAGE PANEL MANUFACTURING

A typical fuselage structure (Figure 2.2) is composed of several panels, joined in longitudinal and circumferential direction, using lap joints and butt strap respectively. Every panel consists of a relatively thin skin, and a backup structure (frames and stringers). These are connected together by means of riveting or bonding (only for stringers). The skin which is made of FML is created by alternated layering of metal and fibre reinforced polymers on a single or double curved mould. Further, it is cured in the high temperatures and pressure of autoclave. Doing so consolidates the fibres and plies, pushing the trapped air towards the edges from where they are removed as panel scrap edges.

The major set-back that GLARE development faced, was with regard to maximum achievable panel dimensions. The maximum Aluminium stock width available, is 1524[mm] as opposed to a typical fuselage panel dimension of 12000[mm]$*$3000[mm]. The mismatch in sizes resulted in expensive joints, as large number of small parts needed to be joined together. This issue was solved by introducing the concept of splicing (overlapping Aluminium sheets with a film of adhesive in between, Figure 2.3). Doing so removed sheet width dependency leaving only restrictions placed by dimensions of autoclave[6, 8]. In addition to solving dimensioning issues, splicing also resulted in reductions in manufacturing cost, as it enabled production of double curved[2] panels without form stretching of sheets.[12, 14].

The ability to tailor local properties and thickness, by design of material layup [15], combined with the capacity to achieve larger panel dimensions, provides GLARE with the benefit of mass customisation. In the world of business, mass customisation is perceived as a competitive edge. Tseng et al. describe mass customisation, as a means to provide customer satisfaction with increasing variety without corresponding increase in cost and lead time[16]. However, this competitive advantage, comes as a highly intricate and time consuming additional task in fuselage design.

Considering short term manufacturing, GLARE, as a material, comes out more expensive than mono-

[2]having different curvatures at different positions of the same part, lead to wrinkling in continuous sheets. This is caused by high stresses on sheet edges.

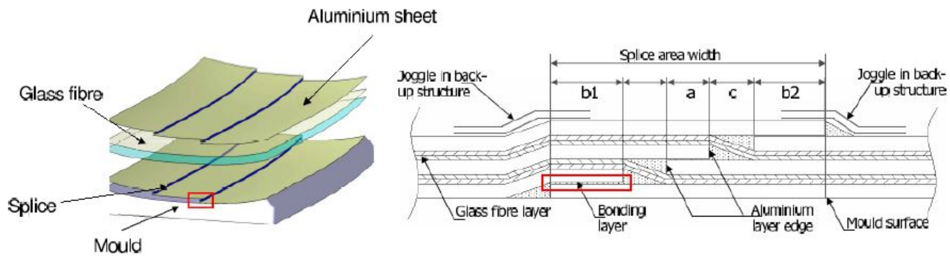


Figure 2.3: GLARE layup and sheet splicing [13]

lithic Aluminium. The major cost of FML components is derived from manufacturing processes and material handling[3], rather than the material cost itself. As design gets more complex in terms of number of layers in material, shape of different layers (can have simple rectangular sheets, but locally shapes can get complex as will be seen later), etc. the amount of man hours required to make it increases. Thus to avoid rising labour cost, it is attempted to keep the layup design simple, requiring little man-hours. For parts with double curvatures a trade off needs to be made at this point by selecting one of the following two techniques:

1. Using preformed sheets[4] for layup, removes edge stress limitation, allowing simple layup with less splices i.e. smaller number of sheets. Doing so reduces weight and man hours. However, pre-forming of sheets, require special tools that contribute to cost[18]. While this cost is non-recurring, there is always debate with regard to benefits that can be reaped. However, this discussion falls under planning and logistics and is out of the scope of this thesis.

2. The second option is to employ more sheets having smaller widths. Doing so keeps the edge stresses in control without investment into special forming equipment. This technique gives a small increase in weight, part-count, and waste. While this is indicative of greater material handling, ignoring controversial planning discussions show lower cost per panel ship set (1 out of n panels of the same kind ordered) than that of panels with preformed sheets.

[3] metal and prepreg sheet cutting (scrap and also shapes), chemical treatment of sheet metal, and placement of in the layup.
[4] Pre-forming is the process where principle of plastic deformation is used to stretch the sheet metal into the desired shape[17]

3

DESIGN PROCESS

As per Kirby "life cycle phases of an aircraft include conceptual, preliminary, detailed design, production, service and retirement". While this is true for nearly all products, the magnitude of time per phase is particularly large for aviation and aerospace products. This is primarily due to the complex nature of comprising subsystems, requiring high levels of multi-disciplinary knowledge sharing in every phase of development[19].

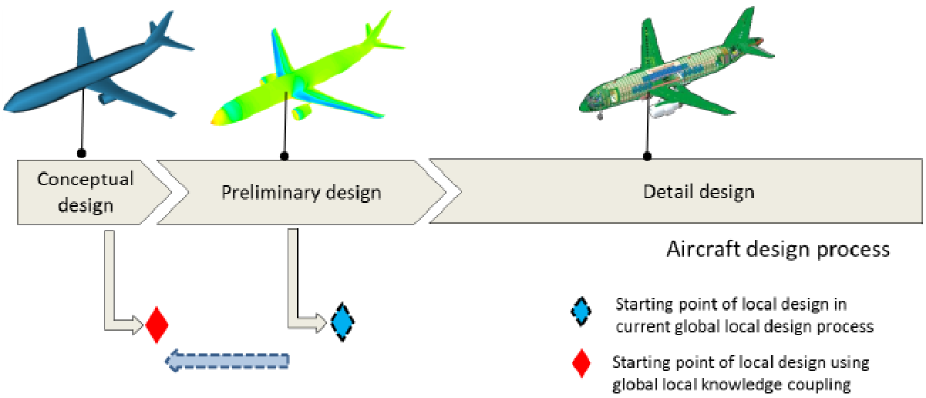


Figure 3.1: Shift obtained in subsystem design starting point by Wang in [20]

The overall aircraft represents a global design[1] and its development can easily span over 6-8 years. The subject of this study however, is much narrower, focusing on local design[2] of fuselage panels, specifically made using GLARE. The conceptual phase of local design begins during preliminary design phase of the overall aircraft. For subsystem suppliers, the main agenda during the conceptual phase is technical marketing to the Original Equipment Manufacturer (OEM), i.e. presenting innovative designs at competitive prices. Wang in 2014 identified the need for "early local design studies" performed by suppliers, and its benefits in reducing the risk of design changes for OEM, increasing supplier competitiveness and capability to cope with changes. He proposed a "global-local knowledge coupling" design approach to enable such studies and allow generation of critical cost-weight results by the supplier, during the conceptual design phase of the overall aircraft. In implementing this approach, he shifted the starting point for subsystem design (Figure 3.1)[20]. Direct impact of Wang's design methodology is seen in the GLARE fuselage panel design process followed at Fokker Aerostructures. Figure 3.2 shows the conceptual design phase split into pre-proposal and in-proposal with a transition FEM phase in between. The image, in addition to describing general design phases, gives details regarding processes followed in individual phases.

[1] Design at system level like an aircraft

[2] Indicates to subsystem or component level design. In an aircraft design of fuselage, wings, tail, etc. are treated as local design along with their corresponding subsystems such as panels, laminate, backup structure, etc.

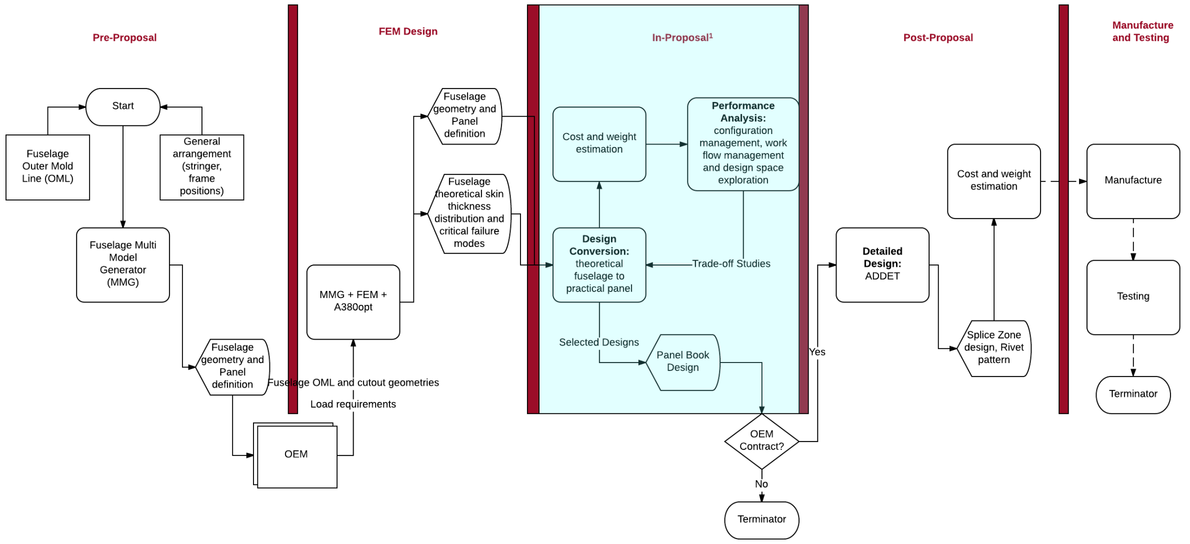


Figure 3.2: Process flow of design and development of GLARE fuselage panels

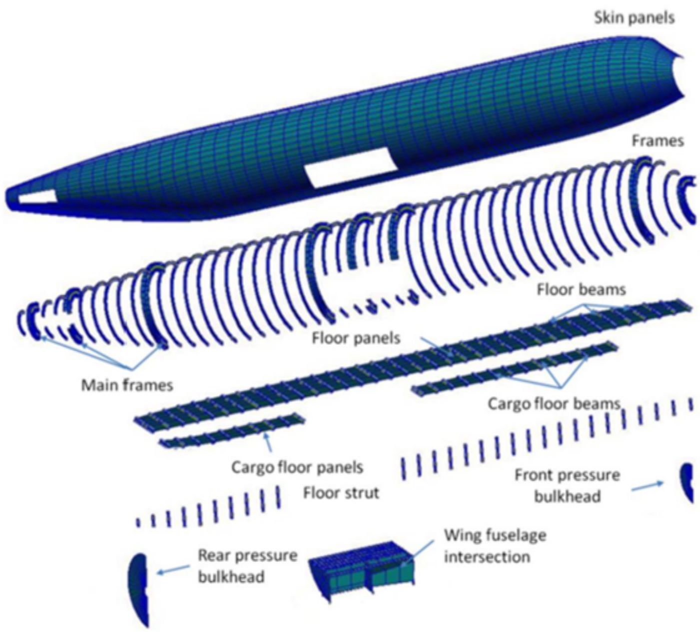


Figure 3.3: Structural members that are included in the design generated from MMG [20]

3.1. PRE-PROPOSAL DESIGN

This phase is usually a part of the front loading methodology[3]. At this point engineers, make simple assumptions based on market trends to generate multiple aircraft geometries. These geometries take into consideration various structural members(Figure 3.3) of fuselage, and are used to perform panelisation[4] (Figure 3.4). Suitable only for a conceptual level design, these panel definitions are accompanied by rough cost and weight estimation. Models thus generated, are used to demonstrate Fokker's capabilities to the OEM. As more information becomes available they can be quickly adapted to match the new parameters. Although not depicted in Figure 3.2, this phase may or may not loop with some of the subsequent phases (mostly FEM design only) to generate the desired results. This interaction is dependent on the level of information the supplier wishes

[3]Thomke and Fujimoto define front loading as "a strategy that seeks to improve development performance by shifting the identification and solving of [design] problems to earlier phases of a product development process"[21].

[4]The process of creating panel geometries and definitions on fuselage Outer Mould Lines (OML)

to present.

In line with Wang's proposed solution, Fokker uses an in-house Multi-Model Generator (MMG) to perform this task. Two versions of the MMG have been developed at Fokker. The main drawback of the older version was with respect to user response. While a highly efficient and independent system, it allowed user involvement only at input stage leaving no room for interaction with designer mid process. Should the designer find the output unsatisfactory, the only option available was to change the input and re-run the application. This lack of transparency in workings of the tool gave designers the perception of an unreliable and creatively limited tool. This being so, many designers preferred to perform the task themselves, than spend time learning the tool and checking its outputs to ensure reliability.

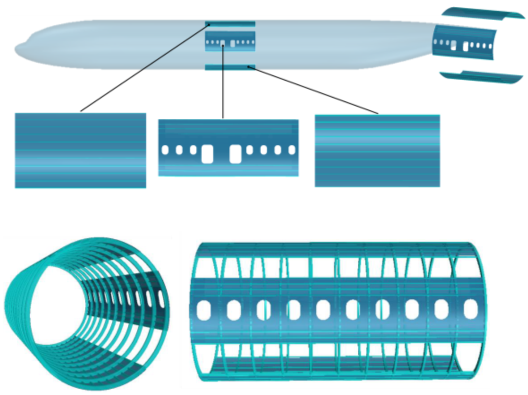


Figure 3.4: Panel definition with back-up structure in a sample aircraft[20]

3.1.1. FEM DESIGN

The Finite Element Method (FEM) design is primarily concerned with sizing of the fuselage skin. To do this, inputs in the form of maximum aircraft loads, FE models of panels, etc. are used to conduct extensive stress analysis. This phase usually starts after a proposal request is made by the OEM. However, depending on the extent of knowledge generation desired under the front loading methodology, it can also be performed earlier using simple assumptions and models. The stress analysis, aid in determining minimum skin thickness distribution, stringer and frame positioning, and sizing (if not already provided). The main idea of this phase is to make an initial estimate of skin thickness and optimise to a skin thickness based on how the skin behaves under loads (from FEM analysis). The skin thickness is considered optimised when reserve factor[5] value is found to be greater than or equal to 1. Like in most optimisation processes, the rate and quality of convergence relies on the initial guess, number of iterations and step size.

When performed manually such an optimisation can be highly time consuming. To overcome this, Fokker uses and in-house tool which employs catalogue files, containing knowledge on different possible skins[6], to assign new theoretical skin thickness based on available knowledge rules. The output thus generated holds thickness information of the fuselage, given per bay[7], with a thickness value and GLARE type (or other material) applied to that bay. Despite the optimality of generated results, thickness distribution often (in all cases till date) proves very expensive to manufacture, if at all possible. This will be further elaborated in coming sections.

3.2. IN-PROPOSAL OR CONCEPTUAL DESIGN PHASE

The thickness distribution from the previous phase acts as input to commence the in-proposal design phase. In certain cases of design studies, this thickness distribution may be provided by the customer. Irrespective of source, focus of this phase is at local laminate design. This includes aspects of laminate build-up, splice

[5]Defined as the ratio of allowable stress in skin element to actual stress in element. Greater the RF value higher the safety margin but also thicker the skin i.e. greater weight contribution

[6]This knowledge includes thickness and material layup based on GLARE type.

[7]Area bounder by two stringer and two frames. Also known as pocket

positioning and splice design.

As stated before, the thickness design from FEM design does not offer feasible manufacture. The main reason behind this is a disregard of the following manufacturing rules:

1. Multiple small thickness steps: having any thickness steps at all, impact the design and manufacturing process. These impacts are:
    - Stringers and frames need to be joggled, for secure fastening, when they pass over a thickness step greater than a minimum value. Typically this minimum thickness if of the order 0.4 [mm]. This value is easily exceeded by addition or removal of a single metal sheet of smallest possible thickness (0.3 [mm])
    - Sheets often require to be cut in shapes to match the thickness pattern. Such shapes would make the sheets susceptible to wrinkling close to edges and add to material handling costs.

    As steps get smaller and more frequent, the above impact tends to magnify.
2. Localized thickness changes: depending upon the aircraft type(single or double aisle, business jet etc.) a bay may signify different physical areas. If the area experiencing thickness change (especially decrease in thickness) is too small, the material handling, waste and stringer/frame joggling outdo the weight savings.
3. Thickness distribution per bay: while such a discretisation is accepted for analysis by a solver, in actual processes, changes are preferred to occur mid bay. This avoids placing stringer or frame over steps and resultant constraints on rivet position.

The above may not be applicable for a distribution provided by the customer. However, it would still be subjected to same principles of splice design, characteristic to GLARE panels design. Typically lasting four weeks, by the end of this phase the aim is to study different design concepts and come up with a winning proposal at a profitable cost.

A concept includes a panel book design, and its corresponding cost and weight performance. A fully feasible design, in terms of customer load requirements and manufacturability, is defined as a panel book design. A complete panel book design accounts for the following:

1. Properties of sheet metal in layup:
    - Sheet thickness's
    - Configuration or direction in which the length is placed: longitudinal/ circumferential.
    - Sheet type(s): flat/ formed
2. GLARE type(s) used in layup
3. Splice design information:
    - Sheet sizes
    - Start and end positions of sheet in panel
    - Splice type i.e. overlap pattern being followed
4. Any critical design features that require extra attention in later stages. Example: sheet ending(s)/ splice(s) occur at unfavourable positions in cut-outs. This needs to be considered properly and adjusted by customisation prior to manufacture, to avoid de lamination.

Unlike previous phases, designers in this phase perform all functions manually without help from automated tools. The reason for this is the nature of tasks that make up this phase. Previous phases, particularly FEM design, are made up of repetitive and calculation intensive tasks. Here need for automation was clearly seen in order to speed up the process and was achieved with development of in-house tools. However, after the first flight of Airbus A380, the freighter version never got built and focus of Fokker moved towards production, temporarily halting development of design process. Recent years have seen a renewed interest in

GLARE fuselage design, and a need for process improvement at the in-proposal phase of design.

Another reason for lack of automation in this phase is the diversity in tasks. This phase sees large variations in inputs, the type of tasks needed to be performed and the solutions that can be offered for each panel. These variation are further elaborated in later chapters along with the reasoning to retain manual efforts.

3.3. POST-PROPOSAL OR DETAILED DESIGN

Provided a contract is secured at the end of the previous phase, detailed design phase commences. It transitions into manufacture and testing with a slight overlap as new challenges tend to constantly come up. In this phase more details of the design are set up, and designers focus on coming up with solutions to overcome any manufacturability challenges that were missed out in previous phases.

One of the important tasks of this phase is rivet positioning. Relying on set rules derived from manufacturing principles[8], the real challenge in designing rivet pattern is the sheer number of focus points and their relative size(similar to one of the challenges in the in-proposal phase). For a typical panel dimensions($3.5 * 12[m^2]$), more than 2400 rivets of different sizes are required to ensure safe fastening.

Automated Detailed Design Tool (ADDET), is a dedicated KBE tool created by Vermeulen in 2007, to avoid painstaking manual effort. It creates rivet patterns and locally modifies splice designs, from proposal, to get least number of intrusive rivets without changing laminate design at panel level. Vermeulen typified the design problem as a Constraint Satisfaction Problem (CSP) and used heuristic techniques to tailor a solution finding algorithm. The algorithm looks for the minimum value of the objective function:

$$f(C,S) = Min \sum cost[C_j(S)]. \tag{3.1}$$

Here, f is the dynamic objective function dependent on hard and soft constraints in C, and solution in S. C_j is the number and type of constraints satisfied/ violated for the given solution[13] .

Currently all the results of previous phases are manually processed and bought into the format acceptable to ADDET. While this manual processing is not as time consuming as manual rivet pattern design, ADDET has not gained much momentum with designers. Like the MMG in pre-proposal phase, this also gave no control to the designer and lacked transparency making the designers sceptical of its use.

[8]Guidelines obtained from extensive testing to ensure secure fastening with minimum number of rivets

4

In-Proposal Phase Design Challenges

Aerospace system/subsystem design pose a complex engineering problem, solution to which is defined using an approach focused on the process. To do so, the current in-proposal phase design process is briefly discussed in this chapter along with its challenges. This is followed by a reasoning for the KBE solution being proposed, and a description of the solution process.

4.1. Process Flow

Figure 4.1a, gives the ideal process flow for creating a proposal. The process can have different starting points depending upon the information provided by OEM (Chapter 3). Baring some extra steps, the customer provided thickness distribution follows the same procedures. Thus, in-house distributions, have been selected for current studies and will be referred to henceforth.

As stated by experts at Fokker[1], despite there being many different possible design concepts per panel, the limited time available at this phase allows for generation and study of one or two concepts per panel. The number of panels to be designed varies from 15-20 for a single aisle, to 25-30 for larger aircraft in the A380 category (double deck, wide body). As time available to create a proposal is largely dictated by the OEM, design process was mapped out to create a methodology that increases productivity.

Comparing the ideal process flow with time values (obtained from previous design experience) in Figure 4.1b for respective processes, it can be seen that time distribution is fairly uneven in practice. While the activity of FEM design already shows a great amount of time efficiency, rest of the activities, particularly creation of panel book design, are fairly intensive and tend to leave no time to conduct trade off studies.

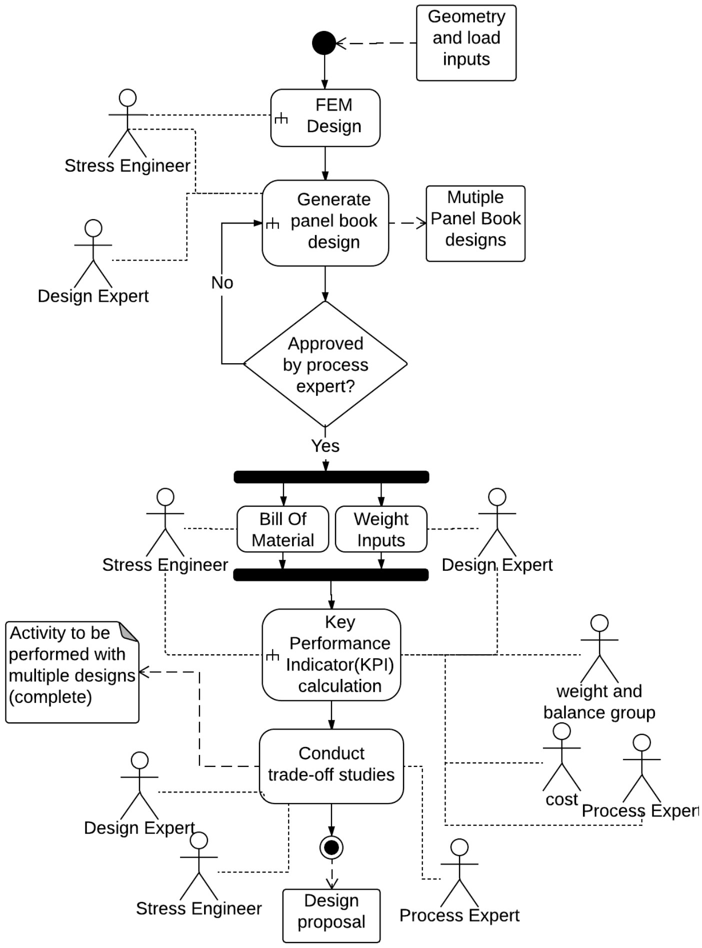
In essence panel book design imparts manufacturability traits, through harmonisation[2] and splicing into the thickness distribution discussed earlier. Figure 4.2, depicts the general process flow and the actual time taken by different tasks. A deeper study of the sub tasks gives a better sense of the time consuming nature of this process.

4.1.1. Resolution Increase

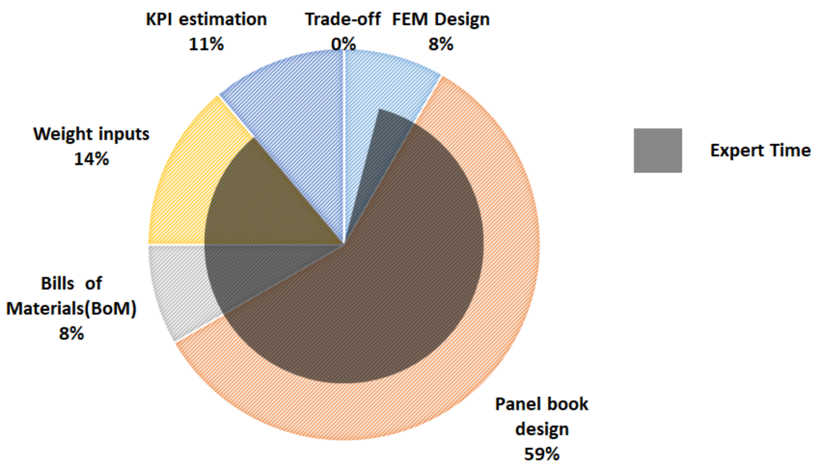
In Figure 4.2a it is seen that resolution increase marks the start of design process. When design is carried out manually, this step proves important for detailing. Thickness sizing in FEM phase is carried out over a fairly coarse grid (defined by bay size), with the assumption that sheet edges are positioned right under backup structure. However, as per design principles, sheet edges are positioned at float value offsets (Figure 4.3) from closest backup structure to avoid uneven surface for datum joining. Increasing grid resolution, in this situation, supplies flexibility to the designer when positioning sheets. Whoever, it has been found often that even a grid with greater resolution, proves too coarse to completely abide by design principles.

[1] Interviews were conducted with design expert, process expert, and stress engineer at Fokker Aerostructures

[2] harmonisation is defined as the process of checking and correcting material be through layup or shape.

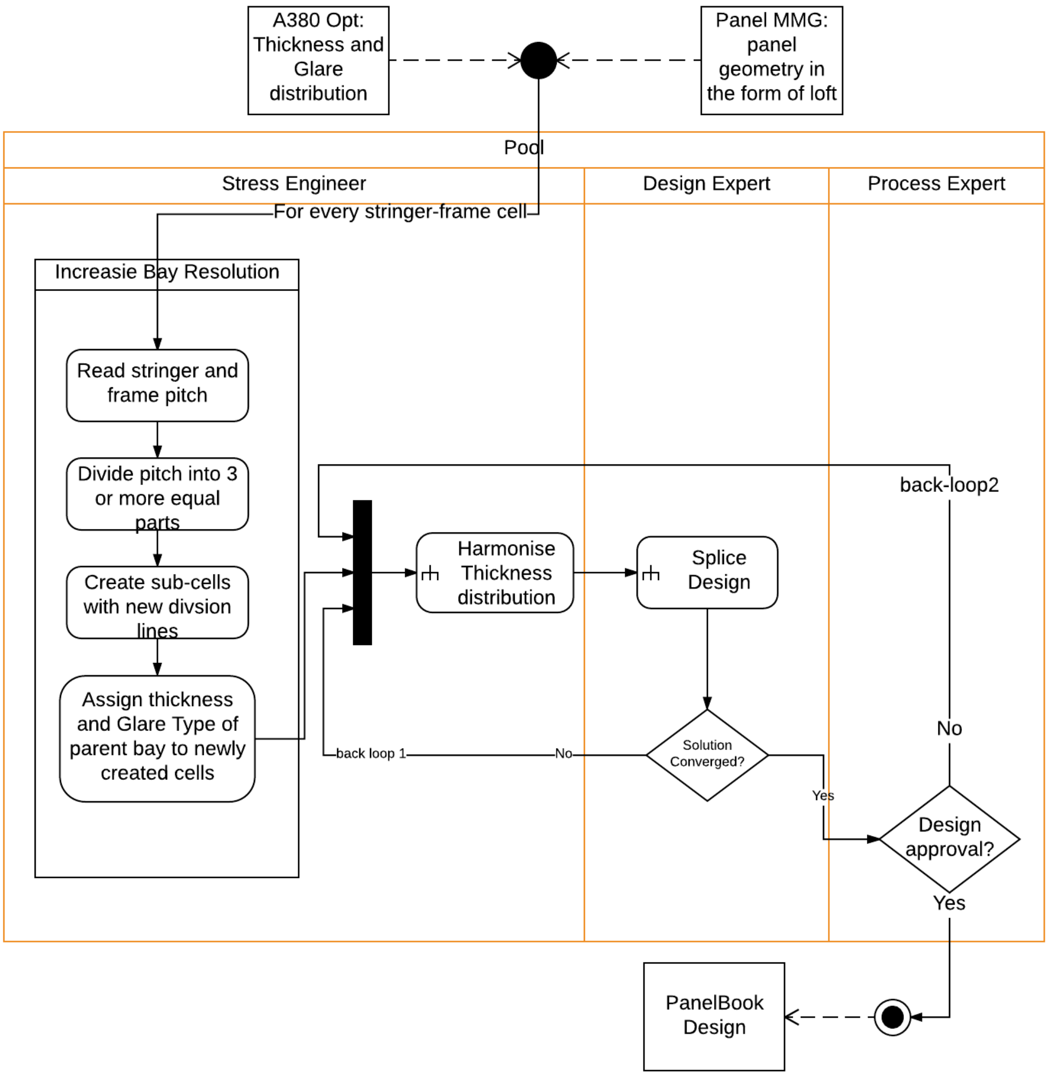


(a) Ideal activity diagram.

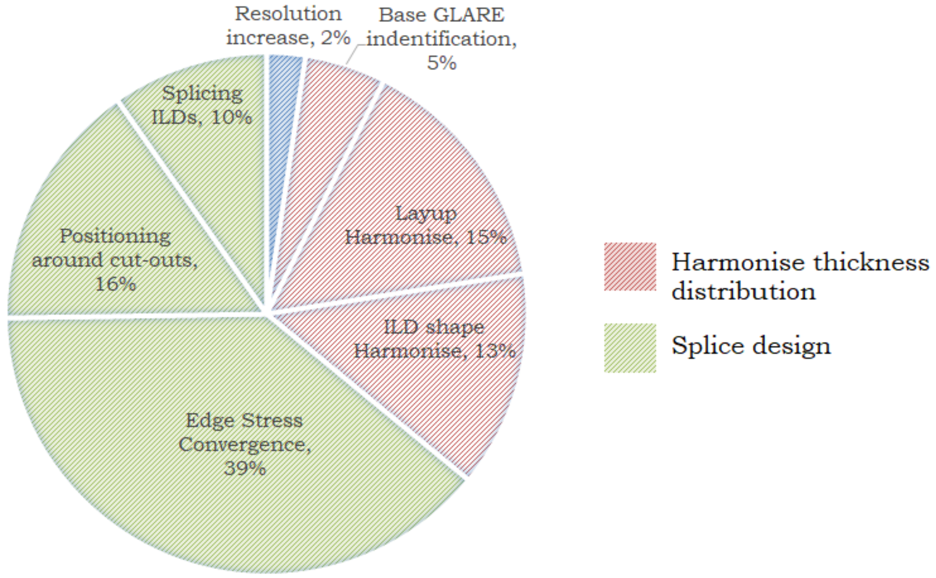


(b) Average time taken(actual) for a set of FML fuselage panels(inclusive of re-work and back loops).

Figure 4.1: In-proposal design process



(a) Activity Diagram.



(b) Average time for a set of panels(inclusive of re-work and back-loops).

Figure 4.2: panel book design process(actual)

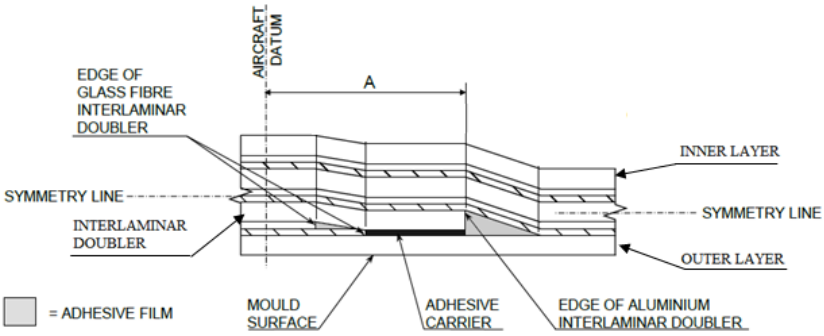


Figure 4.3: Start/ stop of ILD

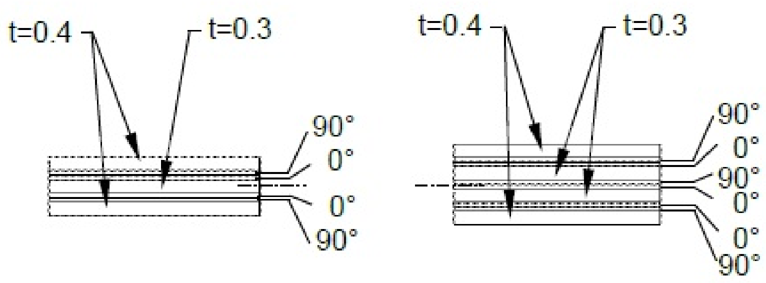


Figure 4.4: Layup symmetry.

4.1.2. HARMONISING THICKNESS DISTRIBUTION

Starting with assignment of base GLARE, an expert usually performs all sub tasks shown in Figure 4.2, iteratively, usually starting with assignment of base GLARE. Base GLARE marks the smallest thickness that can exist over a panel. It serves as base over which all local thickness' are built up and also sets the standards for symmetry (Figure 4.4). Often the smallest thickness assigned in the FEM phase is selected as the base GLARE. However, this is not always beneficial. Following are some cases where selection of thinnest base can be counter productive:

- Smallest thickness exists over a very small portion of panel: this creates unnecessary steps in laminate.
- The layup of smallest thickness, forces a significant number of bay skins to jump to higher thickness' in order to meet symmetry.

4.1.3. ILD SHAPE HARMONISATION

Within the scope of current studies, no clear rules could be identified for this step. Different techniques (logical in themselves) have been known to be used for different panels. Thus, for the extent of this thesis, ILD shape harmonisation, step has been treated as purely creative. A small study to show the importance of this process has been presented in Figure 4.5 and Table 4.1[3].

Ranking of different Shape harmonisation in the table depict the importance of testing and trade-off in determining which harmonisation suits best. Further, shapes depicted in Figure 4.5 are only a small sample of the simplest possibilities. More complex shapes can be generated and these would not necessarily lead to a drop in performance.

[3]Back-up structure complexity is based on number of joggles required in both stringers and frames. Material handling is based on number of edges to be cut

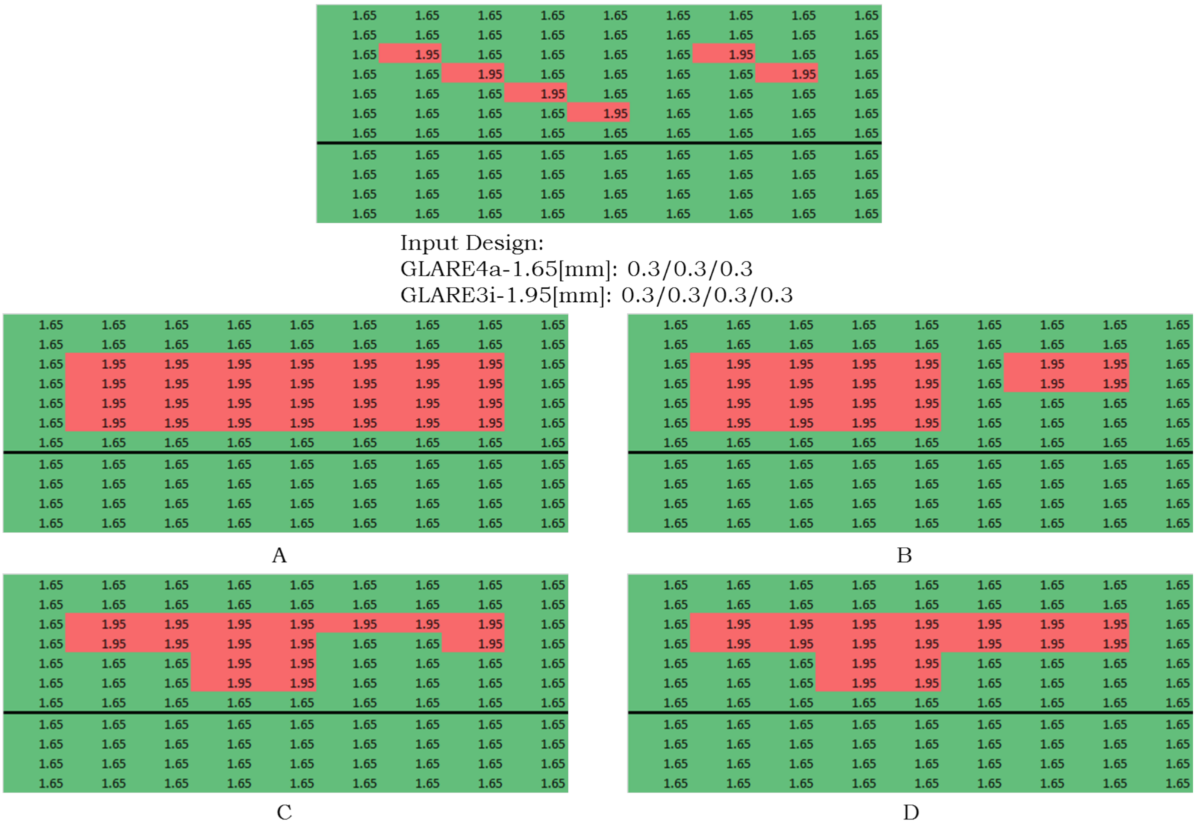


Figure 4.5: Shape harmonisation.

	Absolute Part Count (Base + ILD)	Weight (ranking)	Manufacturing Complexity (ranking)		
			Back-up structure complexity	Wrinkling at sheet edges due to shape	Material Handling
Unharmonised	6+2	1	5	5	5
A	6+1	5	1	1	1
B	6+2	4	5	1	2
C	6+1	2	5	3	4
D	6+1	3	1	2	3

Table 4.1: Ranking of Shape harmonisation from 1(lowest i.e. best) to 5(highest i.e. worst).

4.1.4. Splice Design

As already mentioned in previous section, sheet splicing is essential to achieve desired panel dimensions in lieu of maximum available sheet widths. Thus splice design is directly a function of sheet width at different positions, as this dictates the position where overlap is required.

In Figure 4.2b, it is shown that the maximum time in splice design is consumed in edge stress convergence. However, this particular task is performed only for double curved panels where edge stresses play a role. Here, it sets the maximum sheet width allowed as per position. At Fokker Aerostructures, in-house tools are available to perform the stress calculations, while experts are tasked with creating sheet definitions to fill the panel. While creating sheet definition, expert usually take panel geometry into account, as shown in Figure 4.6. This is done to avoid positioning sheets in such a manner that can be unfavourable during and/or after manufacture.

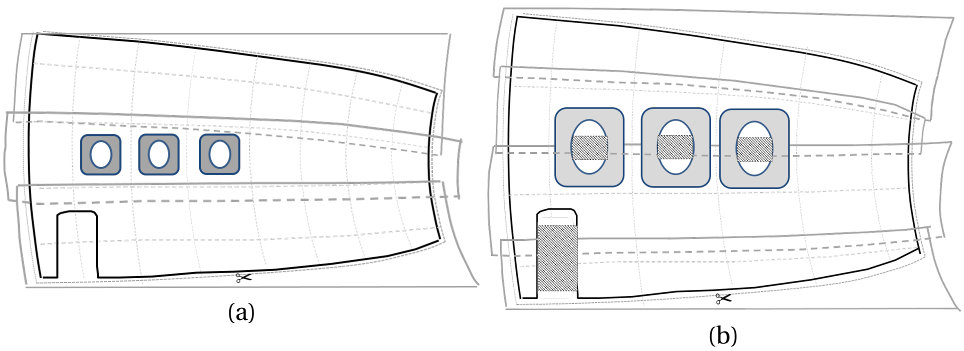


Figure 4.6: Sheet width positioning techniques.

A third function that is performed almost simultaneously is that of Inter Laminar Doubler (ILD) splicing. There are two available techniques to do so:

1. Similar to base layer, they can be spliced as per maximum sheet width and allowed to pass continuous (without any splices) through the base splice. While this may reduce the part count, it results in additional thickness steps at position of ILD splice.

2. The other option is to splice ILD next to base (Figure 4.7). With a small increase to splice width, this techniques of splicing reduces the number of thickness steps over the panel with a possible increase in part count.

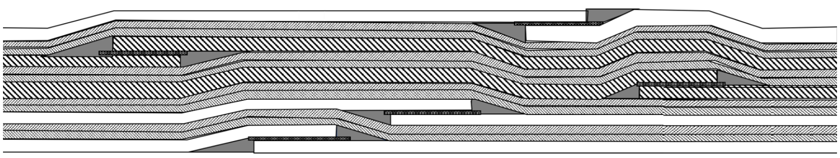


Figure 4.7: ILD spliced adjacent to base splice

4.2. Time Dependence of Panel Book Design

Performed almost simultaneously, all three tasks mentioned so far are repetitive in nature. Having studied the practical process of panel book creation and comparing it to the information presented in Figure 4.2 and 4.1, the following reasons can be extracted for the lag experienced here:

1. Number of actors: the in-proposal phase composed of a specialised set of tasks is performed by the same actors, whose expertise are required for different activities throughout the phase. While increasing the number of actors could be one solution, doing so would require improvements to knowledge sharing infrastructure, and may lead to inefficiencies.

2. Looped and iterative sub-activities: most activities and sub-activities are iterative in nature, requiring back-loops and rework for information generation.

3. Preparation time: literature research and study of the designers activity flow, yield that an approximate of 20% of expert time is spent on searching and absorbing information[22].

Keeping the above points in mind, a knowledge based solution is proposed that frees up expert time, by automating (partially/fully) their task.

4.3. KNOWLEDGE BASED ENGINEERING

Knowledge Based Engineering (KBE), has had many different and exhaustive definitions, depending on the customer. La Rocca defines KBE as "a technology based on dedicated software tools called KBE systems, that are able to capture and systematically re-use product and process engineering knowledge"[23]. Through automation of non-creative and repetitive tasks in the process of product development, and support to multidisciplinary design optimisation, KBE aims to deliver products in reduced time and cost[24]. Further, it frees experts to engage their creative and engineering skills elsewhere[25]. Apart from the benefits that KBE has to offer in immediate product development, it also shows long term promise as a knowledge repository. Knowledge once captured and stored, can easily be accessed, re-used, shared and updated with every new project reducing the risk of loss.

4.4. REQUIREMENTS OF TOOLS

Following are the requirements from a tool that aids design:

1. Robust with the capacity to handle diverse panel geometries, from different positions on fuselage and also for different fuselage designs altogether.

2. Reduces the time spent by experts on generating the design.

3. Increases design capacity i.e. number of designs generated per hour.

4. Quality and level of detail in final proposal must be comparable to those generated manually by designers.

5. Modules of the tool should be capable of supporting an optimisation process.

6. Tool must be easy to update, transparent, user friendly and intuitive for experts in order to encourage usage and increase confidence in results.

Performance of the tool w.r.t. above requirements is measured in later sections, using multiple test panels.

5

Solution Finding Process

In an effort to improve efficiency - quality of design process, and level of details in design, modifications are made to the process itself. This modified process has been captured using a KBE application called PANADEE-II. The most significant process changes are given below:

5.1. Resolution Increase

The importance of resolution increase to the quality of a manual process has already been established. PANADEE-II however, performs design with greater detail right from the start. Despite reading input information per bay, it uses knowledge rules to offset sheet edges from the bounding datum lines(defined in input file).

5.2. Solution Space Search

To push the boundaries of searched solution space, designs are generated and tested for all possible combinations of identified control parameters. Control Parameter typically represent certain user defined hard constraints that limit the available solution space and define aspects of the solution finding process. These have been selected as user defined control parameters rather than design variables for the tools, as they have discrete on/off values. In the conceptual design of FML fuselage panels, the control parameters are given as follows:

5.2.1. Base Glare

In an effort to find the least intrusive base thickness, all values existing over panel are tested as base glare. Impact of the base layup on other layups existing on panel is measured in terms of estimated laminate weight. It should be noted the the shape of local thickness' is still unharmonised.

5.2.2. Splice orientation

Commonly referred to as roof tile splicing or splice dakpan (dutch word to describe the roof-tile pattern), it signifies the pattern of sheet layup. Typically the metal sheets follow the roof-tile pattern, wherein the sheets coming from the crown/top-line overlaps the sheet going towards the belly/bottom-line, on the outer side of fuselage. As in the case of roof tiles from houses, the intention is to avoid moisture accumulation. However, the current splice designs have overcome this problem all-together, and the possibility to reverse the overlap pattern(in the entire panel) is available.

While reversing splice orientation has no significant impact on sheet width, it might help in avoiding minor interaction with cut-outs that lead to insertion of additional sheets for flattening (Figure 5.1). Further, having both orientations for same sheet width combination might prove useful in the detailed design phase wherein rivets pattern is designed, and studied for interaction with back-up structure and laminate.

5.2.3. Sheet preforming

Applicable only to double curved panels, it uses true/ false value for this control parameter to create designs with both sheet types. For single curved panels, or double curved panels that display very small edge stresses

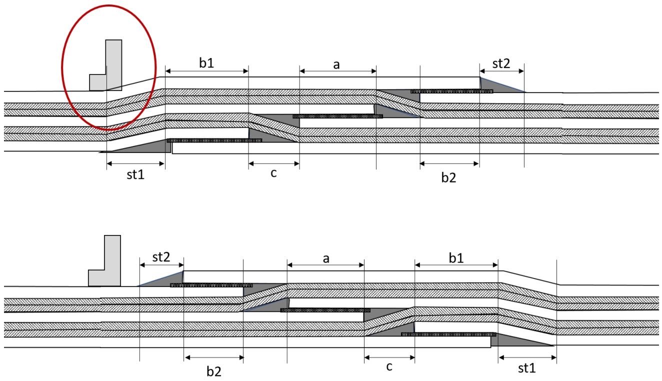


Figure 5.1: Impact of splice orientation on interaction between laminate and backup structure

even at full usable stock width, only flat sheets are tested.

5.2.4. ILD SPLICING

As already mentioned there are two techniques that can be employed for ILD splicing. This control parameter uses true/ false values to test both. Independent ILD splicing is skipped only if one or more of the following conditions are met. Note that dependent splicing will also be skipped if either one of the first two conditions is met:

1. No ILDs exist.

2. Maximum ILD width(s) are within the allowable thus do not need splicing.

3. All ILDs extend over full panel width, essentially coming adjacent to base even at maximum sheet width.

5.3. SPLITTING PROCESS OF PANEL BOOK DESIGN

To fuel a time efficient solution space search, the panel book design process has been divided into two automated phases separated by a manual phase. Both the automated phases are followed by designer supported trade-off studies. While both utilise the same modules, their solution space is modified by different sets of control parameters (Figure 5.2). Re-use of computational knowledge within and amongst these phases, lead to a reduction in the average time spent per concept. Further, the first automated phase gives a general indication of the possible solution space and is performed only once. The manual and second automated phase can be performed (does not have to be) multiple times in an iterative fashion to converge to results in a desired direction.

5.3.1. PRE-HARMONISATION

This phase creates solutions(sheet layups) for all possible combinations of control parameters from a dedicated set (Figure 5.2). Studies performed during literature research, showed that as splice size and position are dependent on thickness. ILD shape, on the other hand, is dependent on splice position. Thus, the iterative loops in Figure 4.2a are completely warranted. The tool in its effort to make search extensive, systematically selects different base GLARE thickness'. Accordingly it checks and corrects layup of all thickness distribution, and generates splice position for these. Further in order to avoid back-loop1, the process of shape harmonisation is split and performed after a trade-off from the multiple splice estimates. With positioning of splices, a first estimate of weight and part count can already be made. These are used to carry out the first trade off studies. At this point promising designs (base GLARE and sheet type combinations) are narrowed down and ILD shape harmonisation(s) is performed manually. This design can be fed back in for second round of solution space search wherein design gets detailed out without a drastic change in the part count and weight estimates.

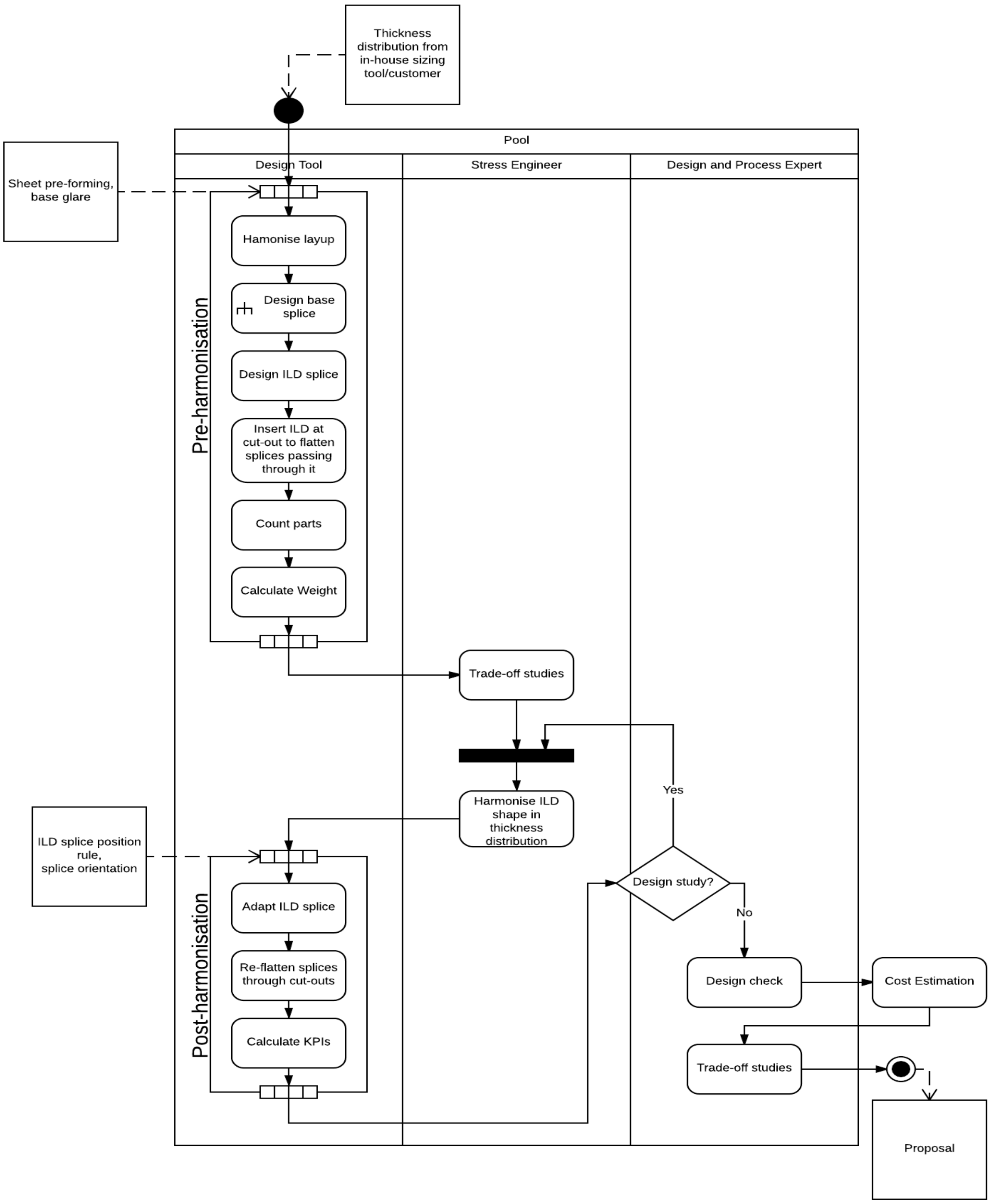


Figure 5.2: Activity diagram representing the modified in-proposal design processes implemented using KBE techniques for automation.

5.3.2. SHAPE HARMONISATION

From studies performed during literature research, it was concluded that from all steps in the in-proposal design phase, creativity played greatest role in harmonising ILD shapes. It was found that harmonisation pattern varies from designer to designer and also with number of iterations carried out by each[14]. As KBE relies on existing knowledge, this step has been left, for now, to be performed manually by experts. However, the accompanying task of layup harmonisation[1] is fully automated in pre-harmonisation (aspects of creative

[1] Ensures all thickness's on panel are symmetric w.r.t. each other

tasks automated to reduce efforts). Additionally, generated output files are equipped to communicate with post harmonisation, with minimum human efforts.

In addition to harmonising ILD shape, this step is also concerned with manual thickness increase at panel edges and cut-out belts. This increase is dependent on extra global level knowledge in the form of:

- Edge thickness of adjacent panels: Edges should be at the same thickness, and as much as possible flatted out for smooth joining. This particularly is true for the edges that form parts of a butt joint.
- Available window frame sizes: Typically, a few different sizes of window frames[2] are made available for a single fuselage. This is done to allow use of window frames that compliment panel thickness i.e keeps laminate weight in check without blowing up assembly costs from using a different frame at every window.

In view of the extra information not available to the tool, this task has been left up to the designer.

5.3.3. POST-HARMONISATION

This phase is concerned with adapting the previously generated splice design to the newly harmonised thickness distribution (from shape harmonisation), and test combinations from a different set of control parameters (Figure 5.2). Reusing most information, it safely skips heavy edge stress computations and proceeds straight to adjusting width around cut-outs (if any). Adaptation of splices around cut-outs have been retained to accommodate any layup changes that the experts might have made in the previous step. At the end of this phase, detailed output files and Bills of Materials (BoM) are generated that allow for next steps (cost calculation and developing of weight calculation to account for extra details) without further lag. This phase also generates plots, similar to previous phase. These plots can be imparted with additional cost values, to enable informed comparison in double curved panels.

A visual analysis of the above plots give a quick indication of the best performing shape harmonisations. Traits from these can be combined and tested in an effort to manually optimise in a desired direction. In essence back-loop 2 from Figure 4.2a, may still occur. However, with a general solution space search already conducted, the amount of work to be performed is reduced to local design tweaking on part of the designer.

5.3.4. BENEFITS OF MAPPING COST AND WEIGHT/SOLUTION SPACE

At this point, the question can be raised, as to why efforts should be put into mapping the solution space. Following are some of the direct benefits of mapping:

1. It gives an indicative of where one can move(manually optimise to) with the design along with the cost and/or weight benefit/penalty.
2. Having a map of the available solution space increases confidence in the design selected, both for designer and customer.
3. In-case of changes in design requirements, knowledge of solution space can quickly allow design modifications with little or no effort.
4. Cluster identification and analysis of these points, can be use to identify characteristic traits of panel and help modify design(s) to desired performance.

[2]Window frame size indicates the flat skin thickness that is require underneath, to ensure secure fastening/ bonding. Flatness ensures that the frame is bonded/ fastened evenly and the thickness is primarily to accommodate fastener height.

6

Solution Algorithm Based on Expert Knowledge

Using heuristic techniques, the solution finding process is simplified to find near optimal solutions in a short time span[13]. The solution process uses bounded sheet width (of every individual sheet in layup)[1] as design variable, and uses trial and error[26] approach to find solution for two Constraint Satisfaction Problems. The trial and error technique employed, assumes a solution/design and uses quantified errors(extent of constraint(s) violated) to determine a new solution. This step is repeated till a maximum sheet width solution is reached, wherein either all constraints are satisfied (i.e objective is met) or maximum number of iterations is reached.

The first CSP is performed only for double curved panels. The objective is to look for maximum sheet width design that fully satisfies the following, hard, constraint:

"Absolute edges stress value for every sheet should be less than/equal to the maximum allowable edge stress value, as agreed with process expert(refer Chapter 2). This constraint is applicable only for a double curved panel and holds no weight-age in single curved panels. For single curved panels maximum allowable widths(stock-scrap) is safely assumed to be the solution."

Results from the first CSP, act as the first assumed solution for the second CSP. Here, the objective is again to find the maximum sheet width solution, however the constraint changes to:

"Minimising(ideally zero) number of inner and outermost sheets being spliced in cut-out zone A (Section 6.3.1), irrespective of cut-out type."

While the process looks to fully satisfy above constraint, unlike the previous CSP, it is bound by a maximum number of iterations. In-case the maximum number of iterations is met before constraint is satisfied, solution with least error is selected.

6.1. Structure of PANADEE -II

The tools holds procedural design knowledge within it's modules. This knowledge enables it to create design for any panel made of layered materials. Different modules of the tool are representative of different panel components and perform function(s) relevant to the component they represent. Figure 6.1 gives structure of the tool and relations between it's different modules. To expand the tool's scope to different designs, configuration(circumferential and mixed)[2] or even material(provide relevant catalogues), new modules can be linked to the designer package.

[1] Lower bound is the largest pitch length in direction of edge to be spliced(stringer pitch if longitudinal) and an upper bound of maximum available stock width(including scrap edges).

[2] Currently designs created by the tool use only longitudinal splice configuration. Being the more dominant and commonly used splice setting, it was selected to answer the research questions within the set duration of 9 months.

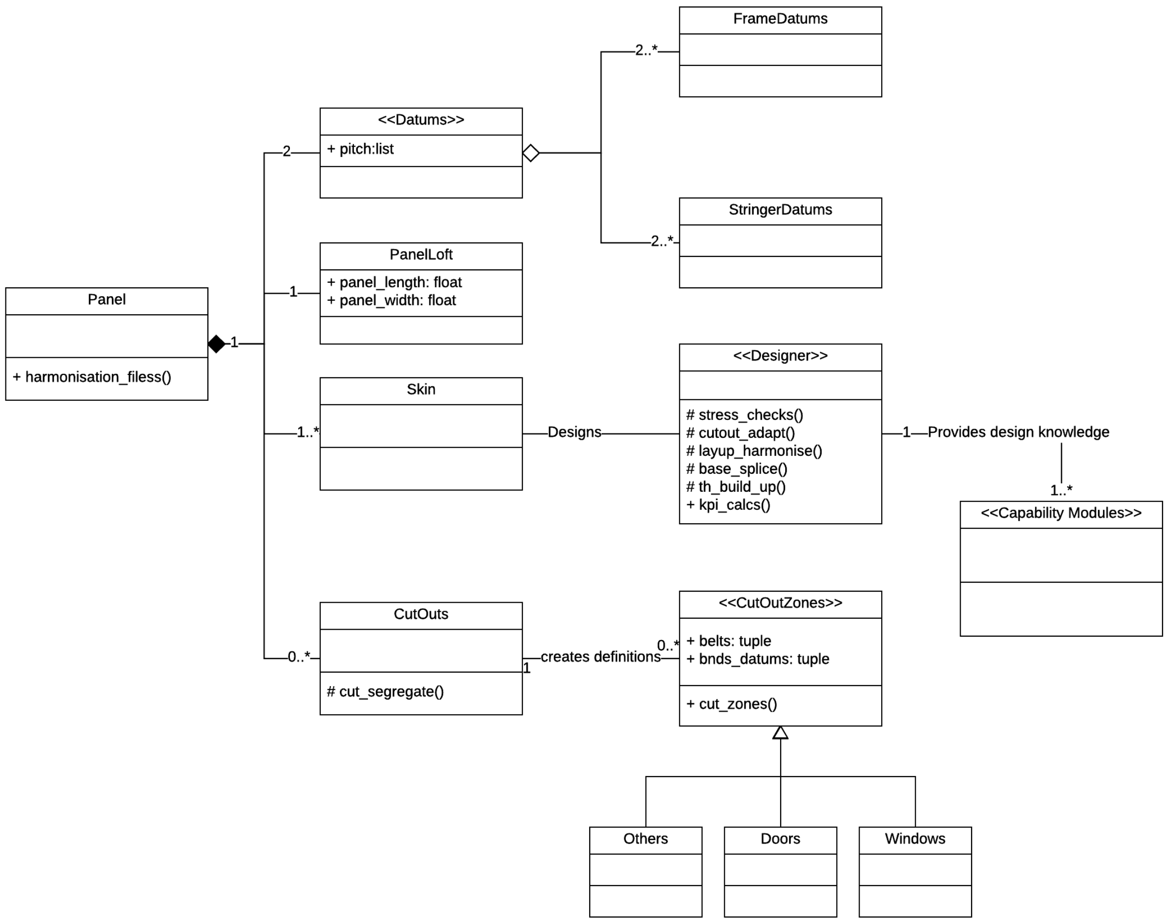


Figure 6.1: UML: Structure of design tool and relation between its different modules

A manual of the tool, containing detailed information on the different modules and their workings, is available at Fokker Aerostructures. Information is stored under different categories to allow easy and intuitive access. Figure 6.2, gives the index page of the manual for PANADEE-II. Here it can be seen that all scripts that an end user can interact with are stored at the very first level. This is to help new users, unfamiliar with python, to find their way. Further, the sub packages have three categories:

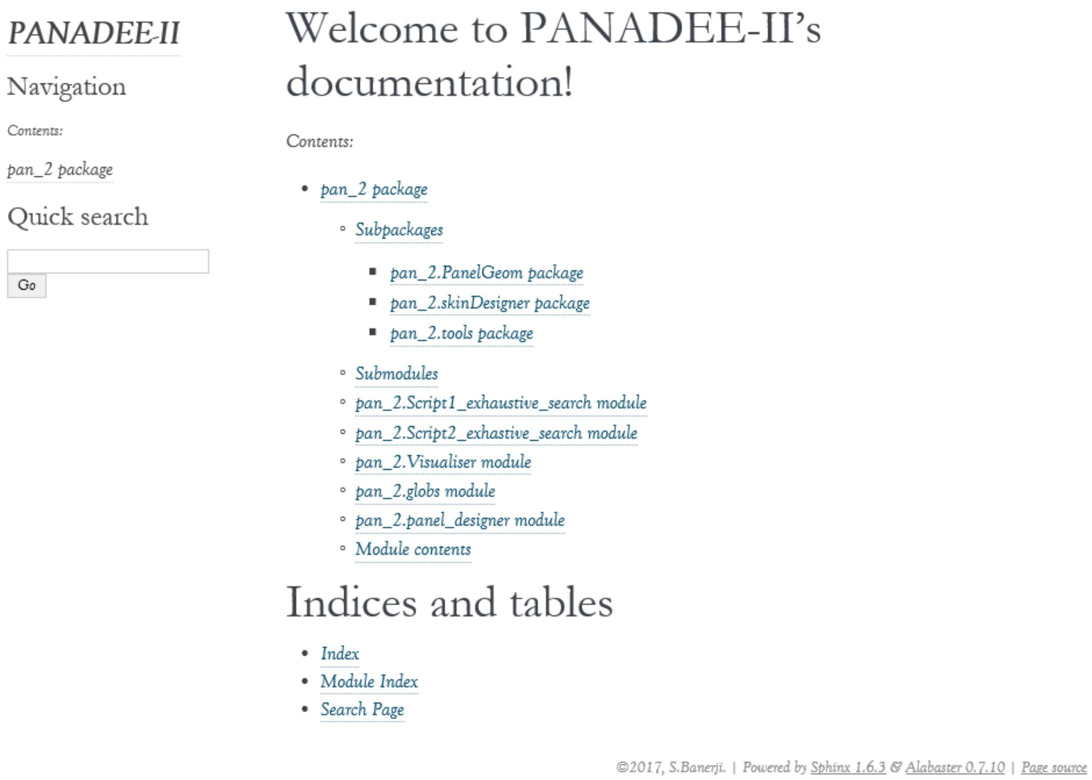
1. PanelGeom: This contains modules that deals with inputs. Here, all components of a panel(loft, stringers, frames and cut-outs) and the excell thickness distribution is read and processed to generate essential geometry information.

2. SkinDesiner: This is the major working packages, containing all modules that are directly employed for skin/laminate design.

3. Tools: It is a general package containing all functions that find use in different packages throughout the tool. These tools are fairly broad in their working and can be applied to general components as well.

6.2. PRODUCT MODEL

PANADEE-II takes in first skin thickness distribution and panel geometry in the form of IGES files. It analyses the loft, frames, and stringers from the geometry information, to set and orient itself. Figure 6.3, shows how the tool orients itself based the set control parameters and splice configuration. For a longitudinal splice configuration with roof tile splicing, it selects the longest width curve for splicing. Further, it sets the direction vector of this curve, such that its starting point is closest to the first stringer. If the splice orientation is inverted, the direction vector of edge to be spliced, reverses to have its start point closest to last stringer. The same applies to frames in case of circumferential splice configuration. Note, currently the tool works only for longitudinal splice, but has been designed to allow easy linking of a module for circumferential splice design.



PANADEE-II

Navigation

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pan_2 package

Quick search

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Welcome to PANADEE-II's documentation!

Contents:

Indices and tables

- *Index*
- *Module Index*
- *Search Page*

Figure 6.2: Index from PANADEE-II manual.

Orientation of the tool indicates the starting position for sheet layup. The first sheets(prior to any edge or cut-out checks) are always placed along the edges closest to starting point of splice edge. From here it proceeds towards the end. Sheet widths, throughout the panel, are attempted to be kept at maximum available. Any smaller widths are kept to the latter sheets, and the excess from these act as free margin[3] for movement.

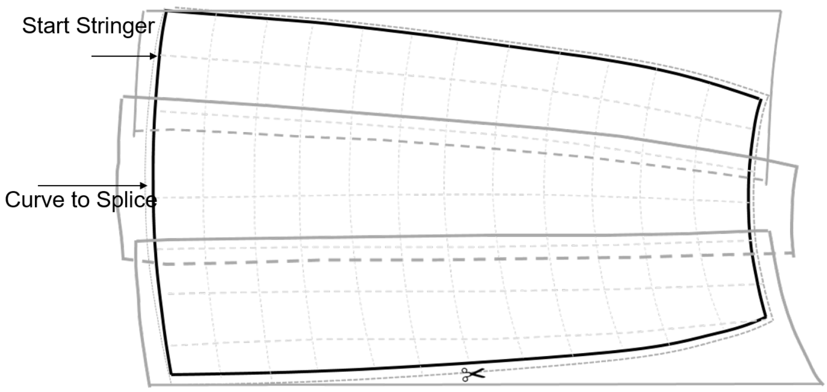


Figure 6.3: Orientation set in tool for longitudinal splice configuration with roof tile splicing

The tool has been equipped with a Graphical User Interface(GUI) that allows generating, examining, and modifying designs in real time. By providing concept information, generated after the two automated phases

[3] Amount of width change that can be made to one or more sheets without insertion of an all new sheet

(Chapter 5), heavy re-computation can be avoided in visualisation. Figure 6.4 shows a product model generated by the tool. The product tree contains information regarding the different parts of a panel. All parts, apart from the skin, have pre-defined information derived from inputs fed. These can be modified to a limited extent to solve any discrepancies that may arise. The skin, being the part that is modelled, can be viewed in the geometry and shows much more flexibility, allowing wide scale design modifications to be made.

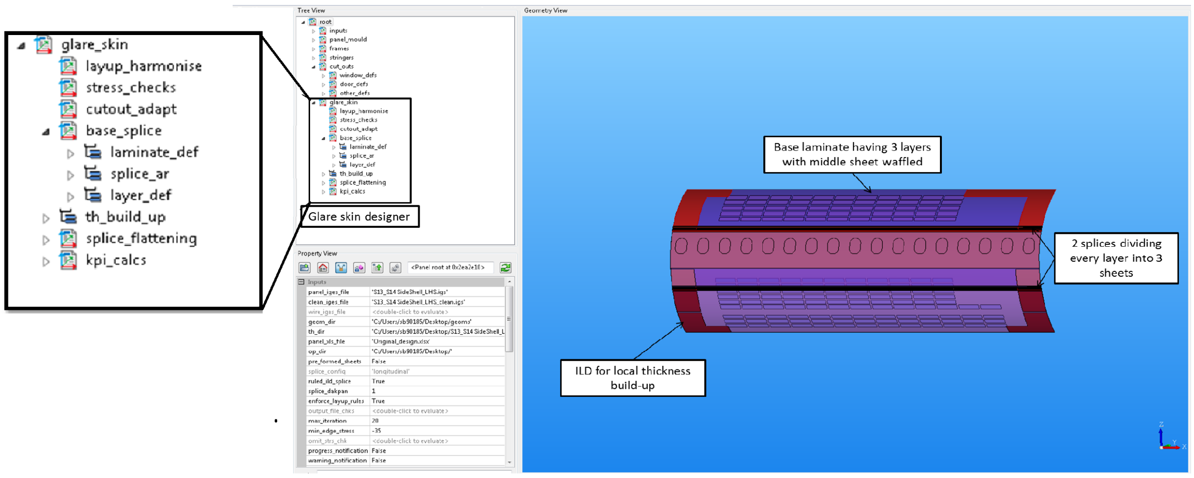


Figure 6.4: Product model

6.3. KNOWLEDGE IMPLEMENTATION

6.3.1. BASE SPLICE DESIGN

The design of base splice(s) in Figure 6.5, is a crucial step that influences the entire outcome. It follows a set of guidelines mentioned in the design principles and is not a creative task in-itself. However, intricate nature of this task contribute to the time and effort it takes for creation. Laminate design is concerned with a [mm] scale for panels with dimensions in[m]. This section briefly describes the current methods used and their limitations. It then proceeds to describe how the problem is tackled by the tool.

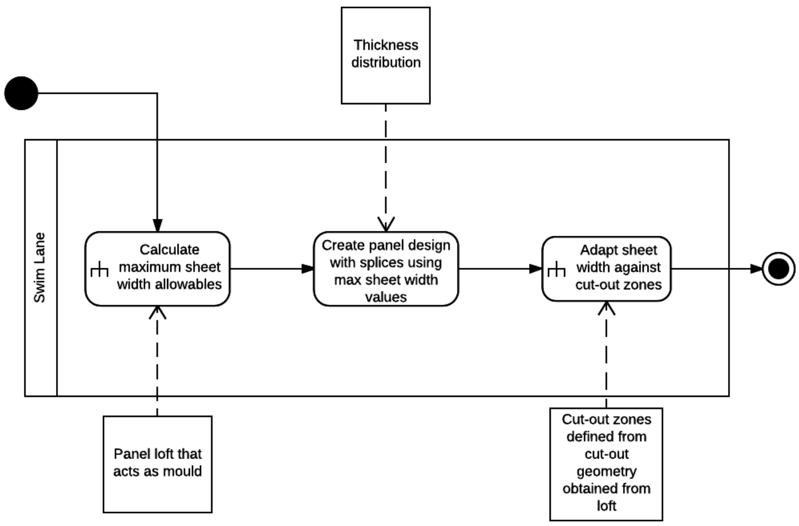


Figure 6.5: Activity diagram: Process followed by design tool to create base splice designs.

MAXIMUM SHEET WIDTH

As already mentioned, the upper bound varies depending on curvature. For double curved panels, designers perform multiple iterations, using computation tool, till edge stresses are brought within allowable. Following are the major drawbacks that this process sees when performed manually:

- Though crucial, it does not explicitly require designer expertise. Thus, it engages designer for a fair amount of time without needing to.

- Experts mostly tend to draw from their experience, for quick convergence to acceptable values. Though this reduces the number of iterations, it provides no incentive, in a time restricted process, to search for greater - maximum width values, to be used safely without violating edge stress allowable.

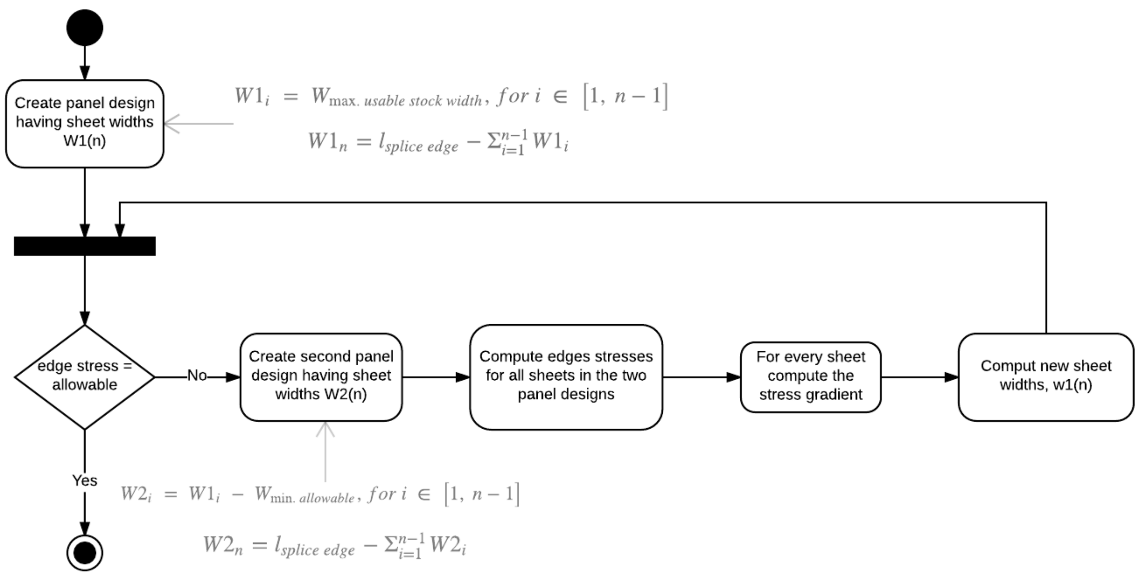


Figure 6.6: Activity diagram: Automated process to modify sheet width upper bound for a double curved panel

POSITION SPLICE AGAINST CUT-OUTS

Another time consuming-intricate task, is of positioning splices around cut-outs. In practise, designers tend to place the first sheet around cut-outs, or, if sheet width is too small, within zone B of cut-out. Then the remaining sheets are inserted. This again has the consequence of limited sheet capacity usage. Further, this is often performed adjacent to edge stress checks and influences the range width(s) tested.

The method implemented in PANADEE-II first inserts all sheets from the first stringer/frame to last, using them to their full capacity. After checking sheets for unfavourable interactions, widths are modified to fit the need(Figure 6.7). Figure 6.8 presents working of the design loop. This loop is followed till either all splices are clear of Zone A, or till maximum number of iterations is met(which ever comes first).

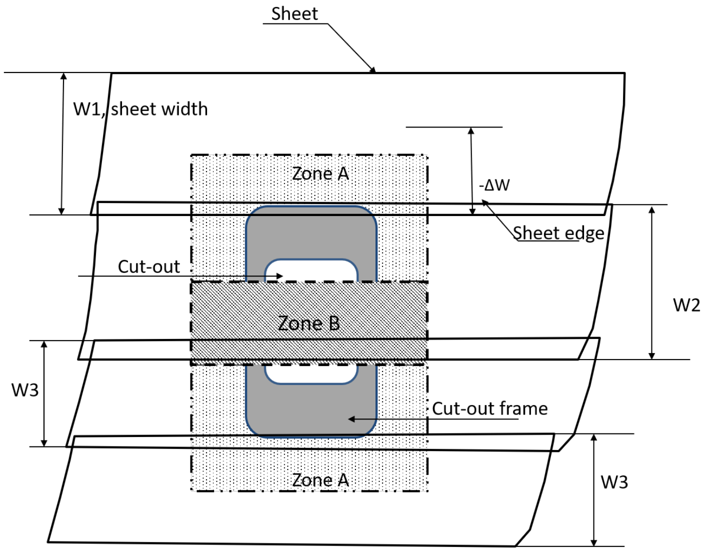


Figure 6.7: Unfavourable interactions with cut-outs and required correction to avoid it(Note: image has been exaggerated for clarity)

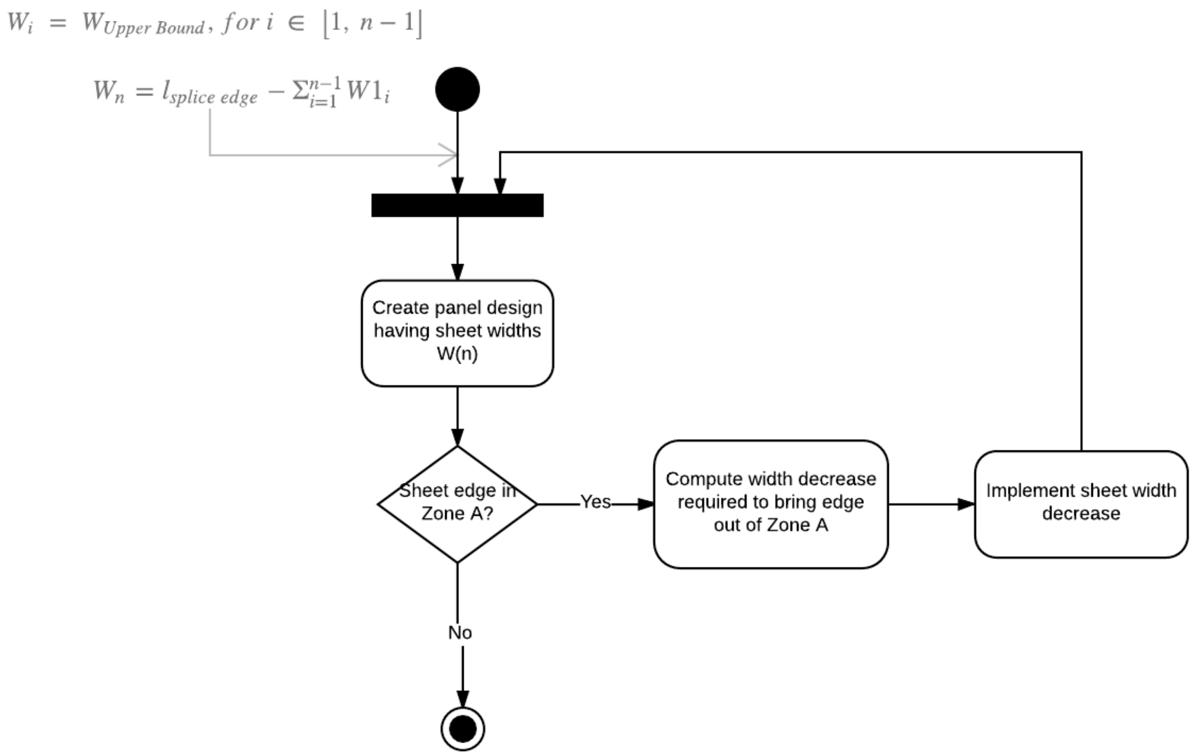


Figure 6.8: Activity diagram: Change in sheet width to avoid unfavourable interactions with cut-outs

6.3.2. KEY PERFORMANCE INDICATORS

In generating layup design(s), the tool holds detailed, and fairly accurate, information regarding the sheets being inserted. These can used to find values for the following Key Performance Indicators (KPI):

WEIGHT

It uses a standard density relation[4], to accurately estimate laminate contribution to panel weight. This weight is by no means the final weight, as it does not account for backup structures, fastener, primer, paint, etc.

PART COUNT

It indicates the number of independent sheet metals in the laminate. This number gives a fair indication of manufacturing costs. This is particularly true for single curved or flat sheet panels, as they require no non-recurring cost for the sheet forming tool.

This part count estimation by the tool is very accurate, it accounts for the smallest of independent pieces, even for the initial infeasible thickness distribution.

COST

The tool generates accurate Bills of Materials (BoM). These are input files that were originally created by experts to be passed on to the relevant department for cost calculation. However, for the purpose of this study, a rough cost estimation model has been made available within the BoM template. This model uses standard factors and part count to project rough cost figures. This cost should be treated as indicative and not accurate projections.

MARGIN

This is an indicator of how change or movement in splice position can be made, before a new sheet needs to inserted into the panel. If a new sheet is added, previous widths maybe decreased to ensure that its width is above minimum and this sheet provides the new margin.

[4] $mass = \rho * Volume$

7

Results and Discussion

Influence of changes made to the design process have been tested over three panels. These panels vary in geometry, position, and complexity and have been previously designed using the manual process. In following sections, the newly created designs are studied in detail, to understand implications of the implemented methodology. For every test panel, the data generated after the two automated stages are presented and their significance to the design process is explained. It should be noted that data in all cost weight plots have been normalised using the ideal thickness from the FEM phase and minimum number of sheet splices (pre-formed for double curved).

7.1. Test Panel 1

Test panel 1 presents a double curved top panel with no cut-out (Figure 7.1). The main challenge faced while designing this panel, is of adjusting sheet widths to keep edge stresses in check. Experience shows that an approximate of 90-120[minutes] of expert time is spent on the design of this panel. Information of the designs created for this panel, using the fully manual original process is presented in Table 7.1.

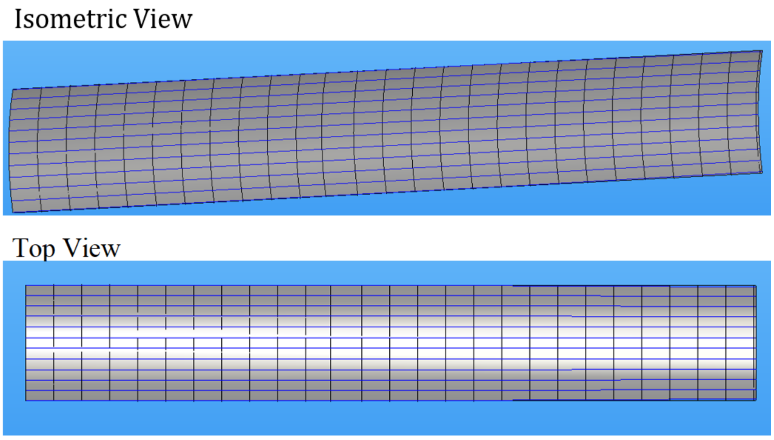


Figure 7.1: Panel Geometry 1.

Design Concept	Sheet Properties	Weight[Kg]	Part Count
1	flat	126	15
2	pre-formed	122	12

Table 7.1: Designs from original manual process for test panel 1.

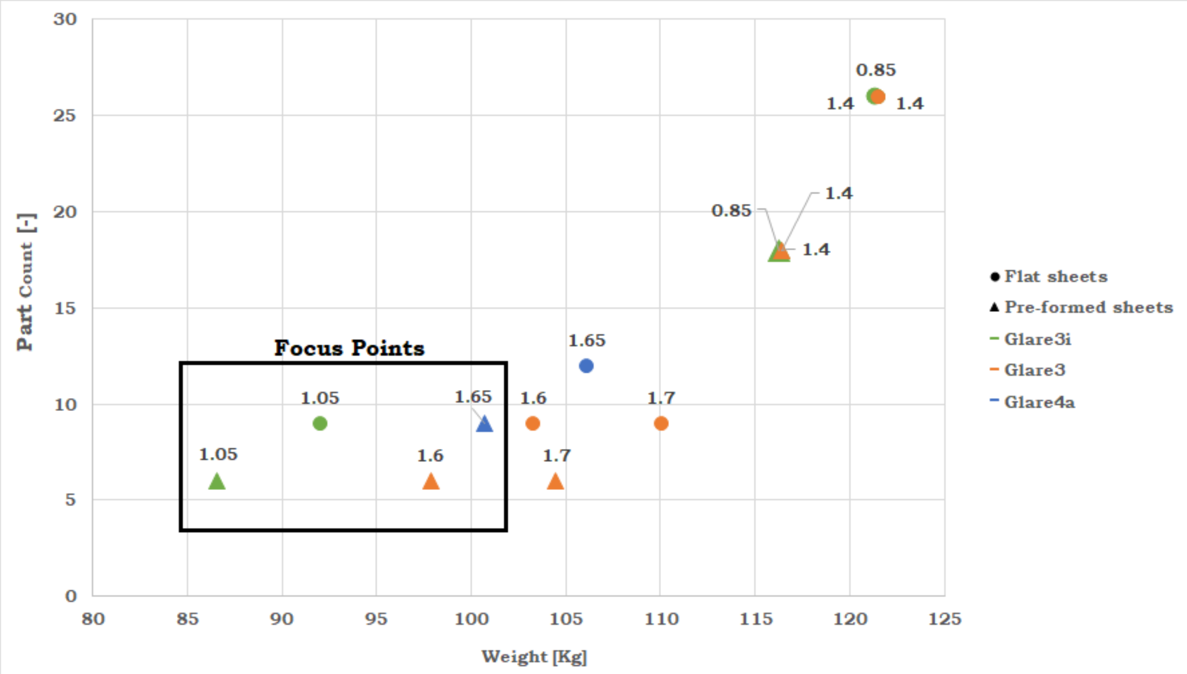


Figure 7.2: Pre-harmonisation output for test panel 1, with focus on concepts selected for shape harmonisation.

7.1.1. Data Plots: Pre-harmonisation

Figure 7.2 gives the preliminary trade-off plot created after an exhaustive search in the pre-harmonisation phase (Chapter 5). All points presented in the plot give out 3 design trait information, in addition to the performance indicator of that design. These traits are: base GLARE type(colour), base GLARE thickness in [mm] (label) and sheet type (symbol). The following can be observed in the pre-harmonisation trade-off plot:

Smaller thickness of base GLARE does not necessarily offer better weight performance. This is most clearly seen for GLARE type 3i[1] with thickness' 0.85 and 1.4 that result in greater weight than other, much thicker base GLARES. Deviation from expected results, is attributed to the increase in local ILD thickness to ensure layup symmetry[27]. This is further confirmed by comparing distribution and layup, in the generated shape harmonisation files with the original thickness distribution.

The focus points, in Figure 7.2, indicate all base GLARE, whose harmonisation files are subjected to shape harmonisation. As already mentioned, this step is manual. The number of concepts generated here, and time taken to do so, is up to expert discretion. In this study 6 different shape harmonisations were created. However, all were not fully manufacturable and were just created to study relative performance. Thus results of these files will not be plotted for trade-off, but their time will be accounted for in total[2].

7.1.2. Data Plots: Post-harmonisation

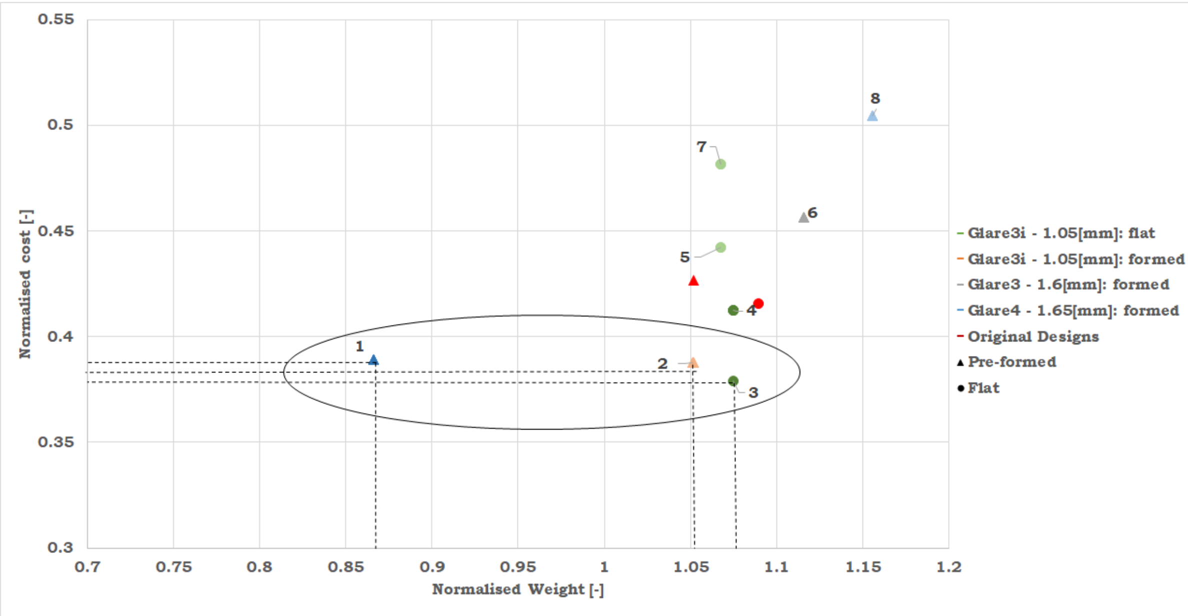
Figure 7.3, gives all manufacturable design performances from post harmonisation. Already for this panel a Pareto front can be seen with design points 1, 2 and 3. However, there might still be room for performance improvement. Manual convergence to near optimal designs is possible, by using these three as starting point for further iterations through shape and post harmonisation phases. Selection of design at this point is circumstantial. It depends on multiple factors such as cost/weight requirements of customer, edge thickness of adjacent panels, and available window frame sizes (provided window belts exist), etc.

In reference to Section 4.1.3, the influence of harmonisation on panel performance can also be seen in design points of above plots. Note that the gradients of same colour indicate different shape harmonisations

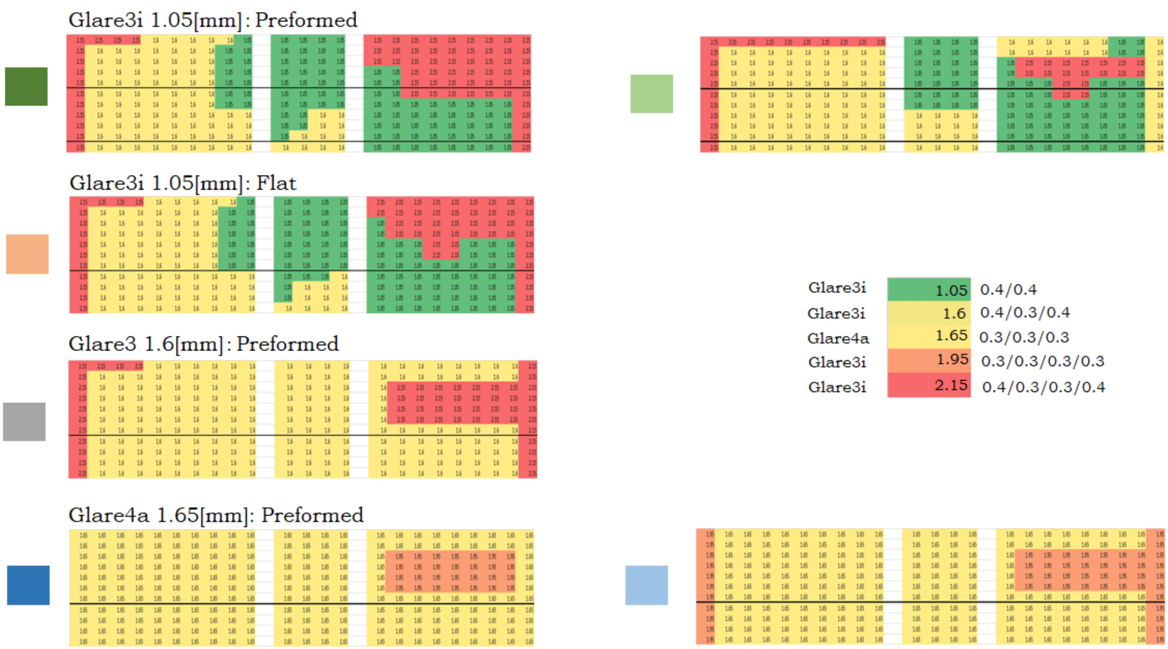
[1] Glare3i is an improved version of Glare3[27].

[2] Such designs might be tested in industry as well wherein they would contribute to actual time spent

for same base GLARE. Figure 7.3b gives the different shape harmonisation tested for different base GLARE designs. Flat sheet designs made from Glare3i 1.05[mm](green marker) and formed sheet design Glare4 1.65[mm](blue marker) have both been tested for two different shape harmonisation each. Observation of these already show some logic, particularly w.r.t. weight, that are concurrent with our knowledge. These are however, not yet fully defined to be used for automation. A dedicated study is required to be performed with a larger data set. This data set is made up of designs from different panels made by multiple designers, under different time conditions and user requirements. Such a study would also require a more accurate cost evaluation with small turn-around time, as the current use of factors only accounts for material handling arising from part count and not that from complex shapes.



(a) Performance of design points



(b) Shape harmonisations [3].

Figure 7.3: Post harmonisation design points for test panel 1.

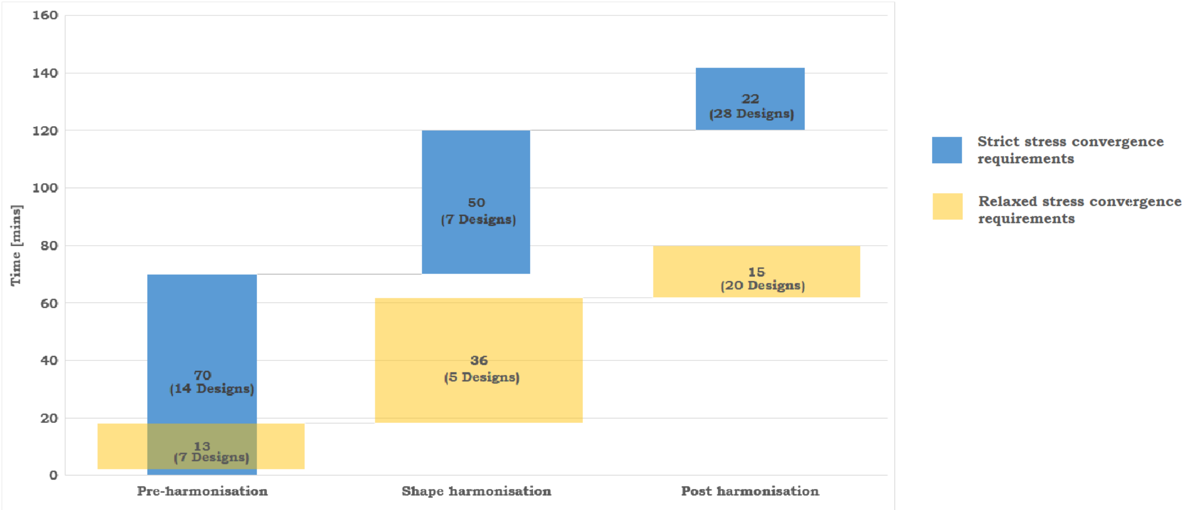


Figure 7.4: Test Panel 1: total time spent on the 3 phases(2 automated, 1 manual) of modified panel book design.

Additional points to be noted in Figure 7.3, are that flat sheet designs made from Glare3i 1.05[mm](green marker) also show some influence of control parameters on cost(can be treated same as part count). This is seen when the ILD splicing control parameters are tested for false i.e. ILDs are free to be spliced at maximum ILD width position (provided within maximum allowable at position), rather than forced adjacent to base splice. In doing so it reduces the part count, thus reducing the cost.

7.1.3. TIME CHARTS

Depending upon panel complexity, the time spent on individual phases and hence the total time is found to vary. Further, time spent on individual panels also rely on how strict the constraints are set. For the purpose of this study there are only two levels of strictness:

1. Strict: maximum sheet width, for a given location for a typical double curved panel[4], is finalised only if round of minimum edge stress(absolute value) is exactly equal to absolute maximum allowable edge stress.
2. Relaxed: maximum sheet width, for a given location for a typical double curved panel, is finalised if round of minimum edge stress is less than equal to maximum allowable edge stress.

Figure 7.4, gives the absolute time distribution between the 3 phases, for the two levels of constraint requirements. Time given is inclusive of all the design concepts generated (even if infeasible) [5].

It has already been mentioned that the two automated phases largely perform the same task. Time allocation between the different tasks is presented in Figure 7.5 and is mostly sequential in bottom-up direction. The following can be inferred from the figure:

1. Pre-harmonisation:
   - Most time is spent on edge stress convergence (for both constraint levels). The time spent is primarily attributed to interaction with CATIA(opening and closing) and PowerCopy[6] functioning for edge stress computation over every sheet.
   - An interaction file is created that contains information for re-use in next automated phase.

[3]Please note that gradations in colour indicates that the base GLARE is same, but different harmonisation techniques have been applied. This is valid for all harmonisation in this report.
[4]Panels that show normal edge stress. Exceptions would be panels in which maximum sheet width(s) give edge stresses much lower than allowable, and panels in which minimum sheet width(s) give edge stress higher than allowable.
[5]Strict Pre-harmonsation:14 designs, shape harmonisation:7 designs, and post-harmonisation:28 designs
Relaxed Pre-harmonsation:7 designs, shape harmonisation:5 designs, and post-harmonisation:20 designs
[6]The dedicated CATIA tool that computes edge stress value for provided sheet definitions

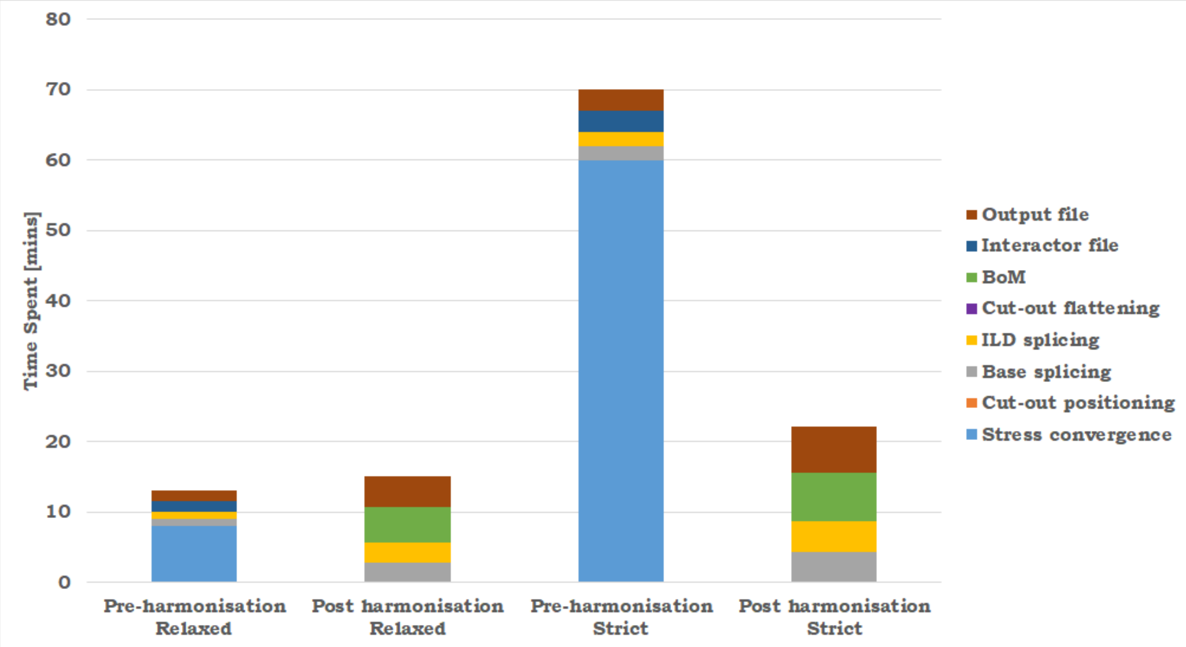


Figure 7.5: Test Panel 1: time spent on individual activities of the two automated phases.

- While all performance information is present in trade-off plots, output files are created with design data for expert reference. It also contains information on how to re-create designs in the visualiser.

2. Post-harmonisation:

   - Reuses most data, taking comparatively smaller time, with certain activities being completely skipped.
   - Detailed inspection of splice design, thus repeating concerned activities.
   - As the final design activity, it does not need to create interactor files.
   - Creates files with BoM. These include the approximate cost-weight information and detailed design properties for accurate computation, of the same, by respective departments.
   - After ILD splicing, creation of BoM takes up a significant portion of time. This is due to the repeated interaction with Excel (separate for every design concept), which is time consuming initself.

3. Relaxed constraint requirement setting, takes less than $1/6th$ the time taken for strict stress convergence.

   - Most sheets converging to width having edges stresses lower than maximum allowable, the last sheet converges at an edge stress of -1.5[mPa] resulting in a maximum sheet width of 199[mm] at this location.
   - This value is only marginally greater than the minimum allowable sheet width for this panel. Thus whatever be the sheet widths being used, the panel will provide no flat sheet design, as the last sheet will always result in violations.
   - Further, the pre-formed sheet designs are exactly the same irrespective of the setting.
   - Shows that relaxing convergence requirement, reduces the time but also the design space being searched.

7.2. TEST PANEL 2

Test panel 2 is a single curved side panel with a single window belt (Figure 7.6). The challenge for this panel is to adjust sheets and splices around the window belt. In experience 90[minutes] of expert time is spent on the design of this panel. Information of the designs created for this panel, using the fully manual original process is presented in Table 7.2.

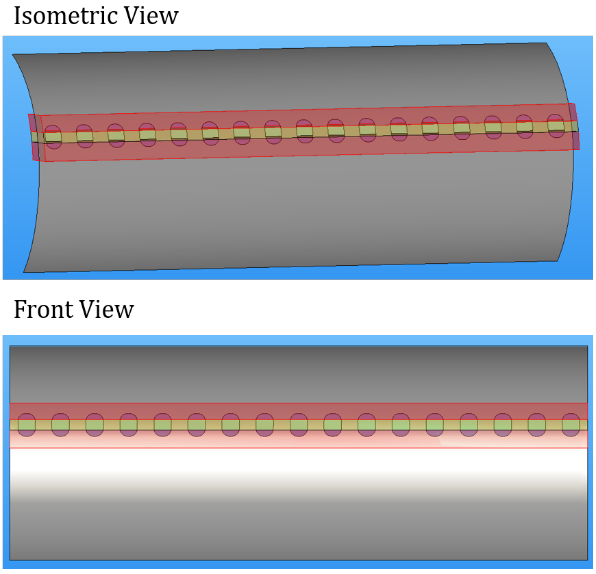


Figure 7.6: Panel Geometry 2.

Design Concept	Sheet Properties	Weight[Kg]	Part Count
1	flat	243.53	25
2	pre-formed	N/A	N/A

Table 7.2: Designs from original manual process for test panel 2.

7.2.1. DATA PLOTS: PRE-HARMONISATION

Figure 7.7, gives seven design concepts, over three different weight performances and 1 part count performance. This panel sees local thickening only in the form of glare type and not addition of sheet metal over the base layup. Also, the thicker design concepts are results of greater sheet thickness rather than increase in number of layer. Thus, all concepts present the same part count performance. The concept presenting lowest weight performance is selected and subjected to 5 different shape harmonisations. These 5 harmonisation present a range of fuselage design scenario. These include different window frame sizes for the aircraft, and panel thickness at edges of adjacent panels. This will be further discussed with post-harmonisation plots in the next section.

7.2.2. DATA PLOTS: POST-HARMONISATION

Analysis of shape harmonised designs is performed in Figure 7.8. On the first glance of the plot, design point 1 presents itself as the clear choice performing much better than the original designs. However, one must note the conditions that apply with this design. Harmonisation 1 uses only 3 thickness', all having a 3/2 layup (base of 0.85[mm] has a waffle plate acting as middle layer). The highest of these 3 is 1.65[mm][7], which is applied around the window belt and also on the edges. This maximum dictates the edge thickness of adjacent panels and also requires a window frame to be made available to match this size. In a front-loaded approach performance of this panel may be used in decision making, provided this is supported by adjacent panels.

[7]Performed after layup harmonisation, this design ensures that thickness at every bay is greater than or equal to that assigned in the input file.

Another dominant feature is that the the original design is more expensive and heavy than any design generated by the tool. This is because a thicker base GLARE of 1.05[mm], was selected for the original design. The same had been filtered out during pre-harmonisation phase of the modified process.

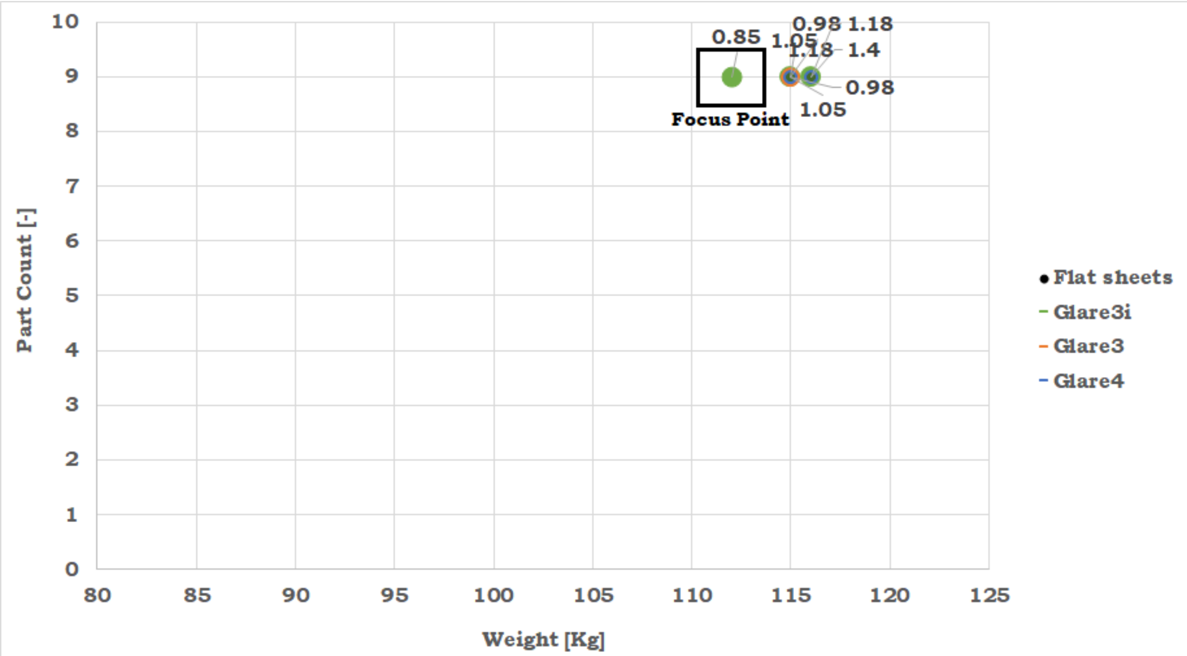
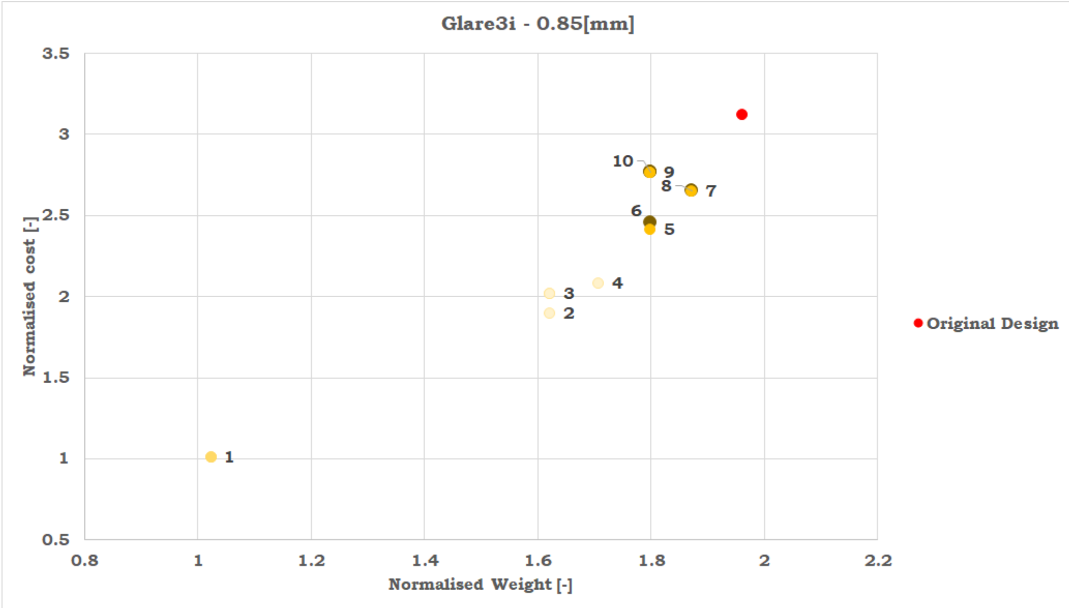


Figure 7.7: Pre-harmonisation output for test panel 2, with focus on concepts selected for shape harmonisation.

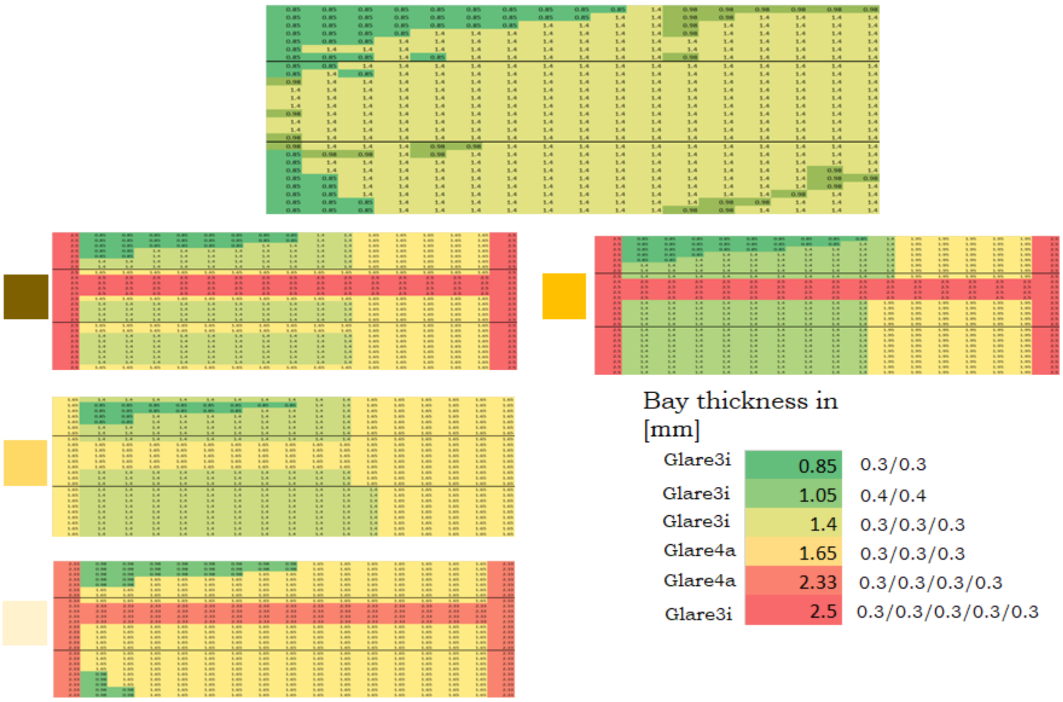
Harmonisation File	Cluster	Part Count	Weight [kg]	ILD + Base Splicing	Splice Orientation
1					
	14	2	188	True	+1
	14	3	178	True	-1
	13	1	178	False	+1
	14	3	178	False	-1
2					
	14	2	188	True	+1
	14	3	179	True	-1
	13	1	179	False	+1
	14	3	179	False	-1
3					
	14	2	190	True	+1
	14	3	181	True	-1
	13	1	181	False	+1
	14	3	181	False	-1

Table 7.3: Performance data for test panel 2.

Different performances(Figure 7.8) within the same harmonisation file shows that the panel is sensitive to changes in control parameters. These changes are large enough to offer some benefits, but still lie within the same cluster i.e. do not give drastic change in performance initially predicted in Figure 7.7. Further, the panel geometry itself makes it an ideal candidate to test control parameter influences. Special harmonisations have been specifically created to test the influence of control parameters that change in the scope of post harmonisation[8]. Part count vs weight has been selected to present this influence in Figure 7.9. Data plotted can also be viewed in Table 7.3.



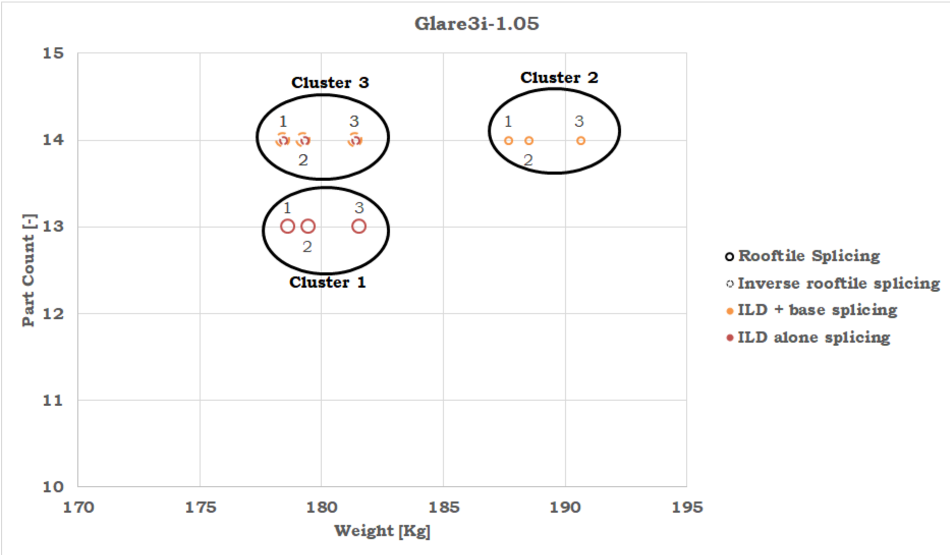
(a) Design Performance.



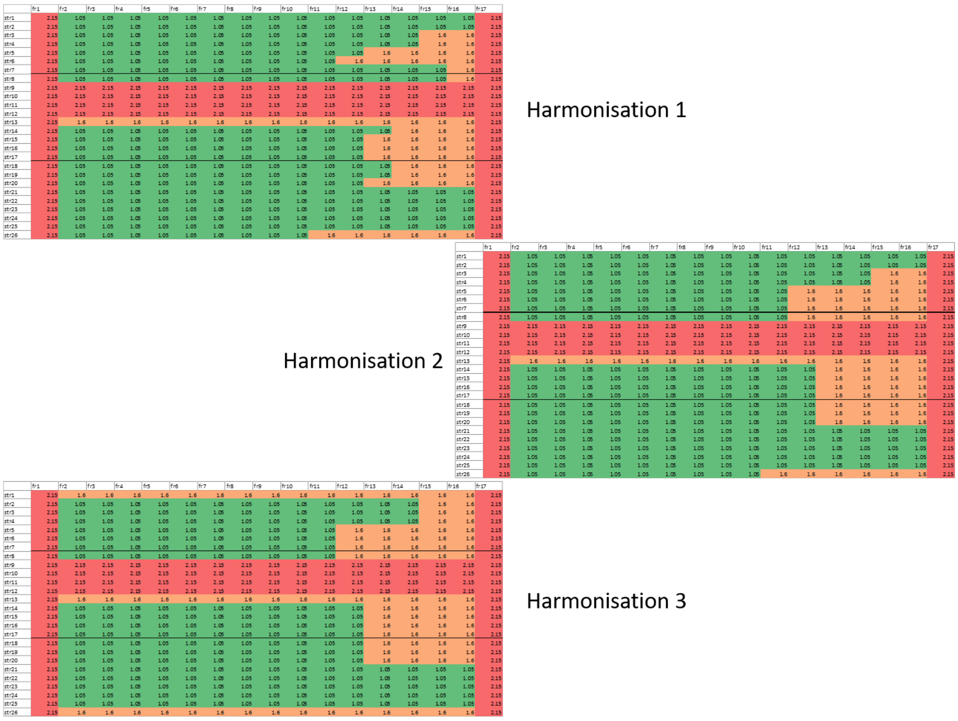
(b) Shape harmonisation presented.

Figure 7.8: Post harmonisation for test panel 2.

[8]influence of splice direction(roof tile, +1 or inverse roof tile, -1) and ILD splicing techniques (ILD spliced adjacent to base, True or spliced at maximum sheet width position, False)



(a) Influence of control parameters on performance of test panel 2.



(b) Harmonisation patterns tested.

Figure 7.9: Testing influence of control parameter on performance of dedicated shape harmonisation

Performances of the three tested files are spread over 3 clusters. The data label attached to each point, indicates the harmonisation file it belongs to. The following have been deduced from studying the cluster properties:

1. Cluster 1- Roof tile orientation and ILD spliced independent of base: This combination for the studied harmonisations result in a part count of 13[9] with weight in the range of 178-192[kg]. This is because the ILDs contributing to thickness build-up on panel edges get connected by a small piece (Figure 7.10) of sheet metal which reduces the part count by 1. Further being a very small part, its 0.2[kg], contribution to weight is easily neglected in rounding.

[9] 9 are standard from base for this design all else are additional from ILDs

2. Cluster 2- Roof tile orientation and ILD spliced adjacent to base base: By forcing the ILD to splice next base and with a +1(roof tile) splice orientation, the ILD splice is moved into the cut-out region. This raises a requirement inserting additional sheets at cut-outs to flatten it for window frame bonding. This additional sheet increases the part count and also adds to weight. However as the small piece of metal joining two edge ILDs is still retained, part count is only increased by 1.

3. Cluster 3- Inverse roof tile orientation: Irrespective of the ILD splice techniques, the -1 splice orientation keeps the ILDs out of the window frame region. However, inverting the splice removes the small piece of metal joining the two parts, nullifying the part count reduction. Thus the part count remains the same as in cluster 2.

These learnings, although dependent on panel and shape harmonisation, can be utilised by designers to keep the final proposal in the desired cluster.

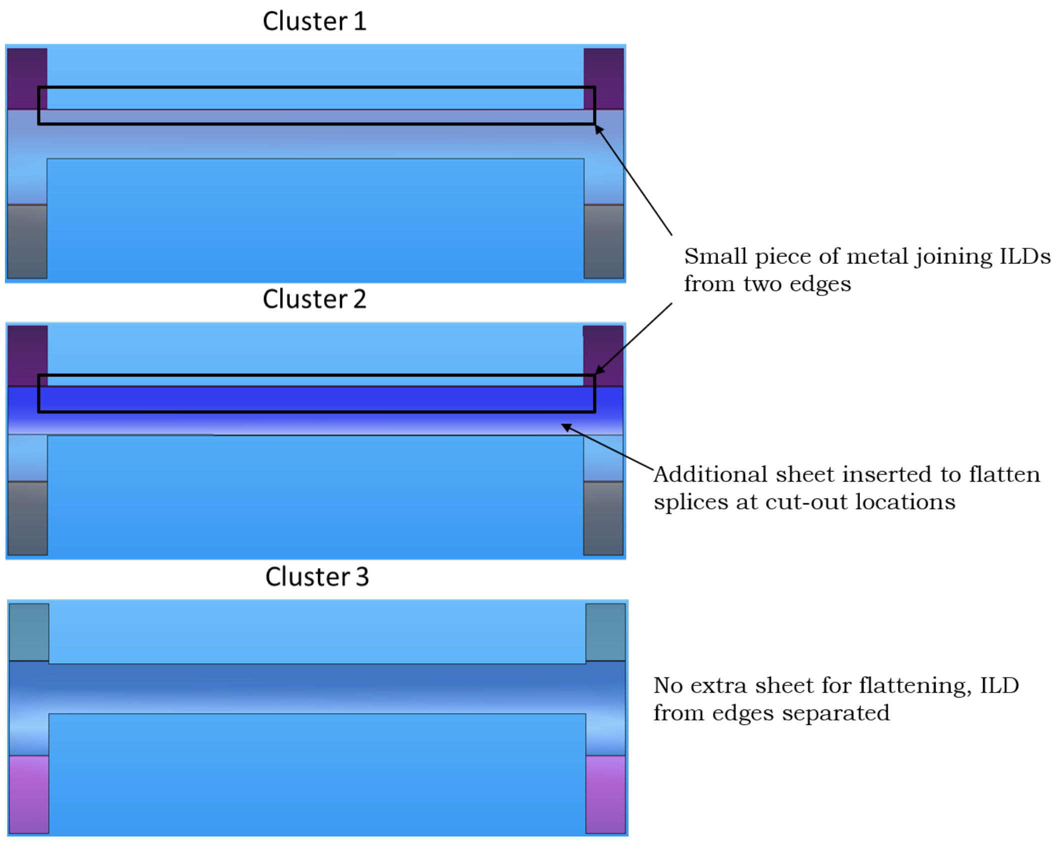


Figure 7.10: Design changes with control parameters

7.2.3. TIME CHARTS

Figure 7.11, gives the absolute time distribution between the 3 phases[10]. It has already been mentioned that the two automated phases largely perform the same task. Time allocation between the different tasks is presented in Figure 7.12 and is mostly sequential in bottom-up direction. The following can be obtained from the figure:

1. Pre-harmonisation: time is more or less equally distributed between all tasks.

2. Post-harmonisation:

    - Unlike in previous test case, time consumed is greater than that of pre-harmonisation. As all but creation of interactor file is repeated, this increase is safely attributed to the increased number of concepts(nearly three times more)

[10] Pre-harmonsation:7 designs, shape harmonisation:4 designs, and post-harmonisation:20 designs

- This also does not show a drastic disparity in time allocation.

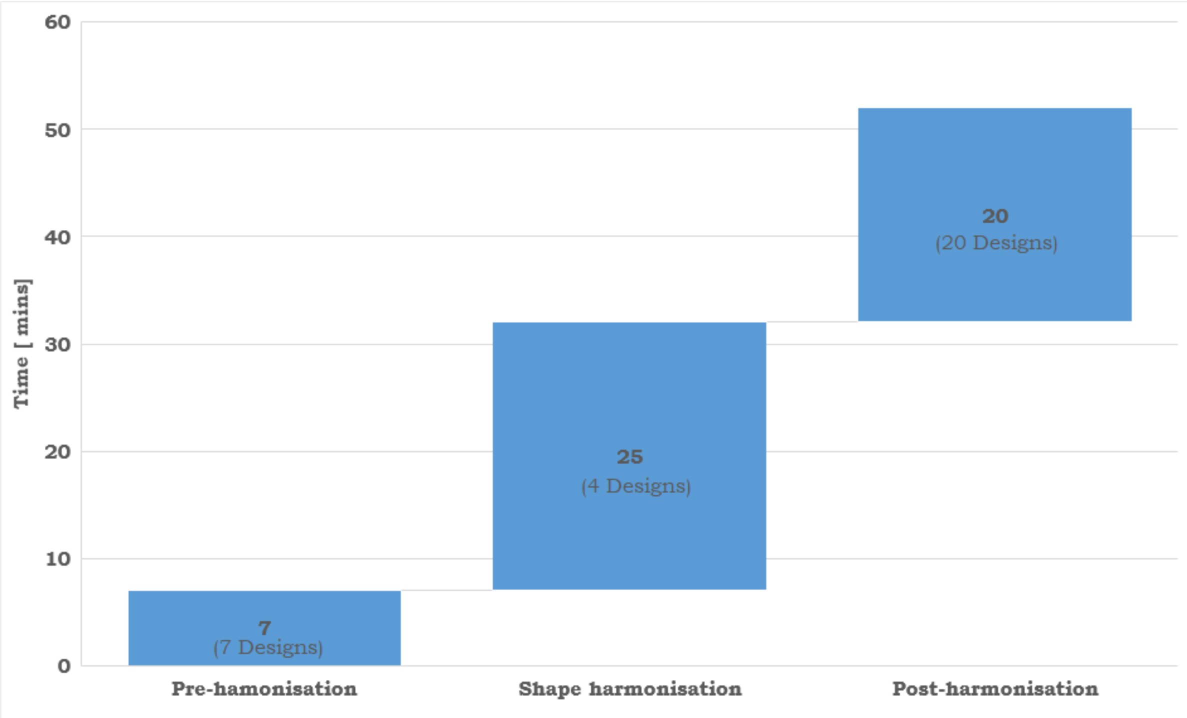


Figure 7.11: Test Panel 2: total time spent on the 3 phases(2 automated, 1 manual) of modified panel book design.

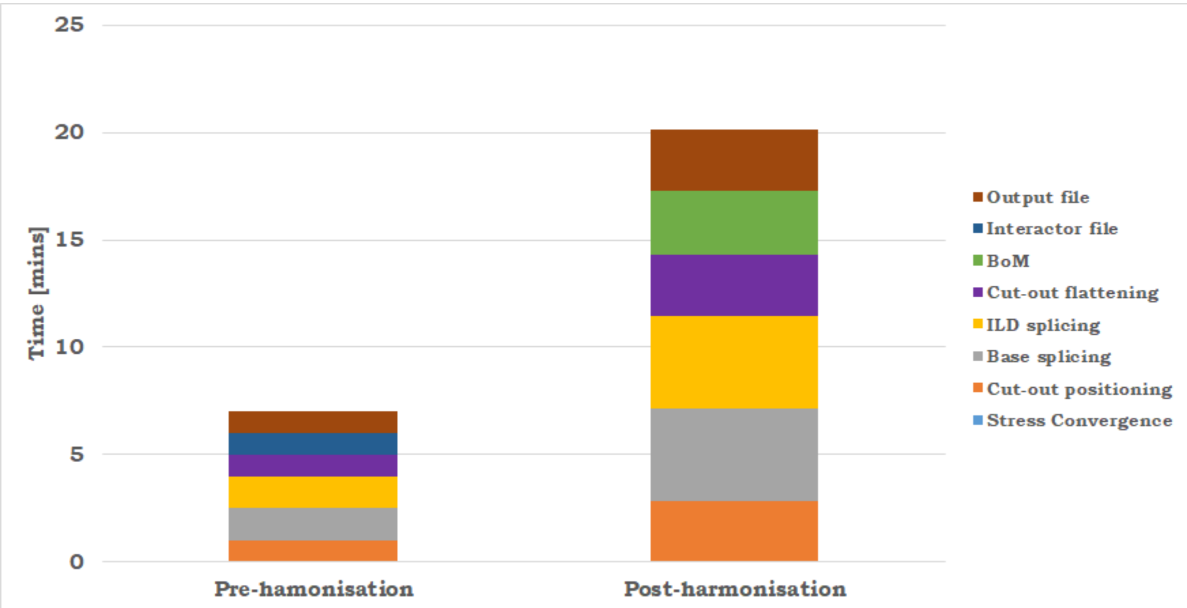


Figure 7.12: Test Panel 2: time spent on individual activities of the two automated phases.

7.3. TEST PANEL 3

Test panel 3 is a double curved side panel with one window belt, a passenger door and accompanying emergency slide cut-out (Figure 7.13). It faces the combined challenge of edge stress convergence and adapting sheet width around cut-outs. Information of the designs created for this panel, using the fully manual original process is presented in Table 7.4. In experience this panel takes about 240-300 [minutes][11] (4-5 [hours]) of expert time when designed manually.

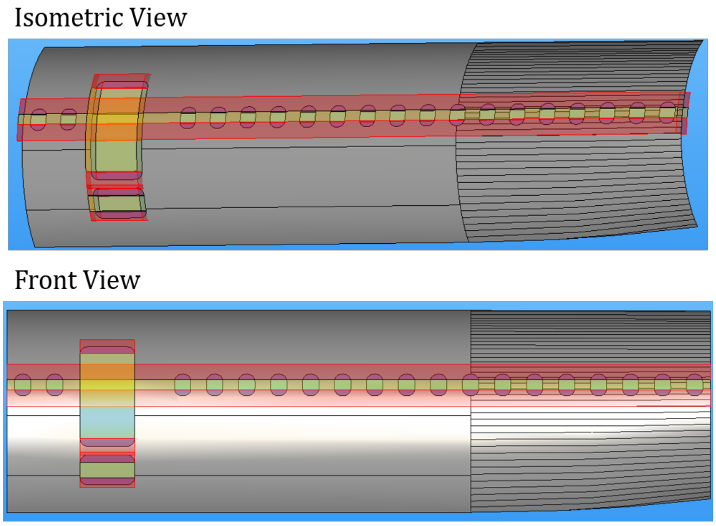


Figure 7.13: Panel Geometry 3.

Design Concept	Sheet Properties	Weight[Kg]	Part Count
1	flat	N/A	N/A
2	pre-formed	315.18	29

Table 7.4: Designs from original manual process for test panel 3.

7.3.1. DATA PLOTS: PRE-HARMONISATION

The pre-harmonisation trade of plot in Figure 7.14, shows that for this panel only use of pre-formed sheets yields designs. A closer look into the output file showed that the maximum sheet width values. set after edge stress convergence, were too small to satisfactorily fit in the combined zone A of passenger door and emergency slide cut-out. This was identified after complete edge stress convergence, in the cut-out adaptation loop before the maximum number of iterations was reached (Chapter 6). As a counter measure an increased edge stress allowable was implemented to no avail. Possible solution to this problem are:

- Use pre-formed sheets.
- Opt for different splice configuration (out of scope).
- Change cut-out zone definition in concerned region. This should be done in agreement with process expert.
- Create an exception for splice position/ splice design, again in agreement with process expert.

[11] Although this time was used to develop 2 designs with flat and pre-formed sheet, only one sheet type design was possible for the panel.

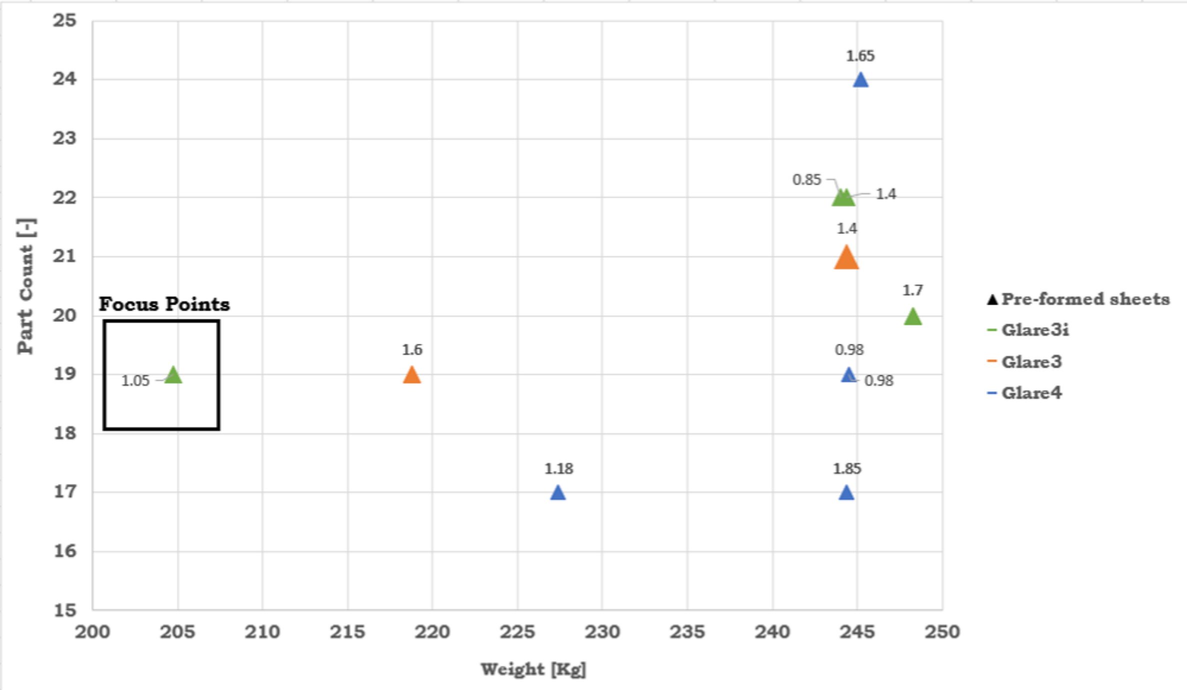


Figure 7.14: Pre-harmonisation output for test panel 3, with focus on concepts selected for shape harmonisation.

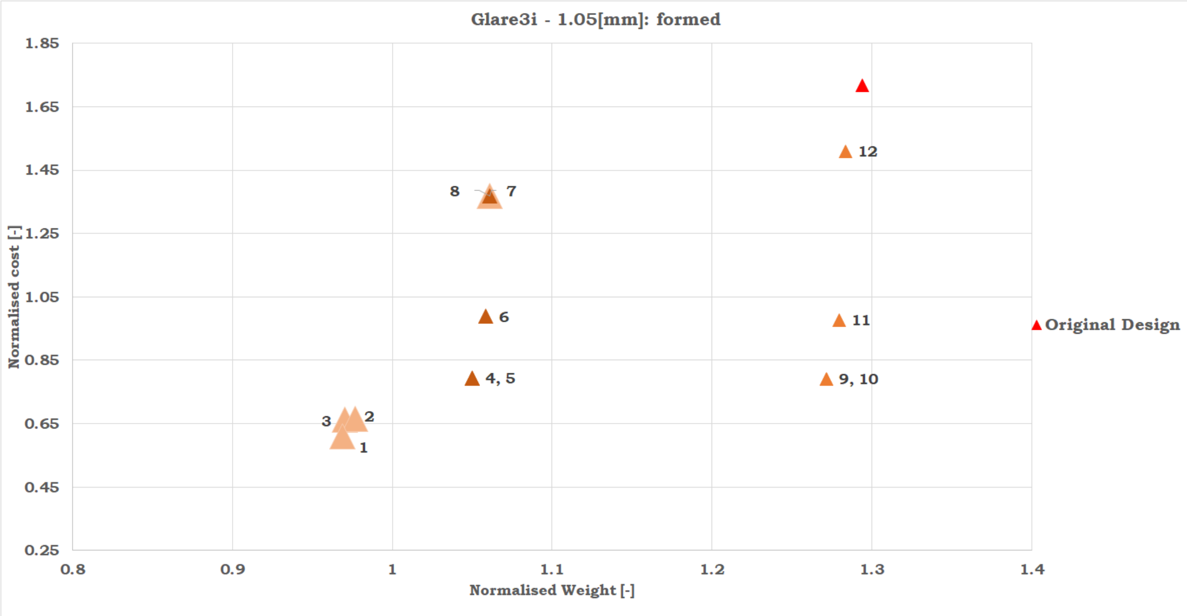
From the available design concept in Figure 7.14, a single concept is selected for further studies. It can be seen that concepts with Glare4 having thickness' 1.18[mm] and 1.85[mm], offer a lower part count. However, this benefit is much smaller compared to the weight gained in these concepts. Three manufacturable shape harmonisations were created for this panel and subjected to further studies.

Harmonisation File	Design Point	Part Count	Weight [kg]	ILD + Base Splicing	Splice Orientation
1					
	27	8	258	True	+1
	17	3	236	True	-1
	17	2	238	False	+1
	16	1	236	False	-1
2					
	27	7	259	True	+1
	19	4	256	True	-1
	22	6	258	False	+1
	19	5	256	False	-1
3					
	28	12	313	True	+1
	18	9	310	True	-1
	21	11	312	False	+1
	18	12	310	False	-1

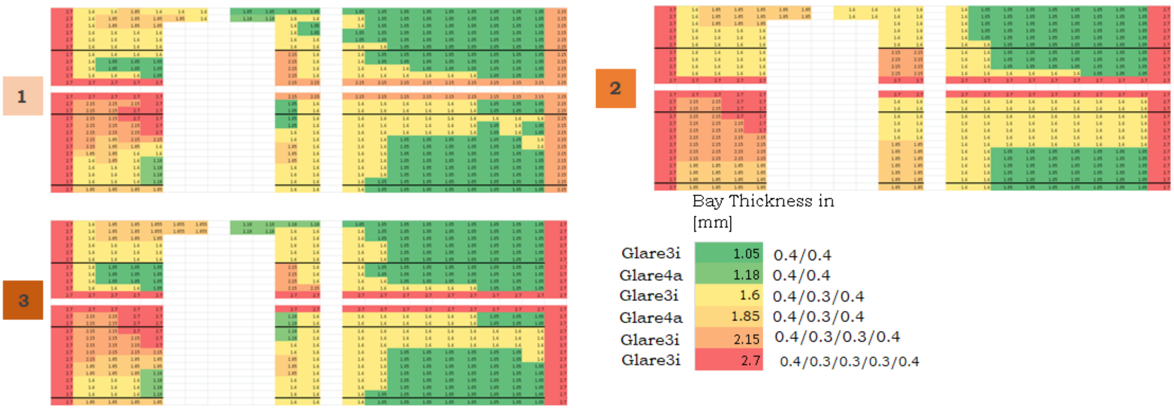
Table 7.5: Performance data for test panel 3.

7.3.2. DATA PLOTS: POST-HARMONISATION

Three different shape harmonisation performed with the same base GLARE have been tested. These are presented in Figure 7.15. Similar to test panel2, the original design is found to be heavier and more expensive, compared to the design points generated. Here again the influence of base GLARE filtering is seen. Unlike previous panel, the original design of this panel has a lower base GLARE at 0.85 [mm] as opposed to 1.05 [mm] selected for this study. In Figure 7.14, a clear prediction of a heavier performance for this base GLARE is seen. This point also shows a high part count.



(a) Design Performance.



(b) Shape harmonisation presented.

Figure 7.15: Post harmonisation for test panel 3.

Further, design points for test panel 3, shows variations with both shape harmonisation techniques and control parameters, while remaining within a clearly discernible cluster. With regard to control parameters influence, in general the following observations have been made with reference to Table 7.5:

1. Design points(7, 8, 12), in all shape harmonisations, having a combination of roof tile splice and spliced adjacent to base show the greatest weight and part count. This particular combinations find the last sheet to be too large to remain unspliced. This results in a third splice (also seen in Figure 7.15b) with a very narrow third sheet. Additionally it forces all ILD's to be spliced thrice as well, increasing the number of parts. Finally it requires an additional sheet to flatten splices around the door.

2. Inverse roof tile splicing (1, 4, 5, 9, 10), for all 3 harmonisations, gives least weight. This is due to the very favourable circumstances it creates for the current panel. An inverse roof tile splice removes the need for third splice, resulting in an appreciable drop in part count.

3. For designs splicing free of base with roof tile orientation(2, 3, 6, 11), both part count and weight were found to show a small increase as compared to second option(design points 1, 4, 5, 9, 10). With a

roof tile orientation these design points require 3 splices. However, as the ILD are independent of the base, they undergo only two splices. It should be noted that design point 2 from shape harmonisation 1 does not follow the above observations fully. These can be written of to anomalies rising form the harmonisation technique.

It should be noted that shape harmonisation 1 does note follow the above observations fully. These can be written of to anomalies rising form the harmonisation technique.

7.3.3. TIME CHARTS

Similar to test panel 1, test panel 2 also shows a great disparity in the time for edge stress convergence between relaxed and strict constraint requirements. Being a complex panel, relaxation of constraints greatly reduces overall time. As was seen earlier even with strict constraints the panel has no flat sheet design. Thus, unlike test panel 1, the solution space does not see any changes with constraint level. Further, apart from stress convergence in pre-harmonisation phase, no other activity (in all 3 phases) sees any change in time consumption. This can be seen in both Figure 7.16 and 7.17, that show the overall time taken by the three phases and time taken by individual activities within the 3 phases respectively.

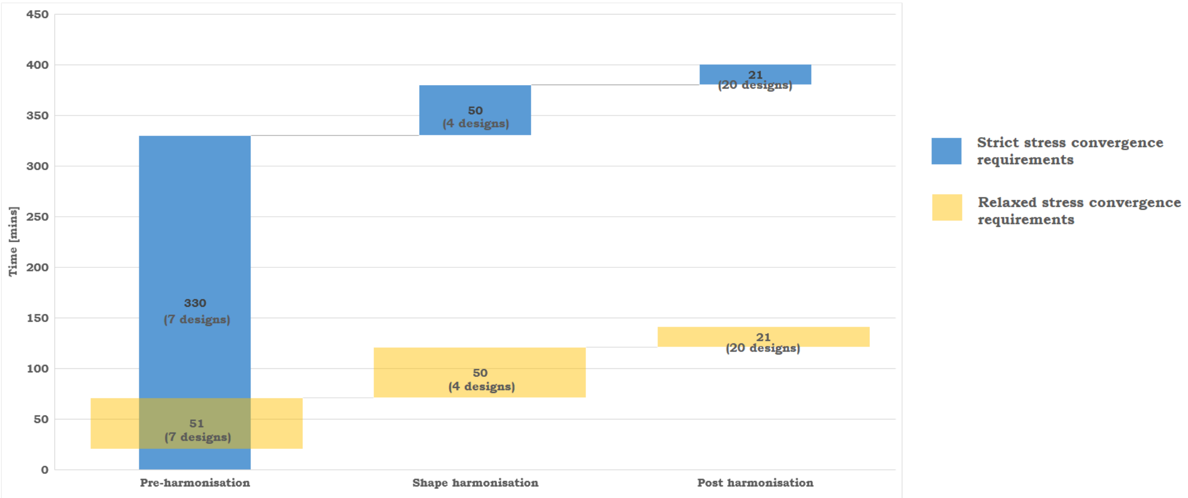


Figure 7.16: Total time spent on the 3 phases(2 automated, 1 manual) of modified panel book design[12]

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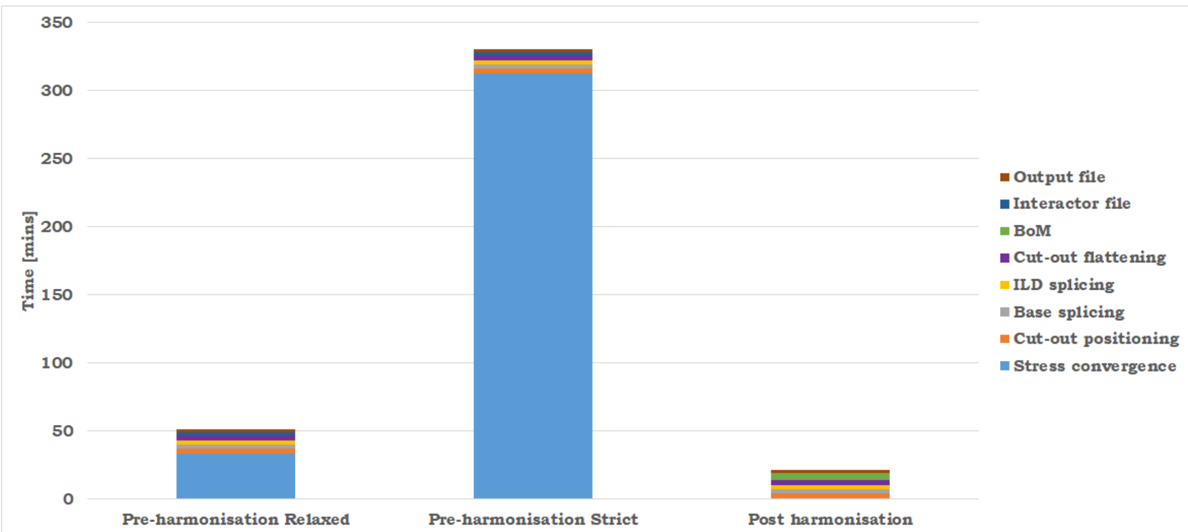

Figure 7.17: Percentage of time spent on individual activities of the two automated phases.

8

Performance of Developed Methodology

8.1. Research Questions

In Chapter 1, questions were framed, that served to guide the research. These are answered in detail in the coming sections along with extra questions that were answered during the course of the project.

8.1.1. Influence of Methodology on Design Space Exploration

As has been seen in Chapter 7, multiple designs are generated in every phase of the new methodology. The final number of feasible design obtained post-harmonisation depends on the number shape harmonisations created by the expert. Tests conducted in span of this project typically had 3-7 shape harmonisations, each resulting in four designs concepts which may or may not differ in performance. Even in the unlikely scenario, wherein the expert creates only 1 shape harmonisation, 4 different combinations of control parameters will be tested. Thus, giving four design points that again may or may not plot different performances. This answer is further elaborated by answering the following sub-questions:

Number of panels that can be designed per hour

The developed methodology has come to significantly change both the number of design concepts generated and the time take to generate these. Both these quantities fluctuate based on the number of shape harmonisation created by the designer. This is also true in-case of the manual panel book design process. Keeping these in mind, this question has been answered per panel[1] and also as an average for the design phase in Table 8.1.

Range of Cost and Weight/Solution Space Mapped by the Entire Process

Except for test panel 2, performance values of the original design(s) indicate that they lie within the cluster of newly generated points. Thus validating the results obtained from PANADEE-II. Despite performance lying within cluster, it is seen that a much broader cost and weight area is mapped using the tool. Depending on the panel, this range can vary from 28%-40% in both cost weight direction. While a big contribution to

[1] All considered designs are generated using strict constraint requirements. All shape harmonisations are considered as they form a part of design study even in actual processes.

Test Panel	Original Manual Process [Designs/Hour]	Modified Semi-Automated Process [Design/Hour]
1	1	8.94
2	0.66	23.01
3	0.2	5.37
Average In Process	0.62	12.44

Table 8.1: Efficiency of original and modified process.

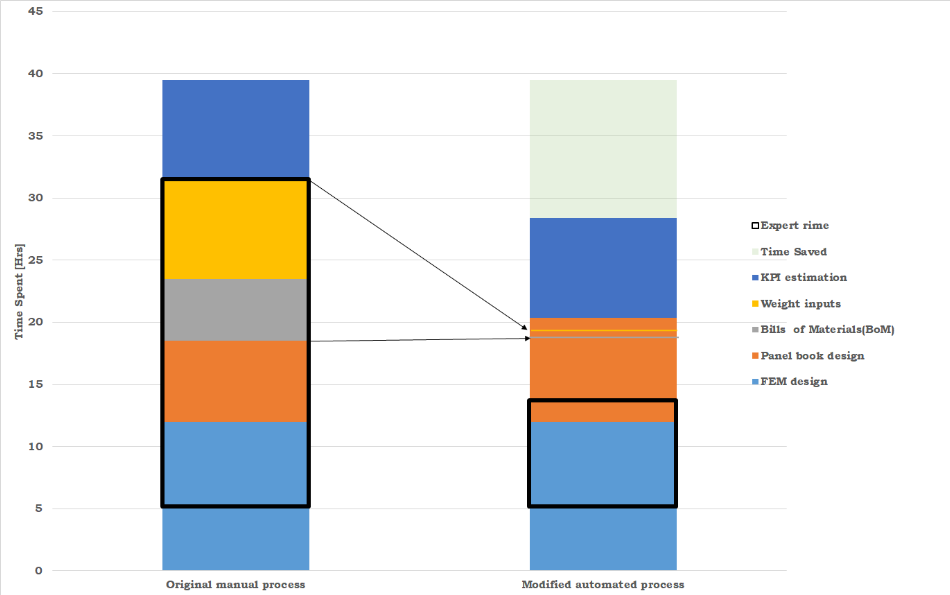

Figure 8.1: 40[hours] of in-proposal design time split up between different activities and time in which expert is employed.

this diversity, is from shape harmonisation, variation of control parameters has also been found to give large variations(up to 70% in cost), within their own cluster.

INFLUENCE ON THE TIME DISTRIBUTION ON IN-PROPOSAL DESIGN

In addition to influencing the time distribution of panel book design, as seen in previous chapter, automation has come to change the time distribution between the different tasks of in-proposal design itself. Figure 8.1 shows the roughly 40 hours of in-proposal design split into different tasks, for both the manual and automated panel book design process. Here it can be seen that though there is a marginal time increase in the panel book design time, when using automation [2], there is still over 10[hours] made available for trade-off studies by expert (topmost box in light green, in Figure 8.1). At this point it is worth noting that the time estimates shown in the figure below, uses a single machine to create panel book designs one after the other for different panels with some parallel manual work. If multiple machines are used and a parallel work plan is implemented, this slot for trade-off can be further inflated without influencing the overall time.

8.1.2. INFLUENCE ON THE PERFORMANCE OF FINAL PROPOSAL

Creation of the final proposal is done after detailed discussion with all experts and is subjective to OEM needs. The major benefit offered by this methodology is the large number of design points to choose from.

DIFFERENCE IN PERFORMANCE OF FINAL PROPOSAL

Since customer requirements in terms of cost and weight performance were not available for this study, it was assumed that the design presenting lowest cost and weight, if not contradicting, would be selected. This question cannot be answered with further clarity, as the amount of information available to support decision making is much greater than before. With this information and time, expert decision becomes very subjective and cannot be quantified within the scope of this thesis.

NUMBER OF ERROR OR UNACCEPTABLE DESIGN TRAITS

The automated tool is designed to allow exceptions. This is particularly true for the routine that positions sheet edges around cut-out zones. As seen in Chapter 6, this routine loops using previous results until such a design is obtained where no cut-out zone A has any splices in it, or the maximum number of iterations is reached wherein it selects minimum error. However, for the three panel tested in this study, with both relaxed and strict constraint requirements, it was found that the tool converged to solutions, or the possibility of having no solution, well before the maximum number of iterations were reached. Further, it should be noted the

[2] Might sound counter intuitive for automation to take longer, please note that the number of design points generated is far greater

Figure 8.2: Complex panel geometries not covered by PANADEE-II

maximum number of iteration for this routine was set to as low as 10.

Similar behaviour is to be expected of the stress convergence routine as well (Chapter 6). Although this routine is not constricted to a maximum number of iterations, for the two double curved panels that were tested, sheet width values, with allowable edge stress, fell between the minimum and maximum allowable.

Thus, within the scope of this project, it was found that as long as shape harmonisations performed by experts are fully manufacturable (disregarding cost of manufacture), the designs coming out from panel book design, will be manufacturable, showing no error or unacceptable traits. However, further testing, using broader test samples, is recommended. This would generate statistical data that can be used to derive probabilities of error. In Chapter 5 a list was presented with requirements expected of the tool. Following states how the tool stand against it:

1. Robust: the tool has displayed the ability to handle a diverse range of panels. However, it still has limitations. One particular limitation is for panels with cargo door(s). As cargo doors often span over two adjacent panels (Figure 8.2), it essentially creates a panel with more than 4 sides with open cut-outs. In such a scenario, the tool is incapable of segregating panel edge from cut-out edge and thus falls short in computing edge lengths and cut-out zone definitions. Further development of the tool is required in this aspect along with extensive testing to identify other limitation.

2. Time spent by experts: a significant reduction has been seen in this aspect. Figure 8.1 shows over 50% reduction in the time that expert is employed in the in-proposal phase using the new methodology. Also, it is seen that a new slot of time is opened up that employs neither the tools nor the expert. This time has been theoretically assigned to the expert to perform manual verification of design and conduct trade-off studies. As mentioned earlier trade-off time can be further increased by parallel work and using multiple machines.

3. Design capacity: being at the heart of presented methodology, the tool has proven particularly effective in this respect. On an average it was found that in adopting the tool based design methodology increased the design capacity of 0.66 [Concepts/Hour] to 12.44 [Concepts/Hour]. This number is expected to vary, mostly based on the number of double curved panels in the set to be designed. The time taken by designer for shape harmonisation is expected to have a comparatively small influence (decimal places) under normal circumstances[3].

4. Quality and level of detail: designs generated for the test cases were verified by experts and their performance was plotted against the original design. As the original designs fell within the cluster(s) of newly generated points, it offered as a validation of results.

5. Supporting optimisation: modules were created with implementation of an optimisation routine in mind. This has also been recommended as future works on the tool.

6. Tool must be easy to update, transparent, user friendly and intuitive: With a clear UML and ample comments the tool is easy to update and transparent for a developer. However experience shows that user friendliness was not achieved to desired extent. This is because the GUI used is intended for developers and not end user. Its depth and layers can often confuse a user not adept at programming. Further execution of the tool is done from dedicated python scripts, which can often discourage end users.

[3] Normal circumstance implies the time invested by experts, which is typically between 25[mins] to 1.5[hours] per panel. Within this time frame, designers are known to come up with multiple concepts.

8.1.3. LIMITATIONS

Critically reviewing results and the developed methodology, has bought to light limitations of the new process and the tool itself. These are stated as follows:

TIME TO DEVELOP

As already established in 2 out of 3 test cases, the methodology has proved effective in reducing average time per concept. However, the time required to develop the tool, central to the solution proposed, is fairly high. Close to 6.5-7 [months] of the 9 [month] thesis period was devoted to acquiring and translating knowledge into a KBE system.

SCOPE OF TOOL

Despite the time invested in creation of the tool, following aspects still need to be accounted for:

1. Splice designs: currently the tool generates multiple design points but all using only longitudinal splices. As it is the most commonly widely used splice design for the company, it was selected to limit the scope. However, relatively new configurations such as circumferential and T-splices, also offer solutions for certain design cases. This was found to be true in the case of test panel 3 that employed t-splices for in one of the concepts. Incorporating these within the scope of the tool would enable a more exhaustive search. Further it would reduce the effort required to examine possibilities using these configurations.

2. Glare grade variations: dealing primarily with sheet metal layup and its design, the KBE tool tends to take the base glare grade for granted and performs calculations assuming the same glare type all over. In doing so, it ignores local variations arising from additional prepreg layers, and thus shows (depending upon how many variation in Glare grade is seen) a small error in the computed weight.

3. Mixed sheet types: currently the tool allows only one time type of sheet (flat/formed) to be used in a single panel. However, certain double curved panels can benefit from having pre-formed sheets only on the double curved parts. For this it can be beneficial for the tool to offer selective sheet forming.

9

Conclusions and Recommendations

The research presents a methodology developed to tackle time challenges in creative engineering design processes. The methodology proposes identifying all the major problems that are tackled by experts in the design process. Further all tasks performed in support of these problems are identified. From these, it proposes isolation of creative tasks, that do not, as yet, have clearly defined knowledge rules, from the rest of the repetitive and rule based (non-creative) tasks. All these non-creative tasks are bundled within an automated tools using KBE techniques.

Implementation and testing of the proposed methodology was performed on in-proposal design process of fuselage panels, made from Fibre Metal Laminates. Particularly it was focused onto the design process, carried out at Fokker Aerostructures. A KBE application called PANADEE-II, was created to implement the methodology suggested. This tool solves 2 critical problems by treating them as individual and successive Constraint Satisfaction Problems. To aid implementation of methodology, within the set time frame of this project, heuristic technique of trial and error is used to generate feasible panel laminate design.

In the effort to capture and translate knowledge into design rules for the tool, a formal flow chart for the in-proposal phase was created. Studying the time chart for this phase, highlighted panel book design, and activity relying on information from it, as the most time processes. It as found that creation of panel book design meant, creation of manufacturable laminate designs for a given panel. This is done by a set of activities, that essentially check and modify input layup at different positions, and defines sheet overlaps or splices. From all the activities that were done in support of these two aims, 3 entangled activities, that were treated as one creative task, were identified. Further studies allowed de-tangling of these three tasks. For this modifications were made to the process flow. This allowed automating two of these tasks as separate rule based Constraint Satisfaction Problems. Using trial and error, these problems proceeded with the aim of finding the maximum sheet width solution that satisfied all, or maximum, constraints of the problem. In doing so maximum sheet widths, at different positions over the panel, were defined. This in-turn defines the splice position(s).

The third task dealt with the shape of sheets inserted (if any) for local thickness build-up. No set knowledge could as yet be identified for this task. Thus, it has been isolated as the lone creative task that takes up expert time. As the third task both relies and has an influence on the combined outcome of the other two, it is sandwiched between two slightly different, automated loops of the same.

In modifying the process flow, changes and/or errors in the final design were expected. For some of the test panels, differences were seen in the designs from the two process flows. Original process designs attempted to have a near even sheet width distribution over the entire panel. The new process however opts for the first sheet width combination that satisfies constraints. This may or may not result in an even width distribution. To ensure viability of the designs, they were verified by experts. Also, plotting of their performance revealed that they fall on or near that of original designs, thus offering a form of validation. Differences between the original design and those generated by PANADEE-II were found to be results of different decisions made during the design process, which were not confined to the creative shape harmonisation.

Testing the new methodology for set of test cases, an improvement in process efficiency is seen in all tests. Complete separation of the creative and non-creative tasks, allow the tool to perform extensive searches of the solution space independent of the designer. Doing so provides a broader study of the solution space while freeing up the expert to conduct trade-off and design studies. It was found that without changing the overall time for in-proposal phase, the new methodology reduces expert time from 21[hours] to 9[hours]. In addition, the test conducted, it offers 11[hours] of time saving. This additional time is also available for expert to conduct trade-off and design studies. It can be further increased by parallel work and use of multiple machines.

As mentioned before, the new methodology also offers a broader study of the solution space. At an average the new methodology generates 12.44 concepts per hour, as opposed to 0.62 concepts per hour from the original process. Further, the automated scripts test multiple design parameters such as minimum thickness of panel, different types of sheets, orientation of overlap/splice, etc. This generates a set of design points that may or may not vary in performance. From the tests it was found that even with the absolute minimum expert efforts, at least four different combinations of design criterion will be tested.

Tests conducted, showed that for some panels, changes in design criterion did not always change performance. Thus they do not always serve to search solution space. The mapped design space do not only serve purpose in providing better cost weight designs. By plotting a number of design concepts it offers a clear indication of where the design stands in the entire space and the ability to manually optimise it. The original process, in creating 1 or 2 design points offered a much smaller sample space. Offering no proof of selected concept being the best in meeting user requirements, neither giving any indication as to which direction changes in design will take the performance. Further, a well plotted solution space enables easy modification of design, with changes in requirements, that is often seen in the conceptual design phase.

The time and design capacity benefits offered by the newly implemented design process, have also created possibilities for front end engineering design in the pre-proposal phase i.e. prior to requirements being made available to part manufacturer by Original Equipment Manufacturer. By making assumptions regarding possible design requirements, the part manufacturer can already start working on design prior to entering the in-proposal phase. These designs and assumptions can be used to assist the OEM with decision making and can be easily modified to match any changes.

9.1. RECOMMENDATIONS

In the introduction (Chapter 1), three phases were proposed for implementing optimisation. This thesis has served in phase I, laying down the path for future phases. These recommendations have been taken forward in the coming sections

9.1.1. IMPLEMENT AN OPTIMISATION ROUTINE

Within the scope of this project, solutions have been found using a trial and error approach. Here an automated tool computes change in sheet width and finds its influence on design, until such a point that all constraints are met or maximum number of iterations is reached. Every problem in the approach is treated individually in separate loops.

Another approach to find solutions is to use a gradient based optimiser that tackles both the problems at the same time in a single Constraint Satisfaction Problems. The objective function for such an optimisation is given below:

$$f(S)_{min} = \sum C_j(S) \tag{9.1}$$

Where, C is the violation value for the constrain j for a solution S.

For this routine sheet widths at different locations acts as the design variable bounded by a lower bound of smallest datum pitch and an upper bound of maximum usable stock width. Constraints that are currently treated separately can be assigned a weight age and error values from existing modules of the tool can be used to calculate objective function. The main benefit of using an optimisation function would be the ability to test smaller sheet width designs that were currently skipped, in keeping to maximum sheet width combinations.

Further, if the tool is equipped with a more accurate cost model (current model is fairly rough using a fixed factor to determine cost from part count), the optimisation can be modified as follows:

$$f(S)_{min} = Cost(S)/Weight(S) \tag{9.2}$$

As before this routine can also abide by the same design variable, bounds and constraints. Implementing such an optimisation would offer the benefit of an even larger solution space as it would not constrict to designs that fully meet constraints. If such designs offer exceptional cost to weight performance, exceptions can be made to design principles and solutions can be manually found by experts to solve critical errors without marring performance.

Implementing an optimisation routine would enable a much wider solution search. Currently the tool only tests designs till it reaches a feasible sheet width design. However, for most panels there are multiple feasible sheet width designs, that lie beyond the ones tested. Implementing an optimisation would allow experts to tap into these zone as well.

9.2. IDENTIFYING TRAITS OF GOOD SHAPE HARMONISATION

The tool already provides a test bed that can be used to quickly test a large sample of creative solutions. Its capabilities can be used to further study the shape harmonisation process, currently being treated as creative. Using a large collection of harmonised files provided by different experts, for different design requirements, and with different levels of knowledge on global design, already provides a large data set. Cluster analysis on the performance points might provide a better insight onto what makes for a better shape harmonisation.

Doing so offers the following benefits:

1. If clear trends are obtained, they can be further validated through post manufacture experiments and stored in the form of design principles.
2. These principles would act as a knowledge repository and be used for automation of the phase.
3. Further, it would enable implementation of a more thorough optimisation process and hence a more exhaustive search can be performed.

9.2.1. ENCOMPASSING ASPECTS OF DETAILED DESIGN

Currently the conceptual design process ignores rivet positioning as it lies within the scope of detailed design and hence ADDET. ADDET locally changes splice design through customised sheet edge positioning, to accommodate rivets without effecting global design or violating previously satisfied constraints. With the current input requirements of ADDET, if a connection is made between the two tools, a high level of information loss and re-work is expected. Instead of updating ADDET, it is recommended that its functionalities can be incorporated into the panel design tool through additional capability modules. Doing so would enable design modifications with minimum customisation. The problem for this capability module can be defined similar to that of ADDET.

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GLOSSARY

ADDET	Automated Detailed Design Tool
Base GLARE	Smallest thickness that can exist over panel.
Bay	Area bounder by two stringer and two frames.
Circumferential Splice Configuration	when sheets are spliced in the circumferential direction.
Concept	It is the panel book design combined with its cost and weight performance.
Control Parameters	Set of user defined requirements that limit the solution space being searched and define aspects of the solution finding process.
CSP	Constraint Satisfaction Problem.
FML	Fibre Metal Laminate.
Harmonisation	The process of of ensuring manufacturing of laminate design.
ILD	Inter-Laminar Doubler. Sheet metals inserted between layers of base layup to achieve local thickening.
KBE	Knowledge Based Engineering.
Layup Harmonisation	The process of checking and modifying GLARE types at different bays to ensure layup is symmetric about imaginary centre axis.
Longitudinal Splice Configuration	when sheets are spliced in the longitudinal direction.
OEM	Original Equipment Manufacturer.
Panel Book Design	It is a manufacturable design accounting for all properties of sheet metal metal in design like shape size type configuration etc. It also has some basic information on prepreg layers.
Post-Harmonisation	The second automated phase that can be be performed iteratively along with the manual shape harmonisation. It generates designs with for all ILD splicing techniques and splice orientation value.
Preformed Sheet	sheets that have been stretched into desired shape.
Pre-Harmonisation	The first automated phase that generates designs with different base GLARE and sheet types.
Prepreg	All layers of glass fibres having same or different orientation embedded in adhesive and sandwiched between two metal layers.
Shape Harmonisation	The creative process of re-defining ILD shape.
Splice Configuration	Direction of splice.
Splice Orientation	The control parameter that defines direction of overlap. Roof tile/+1 indicates sheets from crown over lap belly. Inverse roof tile/-1 is the opposite of roof tile.