STIFFNESS AND PLIABILITY

Developing an Algorithm to Identify Intrinsic and Reflexive Stiffness during Voluntary Movement

and a Shared Mental Model Making Cross-Disciplinary Collaboration Dynamics Meaningful to Engineers

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Master Thesis Mechanical Engineering and Science Communication

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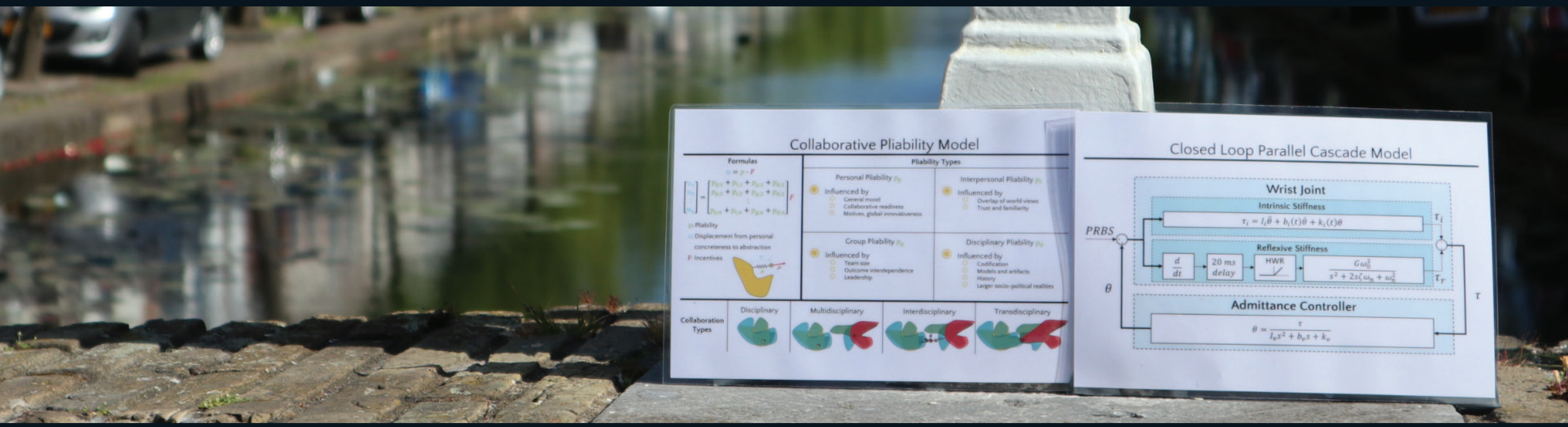

Stiffness and Pliability

Developing an Algorithm to Identify Intrinsic and Reflexive Stiffness during Voluntary Movement and a Shared Mental Model making Cross-Disciplinary Collaboration Dynamics Meaningful to Engineers

by

Jorik van Koppen

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Preface

Stiffness and pliability. While their definitions are narrowly linked, they can have completely different meanings when they are used in different contexts.

I spent a lot of time thinking about how this thesis would be perceived by my technical peers. In an environment with a lot of technical students, disciplines are often ranked from highest to lowest. The disciplines that are the most technical always end up at the top. These disciplines are perceived as ones that require you to be smarter and teach you to become superior as opposed to people with backgrounds that are less technical.

This way of looking at other fields can be seen as a magnification of what happens at a larger scale in society. Every discipline has its own definitions of what is perceived as competent and many disciplines claim to solely possess the truth.

This image ignores the enormous added value that the combination of different worldviews can bring. Now, more than ever, collaborating across disciplines is crucial. Our brains conceive the world in similar ways, even though disciplinary differences sometimes make it difficult for us to collaborate. If we want to address today's grand challenges like climate change, food security and keeping up with the pace of technology, professionals across all disciplines have to work together. I would like to invite you, the reader, to think about in what ways you can cross your own disciplinary boundaries. If the opportunity arises, immerse yourself with someone else's conceptualisation of the world. It might bring creativity, imagination and coherence to your thinking in ways that you had not imagined.

Acknowledgements

As time and my project progressed, I received a lot of support from numerous people.

First of all, I would like to thank Alfred, Eva, Maarten and Winfred for their council for the duration of this project. It was a pleasure to have the four of you guiding me in conducting this project - I enjoyed working on it a lot and all of you definitely played a big role in that.

I would also like to thank 'The Squad' for the endless study sessions in the 3mE study landscape and the Science Communication graduation group for the great brainstorm sessions at TNW. In particular, I would like to thank Thijs for all of the great input during the countless brainstorms that we had with regards to my topic – Your input and insights have definitely made my project more fun for me. I also want to thank Nelle, Johan and Gailey for their time and dedication towards proof-reading my thesis and for giving me additional input during the final weeks. Also, a big thank you to Melina for being my study buddy over these last few months and for going through the process of graduating in quarantine together.

Moreover, I am grateful for my family for providing me endless directions and support during the first twenty-five years of my life. Parents, I am extremely grateful for the way that you support me, care for me are always there for me. I feel grateful to have a brother and two sisters who are so different and each figured out how to live life in a unique way. Having three distinct examples of how life can be lived to the full extent of happiness has been an inspiration while figuring out who I want to be myself.

Lastly, I would like to express my deepest gratitude to anyone who has inspired me, helped me, laughed with me and motivated me over the past years. Studying in Delft has been an absolute delight, and it has been so for all of the amazing people that I have been able to meet and befriend over the years.

Jorik van Koppen
Delft, 2020

Contents

Summary

Part I: General Introduction

System identification techniques to analyse movement disorders are in development, but concrete clinical evidence to receive broad support from the clinical world for these techniques is lacking. This master thesis proposes two ways to accelerate their development. Part II focuses on the development of system identification techniques themselves that are useful in diagnosing movement disorders. Part III focuses on engaging medical scientists in cross-disciplinary development by developing a shared mental model to transfer knowledge on the processes behind cross-disciplinary collaborations to mechanical engineers.

Part II: Joint Stiffness (Abstract Scientific Paper)

Being able to separately identify intrinsic and reflexive contributions to dynamic joint stiffness helps in developing more comprehensive analysis methods for movement disorders. For this study, an ensemble-based algorithm is developed to identify intrinsic and reflexive joint stiffness during voluntary movements. The algorithm combines two methods from previous research: the Parallel-Cascade method to separate intrinsic and reflexive stiffness and an instrumental variable approach to allow subjects to carry out voluntary movements and apply closed-loop identification. A simulation and experimental study are conducted with the human wrist joint in which a sinusoidal angle reference trajectory is followed using multiple realisations of the same trial. To elicit the modulation of intrinsic parameters, a torque field is applied that is linearly dependent on the wrist angle with a greater flexion resulting in a higher torque. In the simulation study, the intrinsic and reflexive pathways are separated and over 98% of the variance is explained. In the experimental study, the modulation of intrinsic stiffness is estimated with an explained variance of over 90%. Intrinsic stiffness is highest during the peaks of the trajectory and lower during the transition phase from one peak to another. However, the torque response of the experimental study shows that no significant extra torque is added during the reflexive EMG peak. The obtained results underline the promising potential of the algorithm and open up new possibilities once the algorithm is tested on an experimental task where more reflexes are elicited.

Part III: Collaborative Pliability

Metacognition plays an important role in interdisciplinary projects, as disciplinary professionals need to flexibly apply conventional procedures for problem-solving to integrate them with the procedures of professionals with different backgrounds. Devoting time and effort to this metacognitive process helps in coping with it. However, most theories on cross-disciplinary collaborations are written from a social sciences paradigm and are inherently difficult to interpret from a mechanical engineering paradigm.

In order to bridge these paradigms, an analogy is developed. Analogy-making is central to cognitive processing and is used to link concepts from both epistemologies together. This is done by assembling a theoretical framework containing concepts on the processes behind cross-disciplinary collaborations. These concepts are linked to analogous counterparts from mechanical engineering by relying on conceptual similarities between mechanical stiffness and collaborative pliability. As a result, knowledge of cross-disciplinary collaborations can be immersed with the existing mental models of engineers and their extensive conceptual knowledge of mechanical stiffness. Collaboration theories become part of the primary discipline instead of being treated as a separate discipline.

The model, called the Collaborative Pliability Model, is assessed by a group of six mechanical engineering students. The students considered the model to be an effective tool for learning about cross-disciplinary collaborations. By using the model, they came up with numerous new factors affecting the success of their collaborative process. This gives a promising outlook for the future and opens the door for new applications for developing an analogy used to transfer knowledge between specific target groups.

Glossary

codification Capturing fundamental concepts and methods into unambiguous and linearly interpretable functions. 45

collaborative pliability Professional's tolerance to move to personal abstraction as a result of incentives. Can be written as a sum of personal, interpersonal, group and disciplinary pliability. Also just called 'pliability'. 41, 64

Collaborative Pliability Model Shared mental model that was designed for this Master thesis, describing the dynamics at play in cross-disciplinary collaborations using concepts from mechanical engineering. 61

constructive conflict Integration process where initial disagreements of unknown concepts and constructs are settled by mirroring them to existing knowledge. 40

cross-disciplinary collaboration Collective term used to describe any collaboration between multiple disciplines. Encompasses multidisciplinary, interdisciplinary and transdisciplinary collaborations. 47

disciplinary collaboration Collaboration with people having similar backgrounds where no cross-disciplinarity takes place. 47, 68

disciplinary pliability Part of collaborative pliability that is made up of factors having an effect on the disciplinary level. 45, 66

group pliability Part of collaborative pliability that is made up of factors having an effect on the group level. 44, 65

incentive Inducement evoking a professional to move to disciplinary abstraction. 63

interdisciplinary collaboration Cross-disciplinary form of working together involving the partial integration of methods, tools, concepts or theories. 48, 69

interpersonal pliability Part of collaborative pliability that is made up of factors having an effect on the interpersonal level. 43, 65

knowledge integration Constructive combination of perspectives. 39

mechanical compliance Concept in the mechanical domain, defined as the relation between the displacement of an object and the force working on it. Inverse of mechanical stiffness. 62

mechanical stiffness Concept in the mechanical domain, defined as the relation between the force acting on an object and the resulting displacement. 61

mental model Description of the fixed patterns that professionals use to structure their knowledge and call upon whenever a problem is being solved. 38

multidisciplinary collaboration Cross-disciplinary form of working together with little integration of knowledge and cultures. Participants remain conceptually and methodologically anchored in their own field. 47, 68

personal abstraction area of personal knowledge containing (partially) unknown, new knowledge, methods of problem solving or disciplinary rules. 62

personal concreteness area of personal knowledge containing familiar concepts, methods of problem solving and disciplinary rules. 62

personal pliability Part of collaborative pliability that is made up of factors having an effect on the personal level. 43, 65

pliability Professional's tolerance to move to personal abstraction as a result of incentives. Can be written as a sum of personal, interpersonal, group and disciplinary pliability. Also called collaborative pliability to emphasize the usage in a collaboration context. 41

shared mental model Overlapping mental representation of the knowledge within a team. 38

transdisciplinary collaboration Cross-disciplinary form of working together where theories, concepts and approaches are fully integrated to address a common problem. 48, 70

Part I

General Introduction

1

General Introduction

1.1 Movement Disorders

Movement disorders cripple and weaken the muscles and control of affected patients. These disorders can target numerous muscle groups and affect the way the patient walks, sits, jumps, breathes, eats and kisses, while the perception of the patient is often completely unaffected. Many disorders progressively worsen the muscle functionality over time and some movement disorders can even be lethal. In the Netherlands alone, an estimated 200,000 people suffer from one or more movement disorders (Prinses Beatrix Spierfonds, 2012).

Different origins can cause movement disorders including problems in the muscles themselves, in the nerves transmitting pathways from and to the central nervous system or in the spinal cord. Still, the symptoms of many movement disorders are similar particularly in the early stages of the disease, while about 500 different movement disorders exist (Prinses Beatrix Spierfonds, 2012). Methods are required to gain a better understanding of how movement disorders work and to monitor the effectiveness of treatment programmes.

1.2 System Identification

Movement disorders can be analysed by using system identification techniques. System identification is a discipline that "deals with the constructions of mathematical models of dynamic systems using measurements of their inputs and outputs" (Westwick and Kearney, 2003). System identification serves three main functions: To be able to predict how a system will behave in the future, to control that system's behaviour and to analyse the system to gain insights in its functioning. In the case of movement disorders, gaining insights into the functioning of the system is the main objective.

Each identification session consists of four basic steps: Collecting information on the system, selecting an appropriate model structure to represent the system, determining model parameters using measurements to fit the model as well as possible and validating the selected model (Pintelon and Schoukens, 2012). This is a widespread task with numerous options that have mutual influence over one another. Firstly, in studying the control of the human limb, information on the system is often collected by applying perturbations that actively excite the limb. This can be done by using a manipulator: A device designed to apply and measure specific forces and positions to a limb, as shown in Figure 1.1.

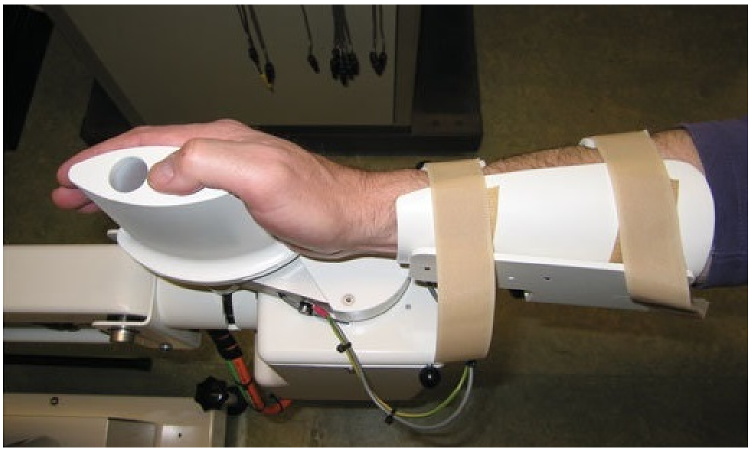

Figure 1.1: Wrist constrained by the Wristalyzer, a perturbator that is designed to apply and measure the force and position of the wrist (Image by van der Krogt et al. (2019)).

Next, a mathematical model structure should be chosen to describe the system. A wide variety of mathematical options is available: Time-varying versus time-invariant, linear versus nonlinear, parametric versus nonparametric, et cetera. Afterwards, in order to compare the measured data with the model structure, an algorithm needs to be developed that estimates the parameters underlying the measured data based on the model structure. Finally, the goodness of the parameter fit needs to be validated.

System identification techniques can be used to analyse human joints such as the wrist, elbow, shoulder, ankle, knee or hip. An advantage of these techniques is that they are non-invasive, meaning that no healthy tissue has to be infiltrated in order to apply them. However, sufficient mathematical knowledge is needed to comprehend the model structures that are used for modelling the neuromuscular system.

Since the inception of system identification solutions to measure joint stiffness, medical and technical researchers have collaborated to further the development of these solutions (Schouten et al., 2003) and since then there have been several cross-disciplinary projects to integrate system identification solutions with medical solutions (Schouten et al., 2008; Meskers et al., 2015). As a result, for example, system identification techniques are now used to identify the origins of wrist spasm after a stroke (Andringa et al., 2019).

1.3 Development

While their potential is great, for many applications, additional development of system identification solutions is needed to create viable and effective methods for clinical applications. The development of these methods should eventually lead to tailor-made solutions for clinical applications. In two interviews conducted for this master thesis, specialists argued that clinical evidence showing the added value of system identification techniques can draw broader interest and support from the clinical community with regard to these techniques (see Appendix C.2). This would pave the way for more easily realisable cross-disciplinary collaborations between medical and technical researchers to further the development of system identification solutions and further clinical evidence. This positive feedback loop is illustrated in Figure 1.2.

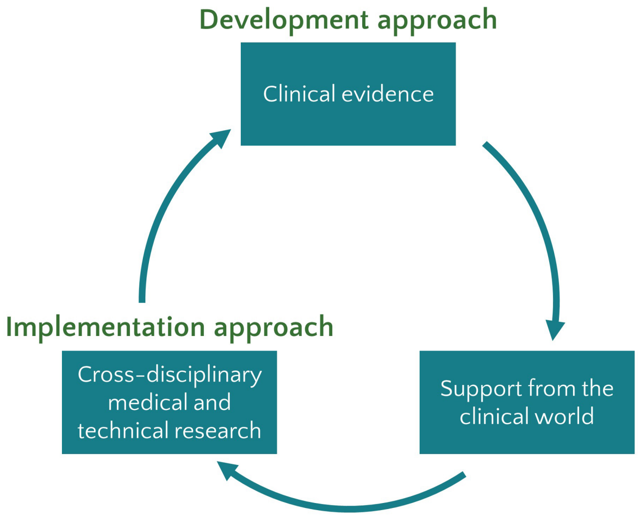

Figure 1.2: Virtuous circle showing the positive feedback loop between support from the clinical world, leading to more cross-disciplinary medical and technical research, boosting the development of clinical evidence. This cycle is based on interviews with medical and technical professionals.

Still, finding a large support base from the clinical world to apply system identification solutions in practice has yet to come. Without clinical evidence, engaging medical researchers in the development process of system identification techniques is difficult. This limits the amount of produced clinical evidence required for their support in the first place. In other words, the virtuous circle illustrated in Figure 1.2 has yet to gain momentum.

1.4 Approaches to Acceleration

Accelerating the development process shown in Figure 1.2 is difficult. Two approaches for doing so are proposed that are indicated in green in the figure. A development approach as introduced in Section 1.4.1 that is the main topic of Part II of this thesis and an implementation approach as introduced in Section 1.4.2 that is the main topic of Part III.

1.4.1 Development Approach

The first approach focuses on the development side of the project. Further development of system identification techniques contributes to providing clinical evidence showing the added value of these techniques. This can, in turn, boost the support from the clinical world.

While techniques to identify joint stiffness during static conditions and constrained movements have been more extensively researched, research with regard to voluntary movements remains limited. Voluntary movements are of particular interest since movement disorders generally hinder a patient while they move voluntarily. In order to perform a more comprehensive analysis of movement disorders, a separation of muscular and neural mechanisms contributing to joint stiffness is desired. For this reason, the following research goal is proposed:

RG1: The goal of this research is to investigate if intrinsic and reflexive wrist stiffness can be identified during voluntary movements.

The topic and research challenges are more elaborately introduced in Part II of this thesis.

1.4.2 Implementation Approach

The second approach focuses on the implementation side of the project. While system identification techniques are not yet at the stage of development where they can readily be used for clinical applications, engaging medical researchers in their development can speed up the development process to create clinical evidence.

Metacognition plays an important role in interdisciplinary projects. Experienced disciplinary professionals have developed expertise and ways of problem-solving in their own domain, which can work counterproductive in a cross-disciplinary environment where multiple representations of a problem need to be integrated (Keestra, 2017). Having knowledge of metacognitive processes and challenges boosts the professional's ability to cope with them.

Theories on cross-disciplinarity and the factors that influence it are often written from a social science perspective, which is an epistemology that is fundamentally different from the positivist paradigm that technical sciences rely on. To make theories on cross-disciplinary collaborations more meaningful to technical scientists, these paradigms should be bridged. For the implementation side, the goal of this research is as follows:

RG2: The goal of this research is to gain insights into the effectiveness of creating a shared mental model using a tailor-made analogy to bring together the epistemological paradigms of collaboration sciences and mechanical engineering.

The topic and research challenges are more elaborately introduced in Part III of this thesis.

1.5 Thesis Structure

This master thesis is a combined project between two master programmes at the Delft University of Technology: Mechanical Engineering and Science Communication. The Mechanical Engineering part of the project focuses on the development side, whereas the Science Communication part focuses on the implementation side. It is structured along IV parts, as is visualised in Figure 1.3.

Part I introduces the topic of this thesis and the two research goals that are the main focus of this project.

Next, Part II consists of the Mechanical Engineering side of the project. This part focuses on the development of a system identification technique to identify intrinsic and reflexive stiffness during voluntary movement. A scientific article is presented that discusses the newly developed algorithm that is tested on two studies: a simulation study and an experimental study.

Afterwards, Part III consists of the Science Communication side of the project. This part is centred around developing a shared mental model between the epistemological paradigms of collaboration sciences and mechanical engineering using an analogy. Theories on cross-disciplinary collaborations are assembled within a theoretical framework and linked to analogous counterparts from mechanical engineering. The model is assessed by presenting it to a group of mechanical engineers and determining their perceptions of it.

Finally, a reflection on the two projects is given in Part IV.

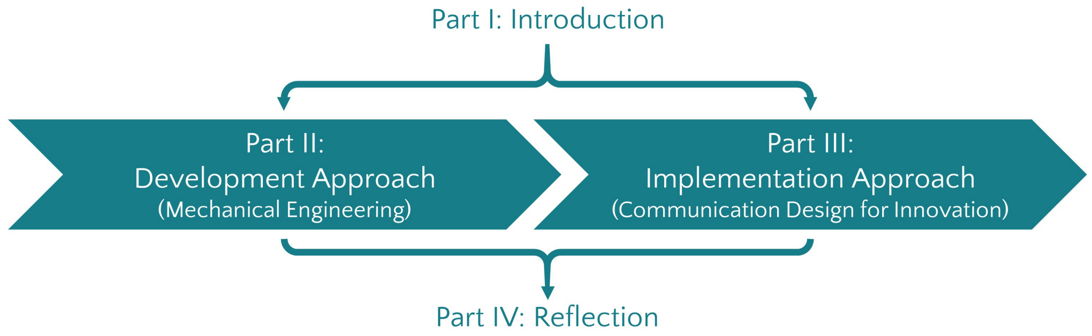

Figure 1.3: Structure of the different parts of this master thesis.

Part II

Joint Stiffness

Developing an Algorithm to Identify Intrinsic and Reflexive Stiffness during Voluntary Movement

2 Scientific Article

In this chapter, research is presented in which a system identification technique is developed to identify intrinsic and reflexive stiffness during voluntary movement. The research is presented in the form of a scientific article.

First, a list of abbreviations used in the scientific article is presented in Section 2.1. Next, the variables and parameters that are used in the article are listed in Section 2.2. Finally, the scientific article itself is presented in Section 2.3.

2.1 Abbreviations

EMG: Electromyography
IRF: Impulse Response Function
PRBS: Pseudo-Random Binary Sequence
VAF: Variance Accounted For

2.2 Variables & Parameters

2.2.1 Variables

Independent

j: Time [s]
k: Time shift [s]
r: Realisation [-]
s: Frequency variable [Hz]
t: Time [s]

Dependent

θ: Angle [rad]
τ: Torque [Nm]

2.2.2 Parameters

I_v: Virtual inertia [Nms^2/rad]
b_v: Virtual damping [Nms/rad]
k_v: Virtual stiffness [Nm/rad]

I_i: Intrinsic inertia [Nms^2/rad]
b_i: Intrinsic damping [Nms/rad]
k_i: Intrinsic stiffness [Nm/rad]

G: Reflexive static gain [-]
ω_n: Reflexive natural frequency [rad/s]
ζ: Reflexive damping ratio [-]

2.2.3 System Identification

Constants

f_{s1}: Sample frequency 1 [Hz]
f_{s2}: Sample frequency 2 [Hz]
$M1$: Minimum lag [s]
$M2$: Maximum lag [s]
N: Window size [s]
R: Total number of realisations [-]
Δt: Sampling interval [s]

Validation

$\%VAF_{np}$: %VAF of the nonparametric estimate [-]
$\%VAF_{np,i}$: Intrinsic contribution to $\%VAF_{np}$ [-]
$\%VAF_{np,r}$: Reflexive contribution to $\%VAF_{np}$ [-]
$\%VAF_p$: %VAF of the parametric estimate [-]

Internal Variables

τ_i: Intrinsic torque [Nm]
$\tau_{i,r}$: Intrinsic residual torque [Nm]
$\hat{\tau}_i$: Estimated intrinsic torque [Nm]
τ_r: Reflexive torque [Nm]
$\tau_{r,r}$: Reflexive residual torque [Nm]
$\hat{\tau}_r$: Estimated reflexive torque [Nm]
$\hat{\tau}_x$: Estimated torque [Nm]

c_i: Intrinsic compliance [rad/Nm]
e: IRF error [rad/Nm]
$h_i(t)$: Intrinsic IRF [Nm/rad]
$h_r(t)$: Reflexive IRF [Nm/rad]
$H_i(s)$: Transfer function intrinsic linear dynamics
$H_r(s)$: Transfer function reflexive linear dynamics
Φ_{ux}, Φ_{uy}: Multisegment cross correlation matrix
ϕ_{ux}, ϕ_{uy}: Multisegment cross correlation

2.3 Scientific Article

See next pages.

Identification of Intrinsic and Reflexive Stiffness during Voluntary Movement of the Wrist

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Abstract

Being able to separately identify intrinsic and reflexive contributions to dynamic joint stiffness helps in developing more comprehensive analysis methods for movement disorders. For this study, an ensemble-based algorithm is developed to identify intrinsic and reflexive joint stiffness during voluntary movements. The algorithm combines two methods from previous research: the Parallel-Cascade method to separate intrinsic and reflexive stiffness and an instrumental variable approach to allow subjects to carry out voluntary movements and apply closed-loop identification. A simulation and experimental study are conducted with the human wrist joint in which a sinusoidal angle reference trajectory is followed using multiple realisations of the same trial. To elicit the modulation of intrinsic parameters, a torque field is applied that is linearly dependent on the wrist angle with a greater flexion resulting in a higher torque. In the simulation study, the intrinsic and reflexive pathways are separated and over 98% of the variance is explained. In the experimental study, the modulation of intrinsic stiffness is estimated with an explained variance of over 90%. Intrinsic stiffness is highest during the peaks of the trajectory and lower during the transition phase from one peak to another. However, the torque response of the experimental study shows that no significant extra torque is added during the reflexive EMG peak. The obtained results underline the promising potential of the algorithm and open up new possibilities once the algorithm is tested on an experimental task where more reflexes are elicited.

Keywords: Wrist joint stiffness; Parallel-Cascade; Instrumental variable; System identification

1 Introduction

Movement disorders affect around 200,000 patients in the Netherlands alone and in total, about 500 movement disorders exist (Prinses Beatrix Spierfonds, 2012). To prescribe accurate treatment, an accurate analysis of muscle behaviour is required, but this is difficult particularly in the early stages of a disease.

Muscle behaviour can be described in terms of dynamic joint stiffness, which is the relation between the angular position and torque working on a joint. Three mechanisms contribute to dynamic joint stiffness: Voluntary, intrinsic and reflexive mechanisms, the contributions of which are referred to as voluntary, intrinsic and reflexive stiffness. Voluntary stiffness is activated by pre-planned, deliberate movements. Intrinsic stiffness is caused by passive visco-elasticity and inertia of the limb, joint and tissue and by co-contraction. Reflexive stiffness is activated by unconscious and involuntary neural responses. Due to neural time delays reflexes are induced after around 30 ms, whereas intrinsic stiffness responds instantaneously.

Some movement disorders, such as spasticity, are known to have separate effects on intrinsic and reflexive pathways and being able to quantify intrinsic and reflexive stiffness separately helps in performing a more comprehensive analysis (Mirbagheri et al., 2001; Bar-On et al., 2014). Additionally, having a better understanding of intrinsic and reflexive stiffness can be used in the design of artificial devices such as prostheses or exoskeletons (Rouse et al., 2014).

Current approaches to analyse intrinsic and reflexive stiffness can be subdivided into three categories: EMG-based approaches, experimental approaches and system identification approaches (Shemmell et al., 2010). EMG-based approaches look at electromyography (EMG) recordings of muscle activity and separate intrinsic and reflexive contributions based on the neural time delay of the reflexes (Kurtzer et al., 2008). However, because the relation between muscle activity and joint stiffness is nonlinear and mostly unknown, these methods cannot be used to get a quantitative estimation (Shemmell et al., 2010). Experimental approaches use ischemia or electrical stimulation to temporarily block the reflexive pathways of a patient. A shortcoming of these methods is that the experiments in which reflexes are blocked also influence the intrinsic contributions (Sobhani Tehrani, 2018). Finally, system identification methods make use of noninvasive experiments and mathematical knowledge of the human body so that the dynamic properties of a joint can be calculated. These techniques require mathematical modelling knowledge of the human body, but they are non-invasive and can be used to get a quantitative estimate of intrinsic and reflexive joint stiffness.

Numerous studies have been conducted to identify joint stiffness using system identification techniques. During time-invariant conditions, in which background muscle activity, position and the parameters underlying the dynamics of the limb remain constant, intrinsic and reflexive stiffness have been analysed in open-loop where the joint position is constrained (Kearney et al., 1997; Zhang and Rymer, 1997; Mirbagheri et al., 2000) and in closed-loop where the subject can move freely (van der Helm et al., 2002; Schouten et al., 2008).

However, fewer studies have been conducted where joint stiffness is identified during movements. This is for two reasons: First of all, the neuromuscular system is nonlinear during movements, which is more difficult to model. The solution that is most often applied is modelling a nonlinear system as a time-varying linear system so that time-varying system identification methods can be applied (Ludvig and Perreault, 2014). Second of all, during voluntary movements the joint torque and angle mutually influence each other creating a feedback loop. Hence, closed-loop system identification is needed (Schouten and Mugge, 2019). To avoid the necessity of closed-loop system identification, research has been conducted in which the position of a limb is constrained so that open-loop identification suffices and time-varying intrinsic and reflexive stiffness is measured (Ludvig et al., 2011; Sobhani Tehrani et al., 2014; Jalaleddini et al., 2017; Guarín and Kearney, 2017; Golkar et al., 2017). These techniques make use of the Parallel-Cascade model, an open-loop model in which angle is used as input and torque as output. Other experiments have been conducted in which closed-loop identification is applied to identify intrinsic stiffness alone (Ludvig and Perreault, 2014; Ludvig et al., 2017; Van de Ruit et al., 2018b; Esteban et al., 2019). These experiments make use of an instrumental variable approach: The torque exerted by the joint is used as an input to an admittance controller to calculate the new joint position constrained by the perturbator (de Vlugt et al., 2002). As a result, the free movement of a limb is allowed and subjects are in control of their movement.

The goal of this study is to develop an algorithm to identify intrinsic and reflexive stiffness during voluntary movement. This is done by combining two methods used in literature: The Parallel-Cascade method to separate intrinsic and reflexive contributions to joint stiffness and an instrumental variable approach so that subjects are in control of their own movement. The developed algorithm is tested on the wrist joint. An external angle disturbance signal is exerted on the joint so that closed-loop system identification can be applied. The method used for time-varying system identification is the ensemble approach, in which multiple realisations of the same trial are used to get an estimate of the time-varying behaviour of a joint (Ludvig et al., 2011). The amount of required ensembles is greatly reduced by assuming a short time window over which joint stiffness is constant (Ludvig and Perreault, 2011).

2 Methods

Figure 1 shows an overview of each data analysis step that is conducted and the resulting output data. In section 2.2 the setup is described that forms the basis of two studies: a simulation study (section 2.3) and an experimental study (section 2.4). The data from both studies is preprocessed (section 2.5) and consequently used for system identification (section 2.6) and parameter estimation (section 2.7). Finally, validation methods are applied to assess the quality of the estimate (section 2.8).

2.1 Subjects

An experiment is conducted with three participants: The researcher himself and two staff members of the TU Delft Neuromechanics & Motor Control Laboratory. Ethics approval for the experiment is given by the TU Delft Human Research Ethics Committee.

2.2 Setup

Figure 2 shows the setup on which the simulation and experimental study are based. Multiple repetitions of a 35 s realisation are performed in which the wrist has to follow a sinusoidal angle trajectory. An angle-dependent torque field is applied to the wrist to elicit modulation of intrinsic damping b_i and stiffness k_i.

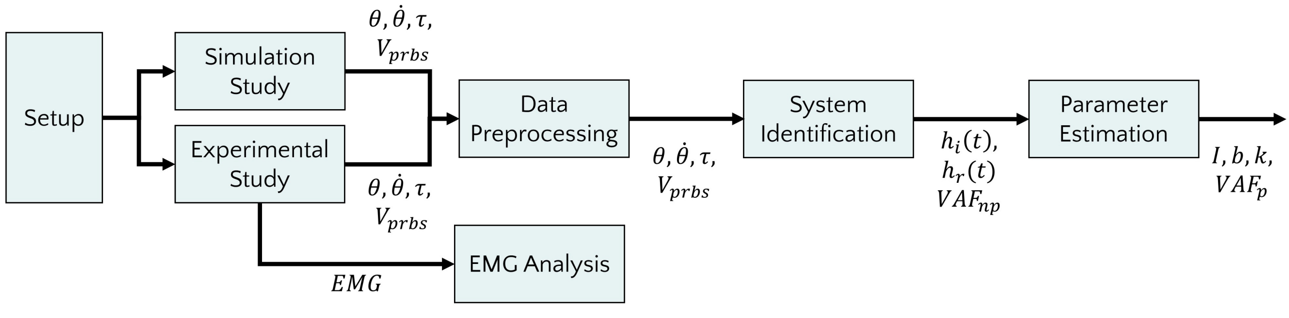

Figure 1: Overview of the data analysis steps that are taken for the simulation and the experimental studies. The output data of each step is shown: angle θ, angular velocity $\dot{\theta}$, torque τ, velocity perturbation V_{prbs}, EMG signal EMG, impulse response function $h(t)$, inertia I, damping $b(t)$, stiffness $k(t)$, variance accounted for after system identification VAF_{np} and variance accounted for after parameter estimation VAF_p.

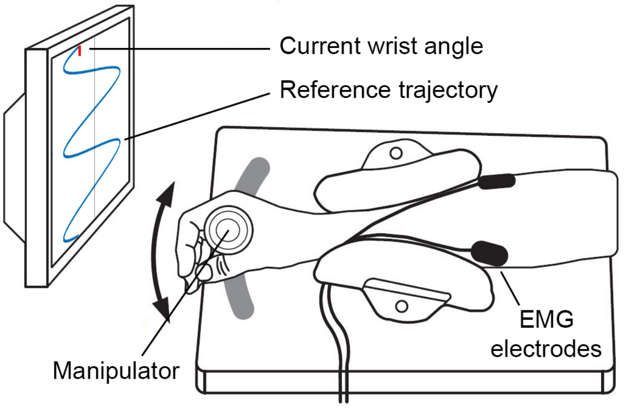

Figure 2: Schematic of the setup that forms the basis for the simulation and the experimental study. A human wrist is constrained by a manipulator so that it can only move in the flexion-extension direction, along the degree of freedom of the handle. Two EMG electrodes are attached to the underarm to measure muscle activity. The reference trajectory that the subject has to follow is shown on a screen together with the current wrist angle. (Image modified from Mugge et al. (2012)).

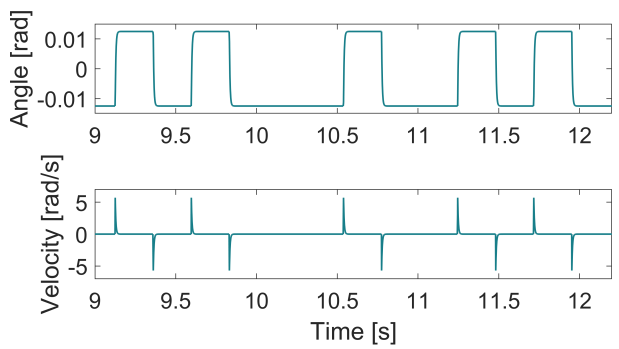

Figure 3: Position and velocity of the filtered PRBS signal for an arbitrary part of an arbitrary realisation.

During each realisation, Pseudo-Random Binary Sequence (PRBS) perturbations are applied to the wrist that perturb the angle to deviate from the trajectory to be followed. The signal has a peak-to-peak amplitude of 0.025 rad, a switching time of $\frac{\sqrt{2}}{6}$ s and a zero-cross rate of $\frac{1}{3.1}$ s. In order to stay within the maximum velocity bands of the physical machine, the signal is low-pass filtered with a 1st order Butterworth filter having a cut-off frequency of 40 Hz. This yielded PRBS signals with a rise time of 8.7 ms and a maximum velocity of 5.7 rad/s, see Figure 3.

2.3 Simulation Study

A simulation study with a series of different conditions is conducted using MathWorks' Simulink software, see Figure 4. Three variations of the same simulation are conducted to investigate the effect on the $\%VAF$: Intrinsic stiffness alone versus intrinsic and reflexive stiffness, open-loop versus closed-loop and a sampling frequency of 250 Hz versus 2500 Hz. All possible combinations are simulated, yielding a total of $2^3 = 8$ conditions. For each simulation 90 realisations of 35 s are conducted.

2.3.1 *Intrinsic Stiffness*

Intrinsic stiffness is modelled using a second-order differential equation:

$$\tau_i = I_i\ddot{\theta} + b_i\dot{\theta} + k_i\theta \tag{1}$$

with intrinsic inertia $I_i = 2.3 \cdot 10^{-3}$ Nms^2/rad. Instead of incorporating an angular reference trajectory, the modulation of intrinsic damping b_i and intrinsic stiffness k_i is modelled directly as a function of time, see Figure 5.

2.3.2 *Reflexive Stiffness*

The stretch reflex of a muscle corrects posture as a result of muscle stretching. It is activated by muscle spindles, which are mainly velocity-sensitive. Reflexive stiffness is modelled as the relation between input angle θ and output torque τ using the following components in series: a differentiator to account for the velocity-dependent nature of the stretch reflex, a 20 ms delay due to neural time delays, a half-wave rectifier to only create a response based on muscle stretch and not on contraction and linear dynamics to

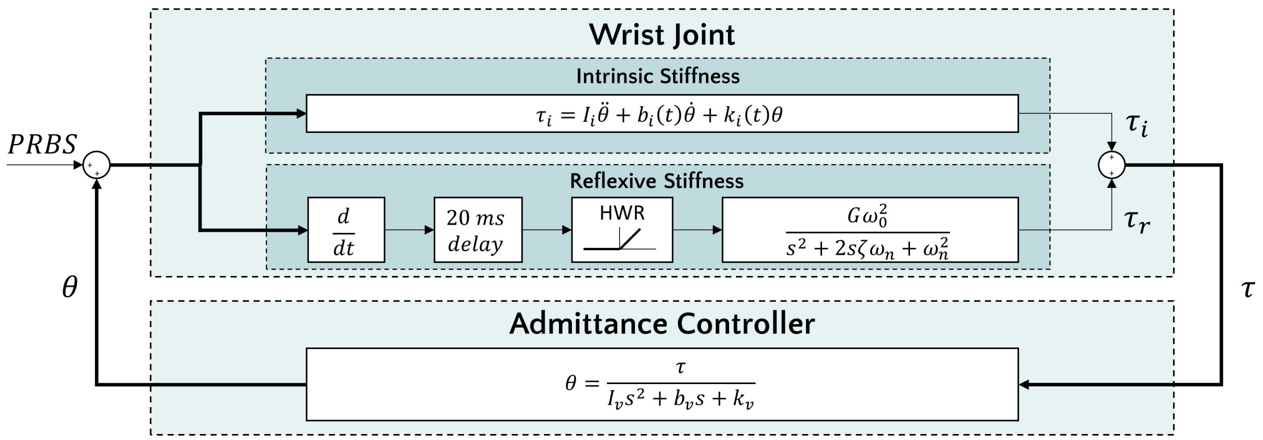

Figure 4: Block scheme of the simulation study with all components included. The wrist joint is modelled using a Parallel-Cascade model consisting of intrinsic and reflexive stiffness. These pathways produce an intrinsic torque τ_i and a reflexive torque τ_r that are summed to create output torque τ. Voluntary stiffness is not modelled. The torque is used as input signal to an admittance controller to calculate wrist angle θ. The imposed PRBS disturbance is added to θ.

account for muscle activation dynamics. The linear dynamics are modelled using a second-order transfer function:

$$H_r(s) = \frac{G\omega_n^2}{s^2 + 2s\zeta\omega_n + \omega_n^2} \tag{2}$$

with static gain G, natural frequency ω_n and damping ratio ζ. An issue that arises when reflexes are modelled in closed-loop, is that its delayed gains can easily create instability. To avoid this, reflexes are modelled with an unrealistically high natural frequency, so that the reflexes damp out quickly and have a limited contribution to the feedback gain, see Figure 6. While this does not give a valid representation of reality, it does give the typical half-wave rectified velocity-dependent response that real reflexes have and enables testing to see if the algorithm can distinguish such a pattern. The following coefficients are used: $G = 0.6$, $\omega_n = 380$ rad/s and $\zeta = 0.7$.

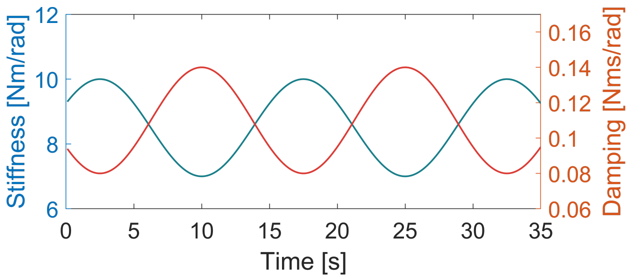

Figure 5: Trajectory of b_i and k_i for the simulation studies. b_i varies sinusoidally between 0.08 and 0.14 Nms/rad and k_i varies sinusoidally between 7 and 10 Nm/rad in antiphase with damping, so that k_i is highest when b_i is lowest and vice versa.

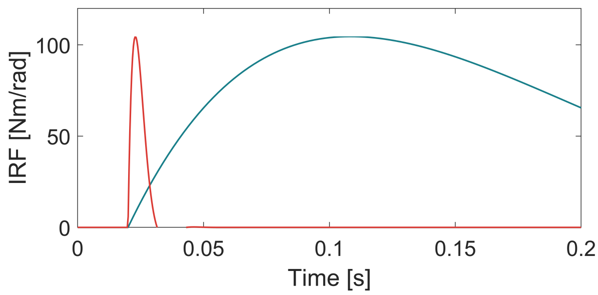

Figure 6: Very fast reflexes (in red) used for simulation compared to reflexes with realistic values (in blue). The static gains are scaled so that the amplitude of the reflex peaks are equal. The very fast reflexes have a natural frequency of $\omega_n = 380$ rad/s, whereas reflexes with realistic values typically have a natural frequency of around $\omega_n = 12$ rad/s. Very fast reflexes are used in the simulation study to avoid instabilities.

2.3.3 Closed-loop

The closed-loop conditions of the simulation study are fabricated by modelling the wrist joint in closed-loop with an admittance controller representing a manipulator. The wrist applies a torque τ to the controller and as a result the controller moves by an angle θ. A second-order transfer function translates the torque to the resulting displacement:

$$\theta = \frac{\tau}{I_v s^2 + b_v s + k_v} \tag{3}$$

with virtual inertia $I_v = 0.1$ Nms^2/rad, virtual damping $b_v = 0.02$ Nms/rad and virtual stiffness $k_v = 5$ Nm/rad.

2.3.4 Sampling Frequency

Two sampling frequencies are used for the simulation study: $f_{s1} = 250$ Hz and $f_{s2} = 2500$ Hz.

2.4 Experimental Study

2.4.1 Apparatus

See Figure 2 for a schematic overview of the apparatus. The manipulator is actuated by a servo motor that controls the movement of the handle. It is connected to a real-time dSpace system with Matlab Simulink running on it. Data is collected with a sampling frequency of $f_{s2} = 2500$ Hz.

2.4.2 Admittance Controller

The wrist position is controlled using an instrumental variable approach (de Vlugt et al., 2002). The torque delivered by the participant is used as input to the controller to calculate the angular velocity to be delivered using a second-order transfer function. This will give the subject control of its own position:

$$\theta = \frac{\tau}{I_v s^2 + b_v s + k_v} \tag{4}$$

with virtual inertia $I_v = 1.6 \cdot 10^{-3}$ Nms^2/rad, virtual damping $b_v = 0.1$ Nms/rad and virtual stiffness $k_v = 1.5$ Nm/rad. These values are chosen by trial and error so that the system feels natural to the subject and resistance is present but minimal.

2.4.3 Experiment Preparation

Before conducting the experiment, EMG electrodes are placed on the skin of the lower arm to measure the electrical activity of the Flexor Carpi Radialis and Extensor Carpi Radialis Brevis muscles. To make the EMG signal as clear as possible, the skin below the electrodes is cleaned with alcohol before placing the electrodes. The chair of the participant is adjusted to align the height of the arm with that of the manipulator. Participants are constrained with their right underarm in the manipulator. The hand is attached to the handle using a velcro strap.

Before starting the actual experiment, the participants perform one or two realisations of the dynamic task to get acquainted with the task and perturbations.

2.4.4 Task

Subjects have to follow a sinusoidal angle reference trajectory, see Figure 7. The actual wrist angle is shown instantaneously to the participant on a monitor together with the reference trajectory. One realisation takes 35 s and in total 60 to 90 realisations are conducted.

After the time-varying sinusoidal realisations, three time-invariant realisations of 35 s are conducted where participants have to keep their wrist still at angles $\theta = -0.15, 0$

and 0.15 rad, also shown in Figure 7. This data is used to get a time-invariant measure of wrist stiffness in these positions.

During the realisations, a torque field is applied to the wrist that is linearly dependent on the wrist angle. The torque increases with an increasing flexion. On the extension peak of the sine, the torque is -0.7 Nm and on the flexion peak, the torque is -1.2 Nm. Since the torque is always negative, the torque field always tries to pull the wrist in the extension direction. The torque profile is labelled on the right y-axis of Figure 7.

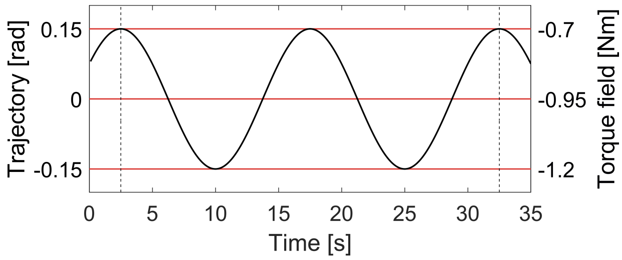

Figure 7: Wrist angle reference trajectories that subjects have to follow and are displayed on a screen. The black line shows the reference trajectory for time-varying realisations having a period of 15 s and an amplitude of 0.15 rad. The red lines show the reference trajectories for time-invariant realisations. The position-dependent torque field is labelled on the right axis. The area between the dashed lines is the area over which the system identification algorithm is applied.

2.5 Data Preprocessing

The following data is recorded: Angle, torque, velocity perturbation and EMG signal. For subject 2 EMG is not recorded.

2.5.1 *Angle, Torque and Perturbation Preprocessing*

Data recorded at sampling frequency f_{s2} is low-pass filtered with an 8th order Chebyshev filter having a cut-off frequency of 100 Hz and decimated by a factor 10 to sample frequency f_{s1}. For the simulation data sampled at f_{s1}, this step is skipped.

The rest of the data preprocessing steps are applied to the experimental data only. The standard deviation and mean-squared error of the angle are calculated for each realisation. Realisations whose standard deviation lie below 5% and above 95% of the ensemble are considered outliers and discarded. Realisations with a mean-squared error above 90% of the ensemble are also considered as outliers. Because of the overlap of segments that are considered outliers by these two criteria, on average 15% of the segments are considered outliers.

All data is consequently high-pass filtered with a cut-off frequency of 0.5 Hz. This is to remove low-frequent drift caused by voluntary torques, including the sinusoidal torque and angle due to the reference trajectory.

2.5.2 *EMG Preprocessing*

The following preprocessing steps are applied to the EMG data: First, the data is high-pass filtered with a 1st order Butterworth filter having a cut-off frequency of 0.5 Hz. Next, the data is full-wave rectified. Finally, the data is low-pass filtered by another 1st order Butterworth filter having a cut-off frequency of 80 Hz.

2.6 Estimation of Intrinsic and Reflexive Stiffness

2.6.1 *Estimation of Intrinsic Stiffness*

Intrinsic stiffness is estimated by calculating a closed-loop linear impulse response function (IRF) from position input to torque output (Ludvig and Perreault, 2014). The IRF is calculated using the following equations:

$$h(t)=\Delta t^{-1}\Phi_{ux}(t)^{-1}\Phi_{uy}(t) \tag{5}$$

$$\Phi_{uy}=\begin{bmatrix}\phi_{uy}(t,0) & \phi_{uy}(t,1) & \cdots & \phi_{uy}(t,M2-M1)\end{bmatrix}^T \tag{6}$$

$$\Phi_{ux}=\begin{bmatrix}\phi_{ux}(t-M1,0) & \cdots & \phi_{ux}(t-M2,M1-M2)\\ \vdots & \ddots & \vdots \\ \phi_{ux}(t-M1,M2-M1) & \cdots & \phi_{ux}(t-M2,0)\end{bmatrix} \tag{7}$$

with u the velocity perturbation signal, x the input angle θ, y is the output torque τ and sampling interval $\Delta t = \frac{1}{f_{s1}} = 0.004$ s. M1 and M2 are the maximum lags used to calculate intrinsic stiffness, chosen so that reflexes have not been elicited yet: $M2 = -M1 = 20$ ms. ϕ_{ux} and ϕ_{uy} are multisegment correlations and calculated as follows:

$$\phi_{ux}(t,k) = \frac{1}{NR}\sum_{r-1}^{R}\sum_{j=t-\frac{N}{2}}^{t+\frac{N}{2}} u(j-k,r)x(j,r) \tag{8}$$

for time t and lag k. r is the realisation of a total number of realisations R. j is used as an extra time variable to sum over window size N (1 s or 250 samples).

2.6.2 *Estimation of Reflexive Stiffness*

Reflexive stiffness is estimated using a Hammerstein identification algorithm (Lortie and Kearney, 2001) with the static nonlinearity modelled as a half-wave rectifier. The Hammerstein system comprises of the following elements in series: a time derivative, time delay, static nonlinearity and linear dynamics.

The measured angle is differentiated to time, delayed and half-wave rectified to get delayed, half-wave rectified angular velocity. The linear dynamics can then be identified as in 2.6.1, only now by using delayed, half-wave rectified angular velocity as input and torque as output. Because the system operates in closed-loop, the perturbation signal that functions as disturbance signal u is also differentiated, delayed and half-wave rectified.

2.6.3 *Subsequent Estimation of Intrinsic and Reflexive Stiffness*

The algorithms in sub-sections 2.6.1 and 2.6.2 imply that intrinsic and reflexive torque can be measured separately. Unfortunately this is not the case: Intrinsic and reflexive torque appear together and have to be separated. To do this, the Parallel-Cascade method is used that iteratively estimates intrinsic and reflexive stiffness. The algorithm works as follows:

1. Intrinsic stiffness is estimated as in 2.6.1 with angle θ as input and torque τ as output. It is measured over an anti-causal time range of $[\mathrm{M1}, \mathrm{M2}] = [-20, 20]$ ms.
2. The resulting IRF is convoluted with θ to get an estimate for the intrinsic torque τ_i
3. The intrinsic torque τ_i is subtracted from the measured torque τ, yielding a residual torque $\tau_{i,r}$:

$$\tau_{i,r} = \tau - \tau_i \tag{9}$$

4. Next, the reflexive stiffness is estimated using the method described in 2.6.2, using the measured angle θ as input and the residual torque $\tau_{i,r}$ as output. It is measured over a causal time range of $[\mathrm{M1}, \mathrm{M2}] = [0, 30]$ ms for the simulation study and $[\mathrm{M1}, \mathrm{M2}] = [0, 500]$ ms for the experimental study.
5. The resulting system is used to get an estimate of the reflexive torque τ_r.
6. The reflexive torque τ_r is subtracted from the measured torque τ, yielding a residual torque $\tau_{r,r}$:

$$\tau_{r,r} = \tau - \tau_r \tag{10}$$

7. The process is repeated from step 1 using measured angle θ as input and residual torque $\tau_{r,r}$ as output until $\%VAF_{np}$ fails to increase.

2.7 Intrinsic Parameter Estimation

Two methods are used to estimate the parameters of the intrinsic pathway: Anticausal IRF integration for stiffness only and parametric fitting for stiffness, damping and inertia.

2.7.1 *Anticausal IRF Integration*

The simplest way to get an estimate for intrinsic joint stiffness k_i is by integrating the obtained anticausal intrinsic IRF h_i from equation 5 over maximum lags $[M1, M2]$ using time step $\Delta t = 0.004$ s:

$$k_i = \Delta t \sum_{t=M1}^{M2} h_i(k) \tag{11}$$

For dynamic realisations, this integration is performed for each time point where the anticausal IRF is calculated, resulting in a stiffness profile over time. For time-invariant realisations, this integration is performed over the entire realisation resulting in a single stiffness value.

2.7.2 *Parametric Fitting*

The anticausal IRF h_i is inverted to yield intrinsic compliance c_i as in (Kearney et al., 1997). This is achieved by calculating the convolution between h_i and a filtered white noise input signal of 30 s, filtered with a first-order Butterworth filter having a cut-off frequency of 50 Hz. The inverse system c_i is then identified by applying the same procedure as in 2.6.1 over a range of $[\mathrm{M1}, \mathrm{M2}] = [0, 300]$ ms with the filtered white noise signal as output and the product of the convolution as input.

As a result of low-pass filtering and decimation, the causal IRF c_i is slightly shifted with respect to the origin, see Figure 8. To make up for this, the causal IRF data is extrapolated to the point where $c_i = 0$ rad/Nm. The difference with $t = 0$, Δt_{shift}, is then subtracted from the time vector to align the IRF with the origin.

c_i is fit onto a mass-spring-damper system, see Figure 8. This is done by calculating the IRF of the following transfer function using the *impulse()* function from the Matlab Control System Toolbox. The difference with c_i is then minimized using a linear least squares optimization with the following error function:

$$H_i(s) = \frac{1}{I_i s^2 + b_i s + k_i} \tag{12}$$

$$e = |\mathrm{impulse}(H) - c_i| \tag{13}$$

In order to achieve a better parameter convergence, an extra step is added to the estimation algorithm exploiting the fact that I_i is time-invariant. Once all parameters across time have been estimated, the median of I_i is calculated and using this value, parameter estimation for each instance of time is repeated to recalculate b_i and k_i.

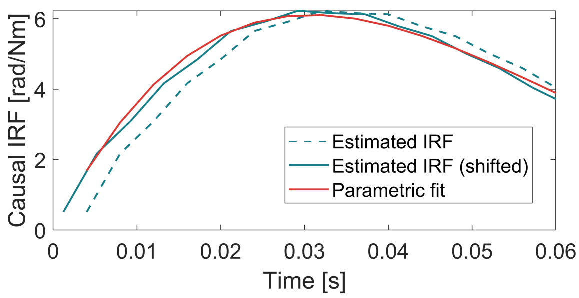

Figure 8: Example of a parametric fit of a second-order transfer function of subject 2 for an arbitrary point in time ($t = 21$ s). The estimated causal IRF (dashed blue line) is first shifted so that it is aligned with the origin (solid blue line). A second-order inertia-spring-damper model is then fit onto this curve (red line).

2.8 Validation

In order to check the validity of the estimated intrinsic and reflexive pathways, the estimated system and parameters are tested on a separate validation data set consisting of 10% of the realisations. The following Variance Accounted For (%VAF) validation metrics are introduced: $\%VAF_{np}$ (%VAF of the nonparametric estimate), $\%VAF_{np,i}$ (intrinsic contribution to $\%VAF_{np}$), $\%VAF_{np,r}$ (reflexive contribution to $\%VAF_{np}$) and $\%VAF_p$ (%VAF of the parametric estimate).

The estimated intrinsic IRF is convoluted with the input angle signal, yielding an estimated intrinsic torque $\hat{\tau}_i$. The estimated reflexive IRF is convoluted with delayed, half-wave rectified velocity, yielding an estimated reflexive torque $\hat{\tau}_r$. These torques are summed to get an estimation of the total joint torque:

$$\hat{\tau} = \hat{\tau}_i + \hat{\tau}_r \tag{14}$$

$\%VAF_{np}$ of the intrinsic, reflexive and total stiffness are then calculated by looking at the contribution of each torque to the variance of the measured torque. τ_x can be substituted for either the intrinsic, reflexive or total torque:

$$\%VAF_{np,x} = 100 \left(1 - \frac{\mathrm{var}(\tau - \hat{\tau}_x)}{\mathrm{var}(\tau)} \right) \tag{15}$$

$\%VAF_p$ is found by calculating the IRF belonging to the estimated intrinsic parameters. The procedure for calculating $\%VAF_{np}$ is then repeated using this IRF. $\%VAF_p$ is only calculated for the intrinsic pathway, since only intrinsic parameters are estimated.

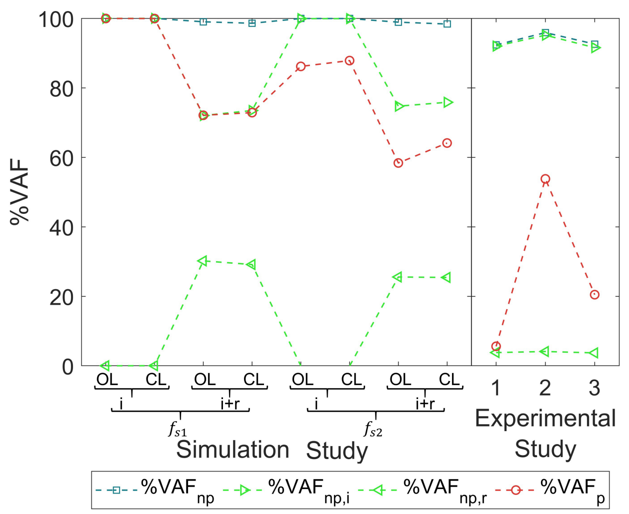

Figure 10: Variance Accounted For ($\%VAF$) for simulation and experimental studies. All numerical values are enclosed in appendix A.

3 Results

3.1 Simulation Study

The left plots in Figure 9 show a typical time series of angle and torque data for 2 conditions of the simulation study: Just intrinsic stiffness in an open-loop configuration and intrinsic and reflexive stiffness in a closed-loop configuration, both sampled using f_{s2}. Apart from the reflex peak, the experimental data shown in the right plot of Figure 9 resembles the simulation data from the closed-loop conditions.

Figure 10 shows $\%VAF$ values for all simulation conditions averaged over time. The $\%VAF$ of the estimated IRF ($\%VAF_{np}$) is above 98% for all conditions. For simulations sampled at f_{s1} the intrinsic parameters describe the system well. For simulations sampled at f_{s2} the parameters describe the system less well, as $\%VAF_p$ is on average 16% lower than $\%VAF_{np,i}$. The reason for this can be found by looking more closely at the estimated anticausal IRFs, see Figure 11. For simulations sampled at f_{s1} a parametric model can be fit perfectly on the estimated IRF. For simulations sampled at f_{s2}, which contain data that has been low-pass filtered and decimated, the shape of the IRF looks different and as a result, the parametric model cannot be fit perfectly anymore.

Table I shows the root mean square error of the estimations for I_i, b_i and k_i. Data that has not been low-pass filtered and decimated yields parameter estimates with a lower error than decimated data. Figure 12 shows the estimated parameters for the simulation conditions with just intrinsic stiffness in open-loop. This figure shows that decimated data gives values that are systematically too low. Estimations obtained through integrating the anticausal IRF give a good approximation of stiffness even with decimation. All estimates for all conditions give a qualitative estimate of the true parameter profile and are enclosed in appendix B.1.

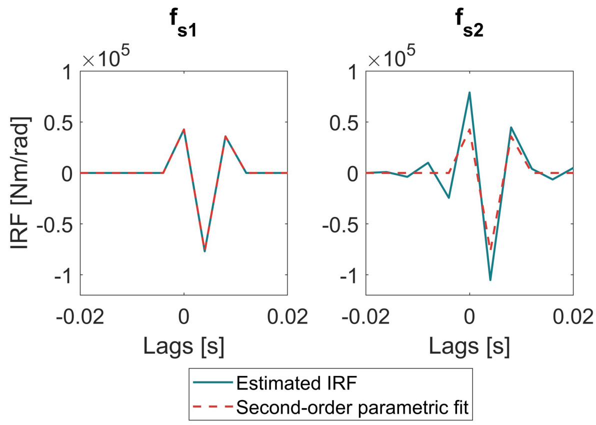

Figure 11: Effect of low-pass filtering on the anticausal IRF estimate. Without low-pass filtering and decimation (f_{s1}) the parametric model describes the estimated IRF perfectly, but with low-pass filtering and decimation (f_{s2}) a bias is introduced.

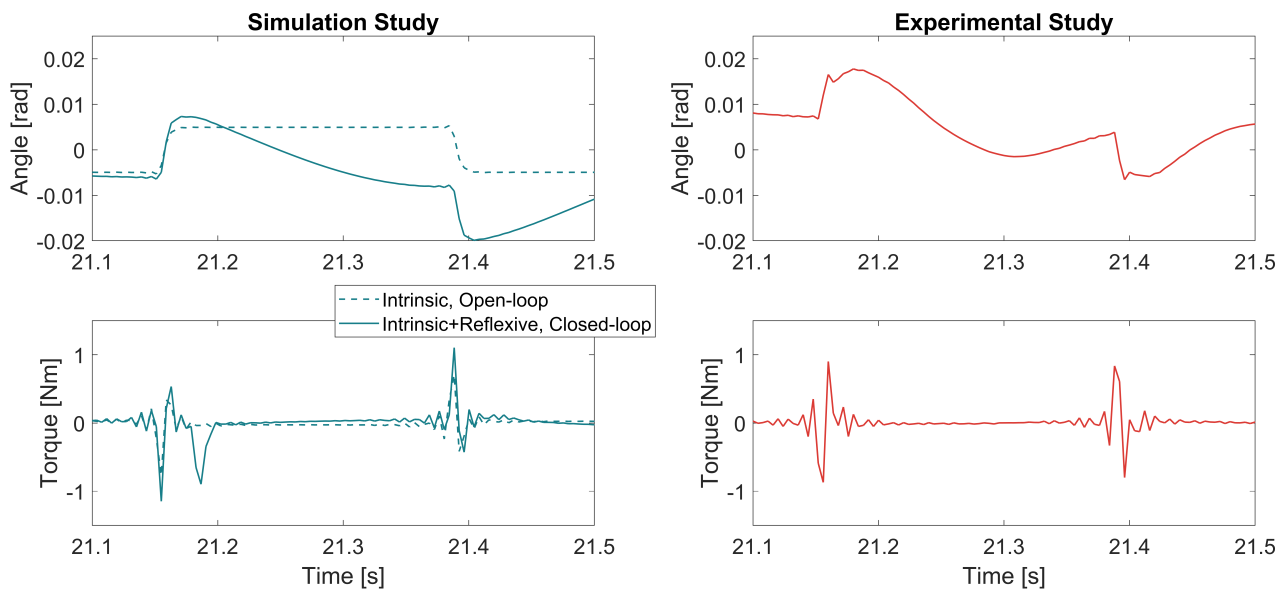

Figure 9: Time series of angle and torque data, showing a typical response to a perturbation inducing flexion and extension. The simulation study with an intrinsic and reflexive pathway in closed-loop shows a second peak after the perturbation inducing extension is applied, caused by the reflexive pathway. Apart from this peak, the simulation data with closed-loop conditions resembles the experimental data.

		f_{s1} (unfiltered + undecimated)	f_{s2} (filtered + decimated)
Anticausal IRF integration	RMSE k_i	3.7%	5.2%
Parametric fitting	RMSE I_i	8.4%	18.1%
	RMSE b_i	15.9%	16.1%
	RMSE k_i	2.1%	11.3%

Table I: Root mean square error (RMSE) of the estimated parameters, averaged over all simulation conditions. The values are expressed as a percentage of the average true parameter value. Applying a low-pass filter increases the error of both parameter estimation methods, but has the largest effect on parametric fitting.

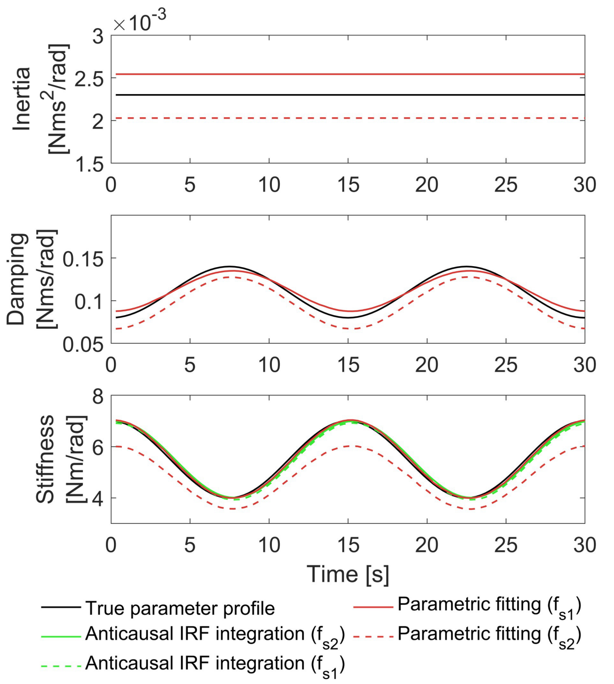

Figure 12: Time-varying parameter estimates for simulation conditions with just an intrinsic pathway in open-loop. Estimates using both parametric fitting and anticausal IRF are shown. Even with decimation, anticausal IRF fitting gives a good estimate for stiffness, whereas parametric fitting on decimated data introduces biases.

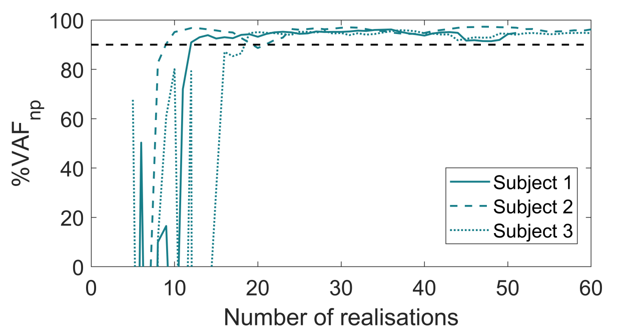

Figure 13: Influence of increasing the number of realisations on $\%VAF_{np}$ for all subjects. The dashed black line shows $\%VAF_{np} = 90\%$. For estimations with over 20 realisations $\%VAF_{np}$ stays above 90% for all subjects.

3.2 Experimental Study

3.2.1 *Required Number of Realisations*

Figure 13 shows the effect of increasing the number of realisations R on $\%VAF_{np}$. For $R > 20$, $\%VAF_{np}$ stays above 90% for all subjects. The number of data points used for one estimation is the product between the number of points within the window N and the number of realisations R (see equation 8), so the number of samples used for a segment of 30 realisations is $N \cdot R = 250 \cdot 30 = 7500$ data points.

3.2.2 *IRFs and Intrinsic Parameters*

For the experimental study $\%VAF_{np}$ is above 90% for every subject, see Figure 10. Figure 14 shows the intrinsic IRF of subject 2 using all 90 realisations. This IRF is integrated for each time point to obtain an estimation of stiffness, visualised in Figure 15 for all subjects. The stiffness of each subject modulates with a similar pattern with a higher stiffness at the peaks of the trajectory and a lower stiffness during the transition phase from one peak to another. The stiffness profile of subject 3 shows the highest deviations from this pattern, which could be attributed to non-repetitive behaviour or co-contraction.

Figure 10 also shows that, based on the values for $\%VAF_p$, the estimated parameters do not describe the system well. For subjects 1 and 3 $\%VAF_{np} > 90\%$ whereas $\%VAF_p < 25\%$, implying a good fit of the IRFs while the parametric fit is not accurate. It is likely that the low $\%VAF_p$ can partially be attributed to a bias introduced by decimation as was seen in the simulation studies.

The parametric fitting results of subject 2, with $\%VAF_p = 53.8\%$, are shown in Figure 16. The estimated stiffness shows the same pattern as was estimated using anticausal IRF integration with a higher stiffness at the peaks of the trajectory and a lower stiffness during the transition between peaks. For time-invariant measurements, indicated by the blue dots in Figure 16, the stiffness increases with an increasing background torque. As this effect is not visible for the time-varying measurements, it appears that the effect of movement versus standstill is more dominant on stiffness than the torque profile is for the movement task.

The middle plot in Figure 16 shows modulation of damping with a higher damping corresponding to a higher background torque. This effect can be explained by looking at the force-velocity relationship of a muscle. A higher muscle force, one that causes shortening of a muscle, results in a lower muscle velocity. This is realised by an increase in the damping of the muscle. In support of this, Figure 17 shows that the EMG activity of the Flexor Carpi Radialis modulates with the same phase as the damping.

3.2.3 *Reflexive Stiffness*

In the experimental studies, almost all variance in the torque response is caused by intrinsic stiffness. Figure 10 shows that VAF_{np} is approximately as high as $\%VAF_{np,i}$ whereas $\%VAF_{np,r}$ is nearly zero. Figure 18 shows the averaged EMG activity of subject 1 after extension and flexion inducing perturbations are applied in combination with the averaged torque response to a perturbation. An EMG peak can be observed at $t = 36$ ms for extension inducing perturbations, whereas the gain of this peak is smaller for flexion inducing perturbations. This could be a peak due to the elicited stretch reflex. Still, this EMG peak is of the same order of magnitude as the standard deviation of the filtered EMG signal. To put it differently, this part of the EMG signal does not stand out within the rest of the measured EMG. In support of this, the top figure of Figure 18 shows no extra torque around this EMG peak. For the time-invariant trials, in which subjects maintain their wrist at one position, a similar response is given.

4 Discussion

4.1 Scientific Relevance

This study developed an algorithm to identify intrinsic and reflexive wrist joint stiffness during voluntary movement. It was tested on simulation data where it explains over 98% of the variance and on experimental data where it explains over 90% of the variance. Being able to identify intrinsic and reflexive stiffness separately during voluntary movement creates new possibilities for identifying movement disorders, the effects of which become visible especially during the execution of voluntary movements.

A difference with previous work is that other methods relied on either a constrained movement (Ludvig et al., 2011; Sobhani Tehrani et al., 2014; Jalaleddini et al., 2017; Guarín and Kearney, 2017; Golkar et al., 2017) or modelled reflexes as part of the feedback part instead of the feed-forward part of the loop, which can only be used to identify time-invariant joint stiffness (van der Helm et al., 2002). Applying an instrumental variable approach has thus far only been used to identify intrinsic stiffness alone (Ludvig and Perreault, 2014; Ludvig et al., 2017). The algorithm developed in this study combines the principles of previous work by modelling the reflexive pathway as part of the feed-forward part of the loop.

4.2 Algorithm Assessment

The simplest simulation study consists of an intrinsic pathway, no reflexes and no required low-pass filtering and decimation. For these conditions, the algorithm predicts the intrinsic parameters with a $\%VAF$ of over 99.9%. In a closed-loop context where the position is not constrained and where reflexes determine about 30% of the torque variance, the algorithm predicts the intrinsic and reflexive pathways with a $\%VAF$ of over 98%.

On experimental data, the algorithm estimates the intrinsic IRF with a $\%VAF$ of over 90% for all subjects. However, the $\%VAF$ of the parametric estimate is below 60% for all subjects. This can partially be attributed to the fact that experimental data is low-pass filtered and decimated. This is done to minimise the presence of voluntary angle fluctuations and because a high sampling frequency greatly slows down the algorithm speed. As a result, a bias is introduced that influences the quality of the identified system and lowers $\%VAF_p$. A sinusoidal reference trajectory is also difficult to repeat perfectly. This lack of repeatability can also contribute to a less valid parametric estimate.

4.3 Modulation of Stiffness and Damping

Stiffness estimates of the experimental study show that stiffness is higher at the peaks of the reference trajectory than at the transition from one peak to another. This is in accordance with earlier findings in literature that stiffness is lower during movement (Ludvig and Perreault, 2014; Ludvig et al., 2017). Previous research showed that the passive stiffness of the knee can drop by 20% during an imposed movement (Ludvig et al., 2017).

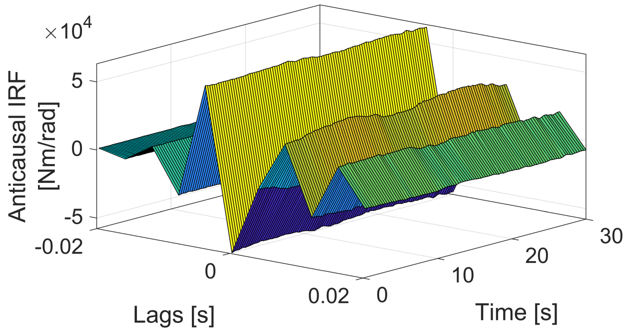

Figure 14: Time-varying intrinsic IRF $h(t)$ of subject 2 ($\%VAF_{np} = 95.9\%$). The anticausal IRF (top figure) is integrated for each instance of time to obtain a measure of stiffness, see Figure 15. The anticausal IRF is also inverted, yielding a causal IRF (bottom figure) to apply parametric fitting to, see Figure 16.

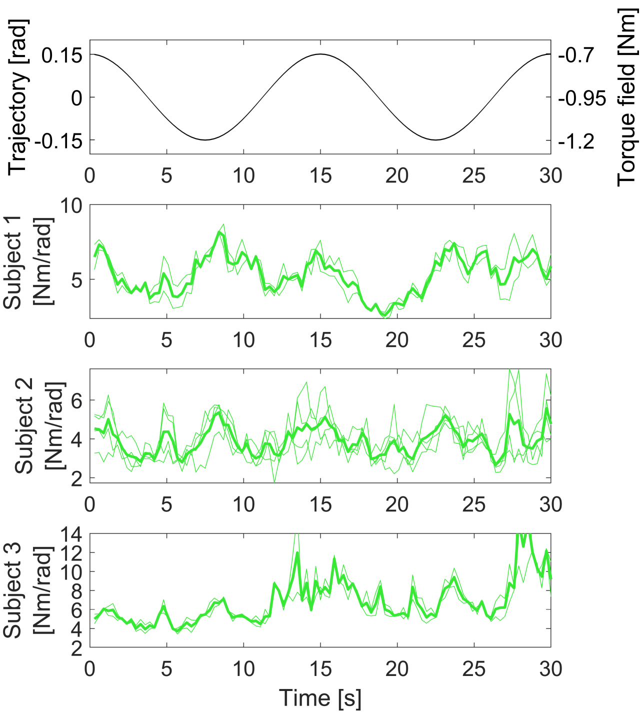

Figure 15: Estimation of time-varying dynamic joint stiffness for subject 1 ($\%VAF_{np} = 92.4\%$) based on 2 segments of 30 realisations, subject 2 ($\%VAF_{np} = 95.9\%$) based on 4 segments of 30 realisations and subject 3 ($\%VAF_{np} = 92.6\%$) based on 2 segments of 50 realisations. IRFs (as in Figure 14) are integrated to obtain different estimates of stiffness, represented by the thin blue lines. All estimates are then averaged to obtain one measure for joint stiffness, visualised by the thick blue lines.

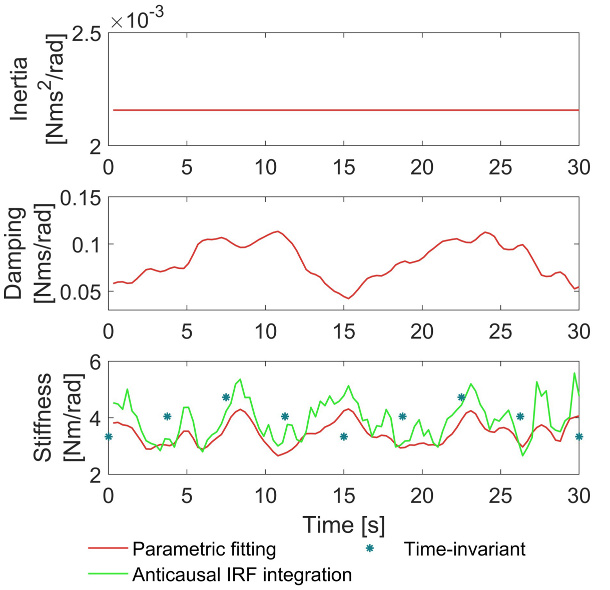

Figure 16: Parameter estimation for subject 2. The time-invariant estimations of stiffness for angles $\theta = -0.15, 0$ and 0.15 rad are plotted for the time points where the time-varying trajectory reaches these points. The stiffness profile appears to be driven by movement, as it is highest at the peaks of the trajectory where there is no movement and lower during the transition from one peak to another.

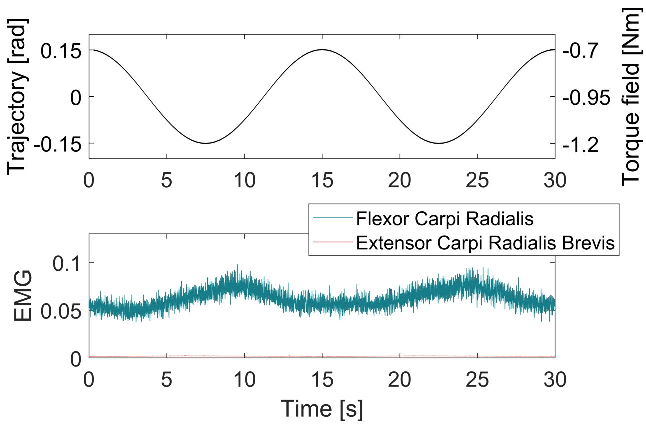

Figure 17: Absolute value of EMG modulation of dynamic realisations of subject 1, averaged over realisations. The average activity of the Flexor Carpi Radialis is a factor 5.9 larger than that of the Extensor Carpi Radialis Brevis. The modulation of the Flexor Carpi Radialis follows the trajectory of the torque field.

No modulation of stiffness due to the torque field can be distinguished. Time-varying wrist joint stiffness has previously been identified with an imposed angle by giving subjects instructions to vary their torque sinusoidally (Van de Ruit et al., 2018a). This resulted in a sinusoidally varying stiffness profile in phase with the reference trajectory, which is different from the current study. However, the conditions of the current study are slightly different, since movement is not imposed.

EMG measurements of the Flexor Carpi Radialis suggest that there is more EMG activity when the torque is higher. For subject 2, the parametric fitting results show that damping is also higher for a higher background torque. Therefore, a possible explanation is that for a higher torque, the damping of the wrist increases, whereas the stiffness is mainly driven by the contrast between standstill and movement.

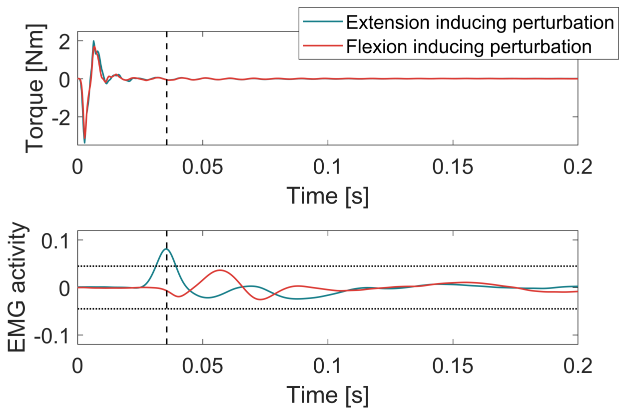

Figure 18: Average torque response and EMG activity after a perturbation is applied, averaged over every 0.2 s after the peak of the PRBS. The means of the signals are subtracted so that they are centred around zero and the sign of the flexion inducing perturbation responses is flipped. The dotted horizontal lines in the EMG figure indicate the standard deviation $\sqrt{\sigma} = 0.0450$ of the filtered EMG signal before averaging. The dashed vertical line marks the EMG peak observed at $t = 36$ ms. No significant extra torque is added at the time of the EMG peak of an extension inducing perturbation where reflexes are expected.

4.4 Dominance of Intrinsic Dynamics

During both the time-invariant and time-varying tasks in this study, stretch reflex contributions are not recognised in the torque response. Previous studies suggest that the contribution of the stretch reflex to the torque response can be as great as 52% (Mrachacz-Kersting and Sinkjaer, 2003) and studies were conducted in which contributions of the stretch reflex to the torque response of the wrist are visible (Xia et al., 2016).

Earlier work found that joint stiffness of the ankle during slow dynamic tasks is higher than during time-invariant and fast dynamic tasks (Esteban et al., 2019), suggesting that a faster dynamic task is required to elicit a stretch reflex response. Another explanation for the lack of elicited reflexes is that the frequency of the perturbations was too high, creating a signal that is unpredictable and that causes subjects to resort to co-contraction rather than rely on their reflexes. However, the PRBS used a switching time of $\frac{\sqrt{2}}{6}$ s and for this switching time, the reflexive contribution to the torque response has been as high as 25% for a time-invariant task of the ankle (Kearney et al., 1997). Another explanation is that the gain of the applied perturbations is too low compared to the gain of the passive torque of $[-0.7, -1.2]$, causing the subjects to rely mainly on co-contraction and less on their reflexes, as this has the biggest effect.

4.5 Recommendations

In future work, a study should be conducted where the stretch reflex delivers a higher contribution to the torque response and where intrinsic parameters can be estimated with a higher $\%VAF$. In order to do so, the following setup is proposed: Instead of following a sinusoidal trajectory, a future experiment can use a ramp and hold reference trajectory in which subjects have to move with a constant velocity from one end to the other and stay still for a few seconds before moving back with the same constant velocity. Such a task offers a higher predictability and also possibly a higher $\%VAF$ in the resulting system identification. Repeating the trial 30 times should be sufficient based on data of this experiment, although a trajectory with a higher repeatability possibly needs even fewer trials to get a good convergence. Additionally, a high damping should be implemented in the virtual controller to limit the variability of voluntary angle movements. The effect of increasing the gain of the PRBS perturbations relative to the torque field should be investigated to see if this increases the amount of elicited reflexes. Finally, the gain of the torque field should be decreased so that the trajectory task is less heavy to perform. As a result, the torque might increase to a value above zero at certain points. In the current experiment, this is avoided because the wrist is attached to the perturbator with a velcro strap and a positive torque means that the wrist comes loose from the perturbator. To be able to allow positive torques as well, the wrist should be placed in a closely connected mould instead.

Additionally, if reflexes are not elicited by the wrist, the algorithm can be tested on a different limb, like the ankle, on which reflexive stiffness has previously already been measured under open-loop conditions.

The parallel-cascade model is designed for open-loop experimenting. In a closed-loop environment, the reflexive pathway of the model easily causes instabilities caused by its delayed gains. This problem is addressed by creating very fast reflexes with an unrealistically high natural frequency, so that the contribution of reflexes is minimized while still keeping the recognizable one-sided velocity-dependent shape of the stretch reflex. In future research, an adjustment to the Parallel-Cascade model can be made so that realistic-looking reflexes can be added to the feedback loop without causing instabilities.

5 Conclusion

In this study, a novel algorithm is developed that identifies intrinsic and reflexive joint stiffness of the wrist during voluntary movement. This is done by combining two principles from previous research: The Parallel-Cascade method and an instrumental variable approach. Intrinsic and reflexive stiffness are distinguished on simulation data, where over 98% of the variance is explained. On experimental data, the modulation of intrinsic stiffness is identified with an explained variance of over 90%. Stiffness is highest at the peaks of the sinusoidal trajectory and lower during the transition phase from one peak to another, supporting the assumption that reflexes are lower during movement. The contribution of reflexive stiffness is negligible within the tested experimental settings. The results give a promising outlook with regard to identifying intrinsic and reflexive stiffness during voluntary movement and open up new possibilities once the algorithm is validated in an experimental environment where reflexes are elicited.

Part III

Collaborative Pliability

Developing a Shared Mental Model Making Cross-Disciplinary Collaboration Dynamics Meaningful to Engineers

3

Problem Description and Structure

In Part II the development side of using system identification techniques to analyse movement disorders was investigated. Technological challenges were tackled that arise and should be addressed for these methods to be used successfully.

Part III addresses the implementation side of the project. Challenges within cross-disciplinary collaborations are analysed and a new way of dealing with these challenges is proposed.

First, in Section 3.1 the problem description that was already introduced in Chapter 1 is discussed more elaborately. Next, in Section 3.2 the main research question and accessory sub-questions are formulated. Finally, in Section 3.3 the structure of the Science Communication research is presented.

3.1 Problem Description

3.1.1 Knowledge on Cross-Disciplinary Collaborations

Realizing more interdisciplinary collaborations between technical and medical scientists can speed up the development process of system identification solutions for clinical applications. The resulting clinical evidence can create broader support from the clinical community, as has been covered more elaborately in Chapter 1. Such an approach could bring great benefits in terms of problem-solving, funding and efficiency.

Interdisciplinary collaborations require integration of methods, tools, concepts and theories (Fam et al., 2018). This process is resource-intensive and when no true mutual understanding is developed, professionals remain conceptually and methodically anchored in their own fields (van den Bossche et al., 2011). While these collaborations have some interdisciplinary traits, their basis is primarily multidisciplinary.

Metacognition plays an important role in interdisciplinary projects (Keestra, 2017). Disciplinary experts have often developed a range of routine procedures that are automatically employed. In an interdisciplinary environment, these routine procedures do not address the full complexity of the problem. Additional monitoring and conscious control of cognition are needed in comparison to a disciplinary context (Keestra, 2017). Devoting time and effort to this metacognitive process and the challenges that arise helps in coping with them.

3.1.2 Two Epistemological Paradigms

Knowledge creation and the underlying social dynamics have too many uncertainties to be expressed in a quantitative manner (Wagner et al., 2011). No holistic model of the processes behind cross-disciplinary collaborations exists, but many social theories exist that address parts of these processes. These theories are written from the perspective of human sciences, an epistemological paradigm that acknowledges the unpredictability of human behaviour in its conceptualisation of the world (Fam et al., 2018).

This approach differs from disciplines like medicine and mechanical engineering that rely on a positivist epistemological paradigm. This paradigm assumes that the world is governed by universal laws and that there is only one correct view of reality. This paradigm has fundamental differences in comparison with human sciences: It prefers objective knowledge over subjective knowledge, a reductionist focus over holism and either-or-thinking over working with ambiguity and paradox (Fam et al., 2018).

These differences in views of the world make it difficult to effectively transfer knowledge between one epistemological paradigm and the other. In order to make theories on cross-disciplinary collaborations meaningful to professionals viewing the world from a positivist paradigm, these two paradigms should be bridged.

3.1.3 Creating an Analogy

Concepts from two paradigms can be linked together by creating an analogy between the two paradigms. Analogy-making has been described as the very essence of cognitive processing (Hofstadter and Sander, 2013). Looking for analogies between ideas and knowledge happens instantaneously and continuously. Cognition can then be seen as the process where a constant categorisation of information through analogy-making takes place. In other words, analogy-making is the mechanism carrying out categorisation, which is central to thinking (Hofstadter and Sander, 2013).

Analogous reasoning requires a degree of imagination to be involved since concepts and relations are taken out of their original context to link them to their analogous counterparts. This process of giving meaning to concepts using imagination creates rhetorical vision (Dainton and Zelley, 2010). As a result, a sense of common identity between the disciplines on each side of the analogy is created, boosting creativity in the collaboration process.

Creating an analogy will be the primary method of this thesis for bridging the epistemological paradigms of mechanical engineering and collaboration sciences. A framework within mechanical engineering will be used that has been validated, expanded and established over and over: Newtonian dynamics. As opposed to using analogous reasoning to make a disciplinary concept understandable to the general public, the analogy used in this thesis serves to transfer knowledge between two disciplines specifically.

3.2 Research Goal and Question

Before moving on to the research question, the research goal as proposed in Chapter 1 is repeated.

RG2: The goal of this research is to gain insights into the effectiveness of creating a shared mental model using a tailor-made analogy to bring together the epistemological paradigms of collaboration sciences and mechanical engineering.

This research goal is reframed into a research question. Answering this question will be the primary objective of Part III of this thesis:

How can cross-disciplinary collaboration dynamics be described in a way meaningful to mechanical engineers?

This question is decomposed into three sub-questions. Each sub-question focuses on a different aspect of answering the main question. When the sub-questions are answered sufficiently, the main research question can also be answered.

SQ1. How can cross-disciplinary collaboration dynamics be described within a theoretical framework?

SQ2. How can this framework be presented in a way that is aligned with the conceptual world of mechanical engineers?

SQ3. Is this framework meaningful to mechanical engineers?

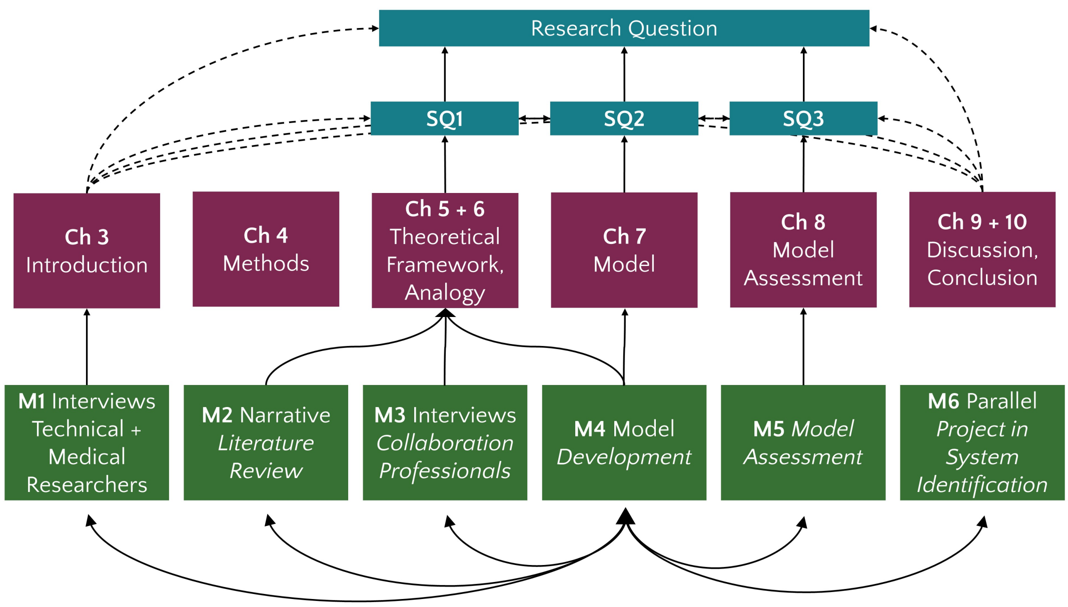

Figure 3.1: Consistency between and structure of research questions, chapters and methods of Part III. The research question and sub-questions that are discussed in Section 3.2 are rendered in blue. Each chapter, rendered in purple, contributes to elucidating or answering one or more research questions and their structure is discussed in Section 3.3. The methods that are employed are discussed in Chapter 4 and are rendered in green. The methods point towards the chapter in which their contributions are most explicitly processed. Each method mutually influences model development M4.

3.3 Part III Structure

Part III consists of Chapters 3 to 10. Figure 3.1 gives an overview of the structure of this part, which sub-questions each chapter focuses on and what chapter each of the methods described in Chapter 4 emphasises on.

In the current chapter, Chapter 3, the research question is introduced and a roadmap for answering it is presented. Chapter 4 then introduces the methods that are used for answering the research question.

Afterwards, in Chapter 5 a theoretical framework on cross-disciplinary collaboration dynamics is constructed in which theories are linked to concepts from mechanical engineering. Chapter 6 then describes the process in which this framework is turned into a shared mental model. Inspirations for the model are drawn from schematics that are commonly used within mechanical engineering.

The result of this development process is shown in Chapter 7, in which the shared mental model is presented. The model is assessed by presenting it to a group of engineers, an experiment that is presented in Chapter 8.

The model and the results of the test are then discussed in Chapter 9. Finally, the research question and accessory sub-questions are answered in Chapter 10.

4

Methods

Chapter 3 described the research question and accessory sub-questions that are the main focus of this research. In this chapter, the methods that were used for answering these questions are discussed.

Six different methods were used and each of the following sections discusses one method: unstructured interviews with medical and technical professionals (Section 4.1), a literature review (Section 4.2), online interviews with collaboration professionals (Section 4.4), the development of the shared mental model (Section 4.3), an interactive model assessment (Section 4.5) and conducting a parallel project in system identification (Section 4.6).

4.1 Interviews with Medical and Technical Researchers

Unstructured interviews were conducted with three professionals experienced with working on the intersection between medical and technical research. These interviews served to get a better understanding of the situation at hand between medical and technical researchers specifically and to get a better view of past cross-disciplinary collaborations regarding system identification solutions.

Since these interviews primarily have an exploratory function, unstructured interviews were the preferred method over semi-structured interviews. Unstructured interviews do not make use of an interview protocol but use at most an aide-mémoire as a guideline to deal with a range of topics (Bryman, 2012). The focus of each interview was slightly different so that the informational needs for the project at the stage of conducting the interview were satisfied. The aide-mémoires that were used for each interview are enclosed in Appendix C.1. The interviews were roughly focused on the following goals:

- Goal 1: To find out what factors played a role in the cross-disciplinary collaborations that interviewees took part in.
- Goal 2: To get an overview of what collaborations were the most important ones over the past two decades and how the successful these collaborations were with regards to system identification techniques.
- Goal 3: To hear what bottlenecks prevent the implementation of system identification techniques according to the interviewees.

Interviews 1 and 2 were conducted face-to-face and interview 3 was conducted over the phone due to scheduling difficulties with the interviewee. Each interview was recorded and consequently summarized. The summaries of each interview are enclosed in Appendix C.2. The results from the interviews were primarily used to get an overview of the situation at hand and their contributions were incorporated in Chapter 3.

4.2 Literature Review

A narrative literature review was conducted to find theories that describe the dynamics that are at play between collaborators in cross-disciplinary collaborations.

The primary goal of this literature review was to build a framework of theories that could be linked to an analogous theoretical framework from mechanical engineering. A 'match' in literature was sought with concepts that have a resemblance to concepts from mechanical engineering. Therefore, the preferred way of working was to get a broad overview of different theories that could potentially be linked to analogous counterparts from mechanical engineering. This was preferred over an all-encompassing overview of the theories with regards to a specific topic such as mental models, integration or constructive conflict. As such, a narrative review was conducted opposed to a systematic review. Narrative reviews are generally more wide-ranging in scope and are used as a means of getting a first overview of a topic. They are means used for generating understanding rather than generating knowledge (Bryman, 2012).

Apart from serving as a framework that can be translated to the mechanical engineering domain, the literature found in this literature review is also used to gain knowledge on how to bridge the gap between two disciplines. Theories on this process are helpful with regards to effectively creating a comprehensible shared mental model. In support of this, four collaboration professionals were consulted to assess if the shared mental model during the development process as described in Section 4.4 and suggest additional theories that could support the development of the shared mental model.

Literature was searched using Scopus. A deliberate decision was made to not work with tight search terms, as this would only limit the scope of the literature review. Instead, a snowball search strategy was performed in which potential analogies with mechanical engineering were further pursued. The following snowball samples were taken as a starting point: Transdisciplinary Theory, Practice and Education by Fam et al. (2018), Metaphor No More: A 15-Year Review of the Team Mental Model Construct by Mohammed et al. (2010) and The Ecology of Team Science by Stokols et al. (2008).

The results from this literature review were grouped into five categories that are each linked to an analogous counterpart from mechanical engineering. Each category is covered in one of the sections in Chapter 5:

- 5.2: Mental models and position.
- 5.3: Knowledge integration and displacement.
- 5.4: Collaborative pliability and mechanical stiffness.
- 5.5: Motives and force.
- 5.6: Levels of integration and configurations.

4.3 Shared Mental Model Development

The shared mental model between collaboration professionals and mechanical engineers was developed by developing an analogy between concepts from both epistemologies. Parallels are drawn between concepts from both epistemologies. Concepts are added and removed iteratively and the visual representation of the model is improved to create an analogy that is as clear and strong as possible.

The development of the shared mental model is done by linking together inputs from the other methodological sources. Input from the literature review (Section 4.2) gave input on theories from the collaboration science background that could be linked to analogous counterparts from mechanical engineering. Similarly, the parallel project in system identification (Section 4.6) gave new input on potential mechanical engineering theories that could be used to consolidate the bridge between the two epistemologies. The interviews with collaboration professionals (Section 4.4) asked for expert opinions on intermediary versions of the model, to see what modifications could fortify the analogy. Similarly, the assessment of the model (Section 4.5) determined up to what extent the model had a desirable effect from the receiving side.

The development of a shared mental model and the analogy underlying it is described more elaborately in Chapter 6. The model is presented in its final form in Chapter 7.

4.4 Interviews Collaboration Professionals

Online semi-structured interviews with professionals specialised in cross-disciplinary collaborations were conducted. They were consulted in the early stages of the model development process to see if the model was theoretically sound and to see if important theories were overlooked. They were also consulted to estimate how effective the shared mental model will be in their views and to see if they had any improvements to suggest. Their feedback was used to adjust the model.

In total, four interviews were conducted and each interview lasted about 60 minutes. The interviewees all live abroad, so the interviews were conducted using an online video connection using Zoom. The at-the-time current version of the model was presented to them using a Microsoft PowerPoint presentation and transcript. The slides and transcript that were used are not enclosed in an appendix but were an intermediary version of the final slides and transcript that were used for the interactive model assessment enclosed in Appendix E.3 and E.4. The presentation was subdivided into three parts and after each part, a list of questions was asked to get the opinions of the professionals on certain parts of the presentation. The interview protocol with the questions is enclosed in Appendix D.1 and summaries of the interviews are enclosed in Appendix D.2. The contributions of the collaboration professionals to the development process are shown in Section 6.2.

4.5 Interactive Model Assessment

In its final form, the shared mental model was presented to a group of mechanical engineering students to see how using the model influenced their perception of cross-disciplinary collaborations.

4.5.1 Participants

The assessment was conducted with a group of six participants that assessed the model at the same time in a group video call using Zoom and lasted about 80 minutes. The participants were approached through personal networking and all meet the following description:

At the time of the assessment, the participant ...

- was a higher education student majoring in mechanical engineering;
- was below thirty years old;
- previously participated in a cross-disciplinary project with fellow students of which the majority did not major in mechanical engineering. During this project, the participant was a mechanical engineering student during the conduction of this project;
- did not conduct the cross-disciplinary project that is to be analysed with any of the fellow model assessment participants.

4.5.2 Test Preparation

Before participating in the experiment, the participants received a two-page participant information sheet with information about the research and a summary of the model assessment. The participants also signed an informed consent form. Both sheets can be found in Appendix E.1.

4.5.3 Test Setup

The assessment consisted of three phases: A first questionnaire phase lasting approximately 20 minutes, a presentation phase lasting 30 minutes and a second questionnaire phase lasting 30 minutes. During each part, there were opportunities to ask questions.

Questionnaire 1

In the first phase of the assessment, the participants answered questions regarding the cross-disciplinary collaboration project that they participated in. The full questionnaire is enclosed in Appendix E.2. The questionnaire was filled in independently, but participants were allowed to discuss with each other or ask questions.

First, questions regarding basic information on the project that participants took part in were asked: Participants were asked to give a brief description of their project, how long it lasted, how many people worked on the project, what their backgrounds were, et cetera. This phase served as a way for the participants to revive memories of their project. The concepts that were introduced during the presentation could then more easily be linked to experiences from memory.

Afterwards, questions were asked regarding their overall experience of the collaborative process and how easy it was to work together with co-collaborators. They were also asked to name what factors influenced the collaboration in a positive and negative way. These questions served to get an overview of their general perceptions regarding their project: Were they generally positive or negative? This part also served to get a first impression of what factors the participants deem consequential in determining the success of their collaboration before being presented with the model.

Presentation Phase

During the second phase of the assessment, the Collaborative Pliabity Model was presented to the participants using 21 Microsoft PowerPoint slides. The slides followed the same structure as was used to exemplify the model in Chapter 7. Appendix E.3 shows a full text transcription of the presentation and Appendix E.4 shows the used slides. The presentation was conducted in Dutch since all participants spoke Dutch as their primary language.

Questionnaire 2

During the third and final phase of the assessment, the participants filled in a second questionnaire using insights attained from the presentation. The full questionnaire is enclosed in Appendix E.2. Again, participants filled in the questionnaire on their own, but discussion and asking questions is allowed.

First, questions were asked regarding the quality of their collaboration based on the acquired information from the model presentation: The participants were asked if the collaboration was primarily disciplinary, multidisciplinary, interdisciplinary or transdisciplinary. They were also asked to categorise the factors that were named before the presentation as personal pliability, interpersonal pliability, group pliability or disciplinary pliability. Afterwards, they were assigned to come up with new factors that influenced their collaboration from another pliability category. The participants also had to mark which factors were the most impactful on the success of the collaboration and which factors are easiest to change.

Finally, participants were asked if the conceptualisation of collaboration theories in the form of a mechanical stiffness model helped with the understanding of the concepts that were explained. They were also asked if the presentation of the Collaborative Pliability Model yielded them new insights.

4.5.4 Data Analysis

Data was analysed using descriptive statistics. These are methods to reduce the obtained data to a manageable size so that conclusions can be drawn more easily (Mann, 2010). Descriptive statistics are used to summarize information on the population sample, as opposed to inferential statistics that are used to deduce properties of an underlying population.

The results of the assessment are shown in Chapter 8.

4.6 Parallel Project in System Identification

Parallel to conducting this research project, a system identification project was conducted that is the main focus of Part II of this thesis. Whereas Part III looks at the implementation side of the project, Part II aims to contribute to the development side of the project. Conducting this project in parallel helped with the model development by giving constant input on the technical side of the analogy. A big part of the model development is to link social concepts to their mechanical counterparts in a coherent way. By going back and forth between developing the shared mental model and working on a technical project involving system identification theories, a constant stream of new input for mechanical relations was available and the relationships in the technical domain were always present at the surface. This resulted in input for developing the analogy as described in Section 6.3.

5

Theoretical Framework

The epistemological paradigms of collaboration sciences and mechanical engineering are bridged by developing an analogy between concepts from these two worldviews. In this chapter, a theoretical framework consisting of theories on processes behind cross-disciplinary collaborations is developed. The components of this framework are linked to concepts from mechanical engineering that are interrelated.

Before going into collaboration theories, Section 5.1 describes the mechanical engineering framework that is used as a basis for the analogy. In the other sections, the theoretical framework on collaboration sciences is described step by step and an analogy with mechanical engineering is developed per section. Section 5.2 discusses theories on how different worldviews can be described in terms of mental models and its resemblance to physical position. Next, theories on how different worldviews can be merged and their resemblance to displacements are discussed in Section 5.3. Afterwards, Section 5.4 describes pliability as the capability of a professional to participate in knowledge integration and its resemblance to mechanical stiffness. Next, Section 5.5 discusses motives that encourage professionals to participate in cross-disciplinary projects and its resemblance to force. The last concept is discussed in Section 5.6: the different cross-disciplinary types are discussed and a parallel is drawn to describing different system configurations using Newtonian dynamics.

To close off, an overview of the theoretical framework and its analogous counterparts is given in Section 5.7.

5.1 Newtonian Dynamics: An Engineering Framework

A fundamental knowledge system within mechanical engineering is that of Newtonian dynamics. Newtonian dynamics describe the dynamics of objects around us using Newton's laws of motion. They are universally accepted laws within mechanical engineering and engineers are generally familiar with applying these laws. Because of its common occurrence, this framework is used as a basis for creating the analogy.

The field of dynamics studies how physical systems have moved in the past and predicts how they will move in the future. The notion of force is used as an exertion of pressure on an object that causes it to accelerate and move. The mass of the object determines the magnitude of the acceleration of the object due to a force.

For the remainder of this chapter, analogies are created between collaboration theories and theories linked to Newtonian dynamics. Throughout the chapter, these analogies are discussed in white text on a blue background.

5.2 Mental Models

In this section, theories describing the framework behind different worldviews and how they can (or cannot) overlap are discussed. First, in Section 5.2.1 mental models are introduced as a concept. Next, the mental models of groups are introduced in Section 5.2.2. Finally, the different content that shared mental models can contain are discussed in Section 5.2.3.

5.2.1 Mental Models

Mental models are defined as a 'mechanism whereby humans generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states' (Rouse and Morris, 1986). They describe the thought processes and worldviews that are part of a discipline (Zaccaro et al., 2001) and allow people to interact effectively with their environment (Cannon-Bowers et al., 1993). It is assumed that professionals structure their knowledge according to fixed patterns that are called upon whenever a problem is being solved. The mental model can contain three types of information: concepts, features and the relationship between those two (Cannon-Bowers et al., 1993).

5.2.2 Shared Mental Models

As opposed to mental models, shared mental models are ways to capture how teams coordinate and communicate (Mohammed et al., 2010). They can be seen as an overlapping mental representation of the knowledge existing within a team (van den Bossche et al., 2011). Shared mental models are also sometimes called team mental models to highlight the performance function of a team (Mohammed et al., 2010). Because this thesis does not look specifically at the functioning of teams, these models will be referred to as shared mental models.

Shared mental models serve three basic functions (Mohammed et al., 2010). The first is a descriptive function: see up to what extent team members similarly interpret information. The second is a predictive function: Assess to what level expectations concerning future events are shared among professionals. Finally, the third is an explanatory function: To develop similar causal accounts for a situation.

5.2.3 Shared Mental Model Content

Different types of information can be shared within a team. Depending on the collaborative task, some types of information are more useful to share than others. Four types of content are distinguished to be shared within a shared mental model (Cannon-Bowers et al., 1993). Firstly, an equipment model describes the equipment of a team, consisting of the detailed models of functions or the equipment that teams use to monitor their functions and acquire information. Secondly, a task model emphasizes different tasks and how they are related. Thirdly, a team model consists of the team members being part of a team and their knowledge, abilities, skills, attitudes, preferences and tendencies (Zaccaro et al., 2001). Finally, a team interaction model describes the interactions between team members.

Analogy: Mental Models and Position

The position of a particle in physical space can be described in the same way that the position of a mental model can be described in mental space. Mental models are islands in a sea of knowledge: Their locations are fixed, but their shapes can change slowly with time. Each professional has a different conceptualisation of the world and thus a different mental model. Some mental models are further apart than others - In fact, mental models can overlap and have shared regions, but can also share no common ground at all. The further apart mental models are, the more distance needs to be travelled to find common ground.

Mental models can be aligned in different ways by looking at procedural similarities, conceptual similarities or strategic similarities. This can be compared to the three different physical dimensions: If this analogy is extended to a 3D physical space, each dimension resembles one similarity. For example, mental models that are only similar in one dimension can share the same altitude, but still be miles apart.

5.3 Developing a Shared Mental Model

In the previous section, mental models as a concept were introduced. This section elaborates on how mental models can be created.

First, in Section 5.3.1 a description of knowledge integration plays a part in developing shared mental models is given. Knowledge integration is then linked to constructive conflict in Section 5.3.2, an essential process of effective knowledge transferring. Finally, in Section 5.3.3 different levels of magnitude on which the knowledge integration process can be viewed are given.

5.3.1 Knowledge Integration

Combining different forms of expertise can also be viewed from the perspective of knowledge integration. Integration can be seen as the constructive combination of perspectives (O'Rourke et al., 2016). It is a process in which inputs are turned into a new integrative relation to yield a single, coherent output. Inputs and outputs can be local and global epistemic events, ranging from concepts, methods and knowledge to theories, fields and disciplines.

Numerous parameters influence the quality and quantity of an integration process, but three are seen as the most prominent (O'Rourke et al., 2016). The first parameter is scale: Cross-disciplinary integration can happen on any scale ranging from the global level, like the disciplinary level, to the local level, like by integrating the views on specific problems. The second parameter is commensurability, saying something about the initial conflict between two inputs that have to be integrated. When conflict is minimised, it is more likely that inputs can be integrated. Commensurability can be reduced to increase the quality of an integration step. The third parameter is comprehensiveness, saying something about how complete the integrated outputs are compared to their inputs. Within an integration of high quality, the integrated outputs are more than just the sum of their inputs, resulting in a more comprehensive view of the subject.

5.3.2 Constructive Conflict

An essential team learning process related to the development of a shared mental model is constructive conflict (van den Bossche et al., 2011). When concepts and constructs are exchanged, there may be initial disagreement on their meanings and further clarification may be needed to fully accept a new piece of information before it can be deemed shared knowledge. This process is crucial for the development of a shared mental model, as both mutual understanding and mutual agreement are necessary. Just acknowledging the contribution of a collaborating professional is not sufficient: The contribution has to be actively integrated into the existing representation. If there is no critical reflection of the new information, the team learning process is referred to as co-construction of meaning (van den Bossche et al., 2011). This process instead hinders the development of a shared mental model rather than advancing it.

There are possible side effects to constructive conflict that should be taken into account when a shared mental model is developed (van den Bossche et al., 2011). First of all, one of the conflicting elements could be ignored which does not lead to conceptual advancement. Second of all, collaborators may be inclined to interpret questioning of what they are bringing to the table as an emotional or personal rejection rather than a constructive dialogue, which discourages team productivity. These side effects can only be overcome when there is an opportunity for an open-minded discussion of diverse views.

5.3.3 Levels of Magnitude

Apart from qualifying collaborations in terms of their integration, another criterion for qualification is the magnitude at which a collaboration is looked at. Three levels are distinguished: The population level, the group level and the individual level (Börner et al., 2010).

Analysing a collaboration on the population level implies looking at bigger, slower patterns that characterise within a society. The overarching dynamics that influence disciplines as a whole are then analysed. In comparison with the other two levels, dynamics on the population level are slow.

On the group level, communities of practice and the way they interact are analysed. As an example, the collaboration between two scientific teams can be described on the group level. A quantitative measure of interactions on the group level can be obtained by applying network theory (Barabási, 2015). A social network containing the involved individuals is then crafted. Their interpersonal contacts can be analysed to see what kind of networks and sub-networks exist within a group. Setting up such a network is resource-intensive, as much data is required on the interpersonal relations exist and the way and amount in which individuals communicate.

Finally, collaborations can be analysed on the personal level. The interpersonal relations and interactions taking place between two individuals are then mapped.

Analogy: Knowledge Integration and Displacement

In the physical space, displacement is the motion from one position to the other. If mental models are analogous to position, knowledge integration is a position displacement.

The projection of concepts onto a different conceptual framework can be seen as a displacement of concepts from one place to the other. Knowledge is temporarily assembled in a place where it is usually not found. To integrate different perspectives that are not at the same position in the 'knowledge plane', two perspectives are displaced to a point of intersection to let these perspectives meet. From the point of intersection, the original viewpoints are further away than they originally were.

Looking at integration on a different level of magnitude, for instance, the population level as opposed to the group level, does not mean that a bigger displacement takes place, but can best be described in terms of the magnitude or amount of mental models that are integrated. The distance between the mental models are not further apart, but integration entails a bigger process as a multitude of individual mental models are integrated.

So far, a purely kinematic description of knowledge and the movement of knowledge is given. This means that only the motion of points is studied without looking at the forces working on them. In reality, when knowledge is integrated, different forces arise that influence the extent up to which displacement is possible. This is discussed when the analogy is further elaborated.

5.4 Tolerance to Divergent Thinking

The previous section discussed the processes that take place when professionals with different worldviews collaborate and what factors play a considerable role when these worldviews are merged. Not all professionals are equally ready to engage in effective constructive conflict. This section looks at a professional's tolerance to divergent thinking by introducing the concept 'pliability' in Section 5.4.1. The factors that influence pliability are then subdivided into four categories: personal factors (Section 5.4.2), interpersonal factors (Section 5.4.3), group factors (Section 5.4.4) and disciplinary factors (Section 5.4.5).

5.4.1 Pliability

The professional's capacity to move towards disciplinary abstraction can be described in terms of pliability, or collaborative pliability to emphasise the usage in a collaboration context. Pliability can be described as the "aspect of a discipline that enables it to remain both flexible and unchanging, and through which these two sides enter into a fold with each other" (Fam et al., 2018). When a shared mental model is created and constructive conflict is dealt with accordingly, the logic, connections and formulas from a discipline can be applied to tackle a problem inherently different from the problems that are usually addressed within the discipline. This new solution space is referred to as disciplinary abstraction: an abstract domain where some of the conventional rules that are valid within a disciplinary solution have to be overlooked to make sense. This stands in contrast to disciplinary concreteness, which is the solution space that feels comfortable and familiar.

Analogy: Collaborative Pliability and Mechanical Stiffness

Mechanical stiffness is a fundamental concept used in technology. It describes the relationship between the force working on an object and its resulting deformation or displacement. It is ingrained in the conceptual world of technology in many ways. Any mechanical calculation translating forces to positions will rely on the description of stiffness. The opposite of mechanical stiffness is mechanical compliance: A higher stiffness means a lower compliance and vice-versa. A higher mechanical compliance means that an object moves more when it is exposed to the same force.

A synonym for compliance is pliability: it is defined as "easily bent, flexible, supple" (Dictionary.com). While the mechanical compliance determines up to what extent a beam, spring or other physical object displaces in the physical space, the collaborative pliability of a professional refers to up to what extent the professional displaces in the knowledge domain. Mental models were earlier defined as an analogy for position in the knowledge domain and integration was defined as the displacement in this domain. If these definitions are combined, the pliability of a professional determines its capability to displace its mental model to integrate it with other mental models.

Mechanical compliance is a property of the object, whereas the object's displacement is a contextual factor that changes depending on the input the object received. Similarly, collaborative pliability is a property of the professional - Some professionals are more pliable than others. Depending on contextual factors, the professional will be capable of applying its mental model in a pliable manner up to a greater or smaller extent. The extent up to which a displacement takes place depends on the system's pliability.

The compliance of many real-life objects is nonlinear: For instance, the compliance of a rubber band decreases as it extends more. Similarly, the pliability of a professional is non-linear: Depending on how close conceptualisation of knowledge is to what is known, professionals can have a different pliability. Many real-life compliances also change slowly with time: Think, for instance, about the corrosion of a metal spring that slowly makes the spring more compliant than was originally intended. Similarly, the pliability of professionals is time-variant: It cannot be captured by a single value but changes as time progresses.

The compliance of an object can be analysed by separately investigating the different contributions and analysing what their contribution is to the total compliance. For physical objects, The total compliance of an object is partially determined by the shape and the material of the object. The pliability of a professional can similarly be determined by looking at different groups of influential factors.

In the next sections, the factors that influence a professional's readiness to move towards disciplinary abstraction are discussed. These factors are grouped into four categories: Personal, interpersonal, group and disciplinary factors. It is important to realise that, while each factor is classified to belong to only one category, most factors can be classified under multiple categories. Trust, for instance, can be both an intrinsic as well as a relational factor.

5.4.2 Personal Factors

The lowest level at which factors are analysed that affect collaborative pliability is the personal level. The part of collaborative pliability that is caused by personal factors is referred to as personal pliability.

The Groan Zone

The process of knowledge integration can go paired with discomfort. It consists of a period of divergent thinking, in which new ideas are generated and diverse points of view are sought, followed by a period of convergent thinking, in which perspectives are merged into one agreeable and coherent whole (Kaner et al., 2007). The period when the ideas and concepts on the table have diverged, but have yet to converge is called the Groan Zone. In this period, personal struggles can influence group cohesion, involving confusion, frustration, insensitivity and being short-tempered. Integrating the diverging ideas effectively and moving through the Groan Zone is particularly challenging when there are a wide diversity of perspectives participating, like in a cross-disciplinary collaboration.

Collaborative Readiness

The success of a cross-disciplinary collaboration is linked with the prior expectations of the kind of issues the collaborators will come across (Stokols et al., 2008). Solving conflicts with a lot of constructive conflict takes more effort than solving a usual linear conflict. If the professional is aware of the extra effort that is required, the collaboration will be more effective (Stokols et al., 2008). A concept that is linked to this is collaborative readiness, saying something about the methodologic flexibility, openness to different disciplinary perspectives and willingness to devote more time and resources on a project than usual (Stokols et al., 2008).

Static Factors

Some personal factors are observed to be positively correlated with the engagement in cross-disciplinary collaboration projects. For convenience these factors have been labelled 'static factors', but not all of them are truly static. Research shows that with more work experience, professionals engage more in interdisciplinary work (van Rijnsoever and Hessels, 2011). Females also tend to engage more in interdisciplinary activities than males (van Rijnsoever and Hessels, 2011). Some individuals are also known to have a higher global innovativeness, which is the degree to which the individual is open to consider new ideas and innovations (van Rijnsoever and Hessels, 2011).

5.4.3 Interpersonal Factors

The first level above the personal level is the interpersonal level, or the direct communication and relationship between two professionals. The contribution of interpersonal factors to collaborative pliability is called interpersonal pliability. Two factors that influence the interpersonal level are discussed.

Overlap Between World Views

A factor in whether or not a collaboration is successful on the interpersonal level is the extent to which personal world views overlap (Stokols et al., 2008). Part of this divergence can be attributed to the gaps that originate due to disciplinary differences as discussed in section **??**.

However, a professional's world view is dependent on many other factors than just the primary discipline that it is a part of. Education background, family, history and hobbies are all factors that can influence the world view of the professional. As a result, each pair of professionals has a different overlap between world views.

Trust and Familiarity

Another factor that is positively correlated with cross-disciplinarity is trust (Stokols et al., 2008). Once trust has been established, collaborators are more likely to have successful constructive conflict. Trust increases as teams get more acquainted with one another, but can also be increased by increasing the communication frequency or changing the communication platform. Trust can also be developed by developing a shared fantasy theme, leading to the building of a sense of common identity (Dainton and Zelley, 2010). Explaining a difficult topic using an analogy is a way of developing a shared fantasy theme. A downside to being more familiar with one another is that groupthink and social loafing effects can occur (Stokols et al., 2008).

5.4.4 Group Factors

Thirdly, factors that affect the group in its entirety can be distinguished. In a cross-disciplinary collaboration, the 'group' refers to the entirety of members from all collaborating disciplines that are involved in the collaboration, assuming that the collaboration is a separable project that can be looked at autonomously. If this is not the case, these factors cannot be distinguished. The contribution of group factors to collaborative pliability is called group pliability.

Team Size

While team size is known to influence cross-disciplinarity, the effect of team size on the results are ambiguous (Stokols et al., 2008). On the one hand, a bigger team requires a greater amount of coordination to align ideas and make decisions. On the other hand, a bigger team has a greater and broader scope of resources available.

Outcome Interdependence

The interdependence of the tasks and rewards within a team have been shown to influence collaborative effectiveness (Stokols et al., 2008). When the tasks and rewards are purely group-oriented, teams perform the best. However, when teams operate in a 'hybrid' fashion where only part of the task description is integrated but part of the objective has to be performed individually, teams performance worsens.

Leadership

A factor that can influence the development of a shared mental model is the leadership of a team. Leaders can play a facilitating role in proposing, developing and communicating shared ideas. The degree to which a leader performs sense-making and sense-giving activities is correlated with the degree of similarities between mental models in a team (Zaccaro et al., 2001). Sense-making and -giving processes are defined as "extracting important environmental cues, placing these cues in a team's performance context and embellishing the meaning of these cues into a coherent framework" (Zaccaro et al., 2001). These activities have to be applied on the equipment, task, team and team interaction levels to be maximally effective.

5.4.5 Disciplinary Factors

Finally, the factors described in this subsection affect one or both collaborating disciplines. The contribution of these factors to collaborative pliability is called disciplinary pliability.

Codification

Disciplines can be categorised based on the extent up to which they are codified. Codification refers to the "consolidation of empirical knowledge into succinct and interdependent theoretical formulations" (Zuckerman and Merton, 1981). A distribution of how codified some disciplines are with respect to one another is shown in Figure 5.1.

Figure 5.1: Axis ranking disciplines from less codified to more codified. Mathematics is rated as one of the most codified sciences, whereas sociology is rated as one of the least codified sciences.

Modern education programs and their devolving disciplines can be subdivided using different categorisations that rely on roughly the same distinctions. Beta sciences (Universiteit Utrecht, 2019), natural sciences (Fam et al., 2018) and hard sciences (Cole, 1983) typically refer to sciences that are more codified, whereas alpha and gamma sciences (Universiteit Utrecht, 2019), human sciences (Fam et al., 2018) and soft sciences (Cole, 1983) typically refer to sciences with less codification.

More codified disciplines are characterized by a positivist way of looking at the world, which is the most dominant in our western way of thinking (Fam et al., 2018). It avoids ambiguity, assumes that everything around us is quantifiable and explainable by mathematical models, assumes that there is only one correct view of reality and prefers quantitative over qualitative data. In comparison, disciplines that are less codified incorporate more human phenomena that are less predictable. These disciplines typically focus on the products of human acts or study human behaviour itself. They are more familiar with working with ambiguity and paradox and dealing with subjective data.

For highly codified disciplines that in essence try to reduce uncertainties, seeing the multiplicity of the world through pliable application of the discipline can be difficult (Fam et al., 2018). Researchers from relatively codified fields are used to applying their concepts using unambiguous, non-pliable relations. Disciplinary pliability, then, is often seen as a failure to uphold disciplinary boundaries (Fam et al., 2018).

Internal Competence

Disciplines have definitions of competence that are constantly redefined (Wenger, 2000). Disciplines, or any groups that share cultural practices, can be described as a community of practice with their own habits, norms, values and rituals. Communities have soft borders that are influenced by the identities that are a part of it. Interactions between disciplines happen at the boundaries between two communities. These boundary interactions also affect how competency is defined within a discipline. By limiting the number of boundary interactions that take place, disciplines' ideas and definitions of competence will be invented from within. Means of problem-solving then diverge as standalone views of the world are created, while within a discipline there is often only a limited view of how the world works. On top of that, a tempting way of cultivating a sense of community is by emphasizing the paramount differences between the own and another discipline (Woudstra Hablé, 2019).

Models and Artifacts

The importance of models and artifacts that are shared within a discipline cannot be overlooked. There are two functions: a cognitive and a cultural function (Nersessian, 2006). As cognitive propositions, models and artifacts are used to transfer knowledge, create a common understanding and develop a shared framework that serves as a mutual starting point between collaborating professionals. Situations of agreement can be saved and brought up at a later stage to re-initiate the collaboration from a shared frame of reference. Additionally, from a cultural perspective, people's habits, customs and mutual differences are captured in the models that they use and the artifacts that they value (Nersessian, 2006).

History

History plays an important role in the cognitive and cultural level as well (Nersessian, 2006). From a cognitive perspective, historical paths to developing a solution have led to either fruitful or fruitless solutions, outlining for a future researcher what kind of collaborations have the highest odds of success. From a cultural perspective, historical feats can create increased cohesion within a discipline, or between two disciplines when the disciplines in question have a history together.

Larger Socio-Political Realities

Collaborations between disciplines are always part of a larger whole that influences the external desire to let a collaboration succeed (Hoffmann et al., 2010). If a working field is more dynamic and changes occur more often, more interdisciplinarity can be observed (van Rijnsoever and Hessels, 2011).

5.5 Motives

Professionals are known to have different motives for participating in a cross-disciplinary collaboration. We distinguish intrinsic and utilitarian motives (Stokols et al., 2008). Intrinsically motivated professionals collaborate because they believe that cross-disciplinary collaborations are fruitful or because they like collaborating with people with a different background. Professionals that have a utilitarian motivation, on the other hand, collaborate because they believe that cross-disciplinarity is good for their career path and that it will help them to deliver publications. Intrinsically motivated people generally show more collaborative readiness than professionals with a utilitarian motivation, and moving through the Groan Zone will be easier for them.

Motives have a fundamentally different nature than factors that influence pliability. Whereas these factors only determine the extent to which a professional is open to pliable thinking when incentives are presented, motives are at the origin of change. They are the incentives themselves that spark pliable thinking in the first place.

Analogy: Motives and Force

Mechanical compliance is defined as the relation between two fundamental concepts: Force and the resulting position displacement. Position displacement was described in terms of mental models and knowledge integration. If force is seen as the driving action behind the displacement that comes as a reaction, the force that drives a disciplinary displacement should be the factor initiating change.

Unlike pliability-influencing factors, the motives of a professional can be the reason that professional choose to temporarily depart from their conventional mental model to explore new regions of problem-solving. But apart from motives, there can be numerous other incentives that stimulate professionals to deviate from their conventional ways of thinking. For instance, professionals can be inspired by colleagues, incentivised by financial motives or get strict orders from a supervisor. In all of these cases, the incentives are the force behind the change, whereas disciplinary pliability determines the extent up to which a professional is sensitive to the input force.

5.6 Levels of Cross-Disciplinary Integration

In the previous sections, mental model theories were used to explain to what extent an area of shared understanding can be created and how knowledge between different disciplines can be integrated. Not always is the maximum amount of integration required or even desired. In this section, finding common ground is taken to a cross-disciplinary context and different levels of cross-disciplinary integration are discussed.

In this master thesis the term ‘cross-disciplinary collaboration’ is used as a collective term to describe any collaboration between two disciplines. However, a clear distinction can be made between four different levels of cross-disciplinarity: disciplinarity (Section 5.6.1), multidisciplinarity (Section 5.6.2), interdisciplinarity (Section 5.6.3) and transdisciplinarity (Section 5.6.4) (Rosenfield, 1992). Each level is visualised in Figure 5.2.

5.6.1 Disciplinary Collaborations

Collaborations in which no cross-disciplinarity takes place are called disciplinary collaborations. These are collaborations with people having similar backgrounds, norms and values fall under the umbrella of a discipline. Mental models between professionals in a disciplinary collaboration have much overlap: Concepts, methodological procedures and ways of problem-solving are generally the same or similar within a discipline. Developing a shared mental model requires less constructive conflict than within the other collaboration types.

5.6.2 Multidisciplinary Collaborations

Multidisciplinary collaborations are cross-disciplinary forms of working together with little integration of knowledge and cultures. Participants remain conceptually and methodologically anchored in their own field (Stokols et al., 2008). Ideas are not transferred between the different discipline clusters and integration does not take place. This usually means that a project is subdivided into different tasks that are solved autonomously by disciplines. During the solving of a task, there is limited communication between the clusters. In the end, one cluster usually presents results to the other clusters without giving insights into all of the processes that went into developing these results. Projects that were meant to be interdisciplinary collaborations can turn into multidisciplinary collaborations when creating a shared mental model was insufficiently successful.

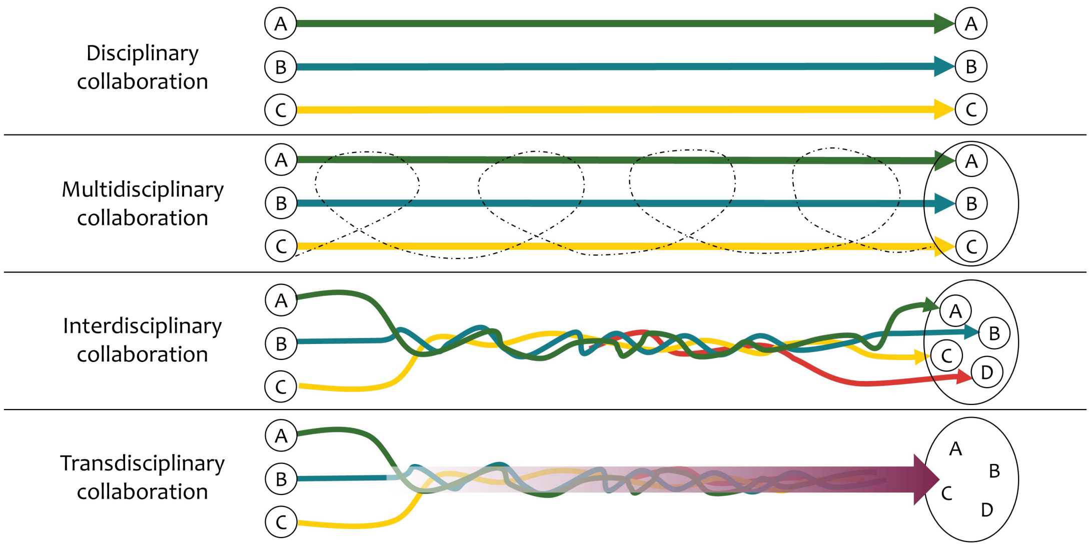

Figure 5.2: Graphical representation of the difference between disciplinary, multidisciplinary, interdisciplinary and transdisciplinary collaborations. The letters A to D each represent a different discipline. The types of collaboration are ordered from 'most discrete' in the top to 'most integrated' in the bottom. (Visual representation inspired by Fam et al. (2018))

5.6.3 Interdisciplinary Collaborations

An interdisciplinary collaboration consists of the partial integration of methods, tools, concepts and theories the collaborating disciplines (Fam et al., 2018). They work jointly but approach the context from a disciplinary-specific basis (Rosenfield, 1992). This form of collaboration is more resource-intensive and requires bigger dedication from both parties to succeed. However, the integration of viewpoints can yield new, more holistic solutions that would not be found within a multidisciplinary context.

5.6.4 Transdisciplinary Collaborations

Transdisciplinary collaborations are the most interwoven types of collaborations. Whereas within an interdisciplinary collaboration integration happens only sporadically, a transdisciplinary collaboration creates a shared conceptual framework where disciplinary theories, concepts and approaches are integrated to jointly address a common problem (Rosenfield, 1992; Fam et al., 2018). Disciplinary boundaries become less distinguishable as the togetherness or concepts has no longer a clear distinction. Paradigm shifts can occur within the view of the professionals, changing the way that the professionals look at the subject at hand. Transdisciplinarity requires the biggest amount of resources, time and dedication to take place. However, when successful the collaborating professionals are at the end more adaptive, reflective and able to apply their knowledge with more pliability.

Analogy: Levels of Integration and Mechanical Configurations

Newtonian dynamics are used to model real-life systems using simplifications that are broadly applicable to all physical systems. Now that a framework of forces, displacements and systems has been defined, this framework can be used to describe different configurations in which professionals with different mental models collaborate.

The first configuration that was just discussed, a disciplinary collaboration, is a configuration in which little to no displacement is needed for the professionals to conceptualise knowledge in the same position in the knowledge domain. Only small forces are required to displace sufficiently and even if professionals exhibit little pliability, a point of intersection can be found.

The second configuration, a multidisciplinary collaboration, consists of professionals that have clusters of mental models that are positioned nearby each other, but there is a distance between these clusters that is not bridged by displacement to other conceptual worlds. The reason for this is an interplay between incentives and pliability: Apparently, the combination of incentives and pliability is sufficiently low that professionals do not conceptualise knowledge in a point of intersection.

The third configuration, an interdisciplinary collaboration, consists of professionals that do find a point of intersection in the mental model domain to share knowledge. Now, the interplay between incentives and pliability yields a sufficient displacement so that integration can occur.

Finally, in a transdisciplinary collaboration, the area of intersection that was only temporarily visited in a multidisciplinary collaboration is visited more frequently and repeatedly. As a result, the mental models of the professionals morph so that the area of intersection slowly becomes less abstract: Their mental models expand with new knowledge. This process requires the greatest amount of incentives and pliability to be successful. Due to the morphing of mental models, less pliability is needed to conceptualize knowledge in the area of intersection after a successful transdisciplinary process.

5.7 Theoretical Framework Overview

An overview of how the theories of the theoretical framework are interrelated is shown in Figure 5.3. It revolves around three concepts: mental models, knowledge integration and collaborative pliability. First of all, mental models describe the thought processes and worldviews of professionals. Mental models of a group of professionals are known as shared mental models and describe how team members interpret information similarly.

When different mental models are merged into a shared mental model, knowledge integration takes place, which is the second primary concept of the theoretical framework. Essential to effective knowledge integration is the happening of constructive conflict, in which concepts that are discussed are mirrored to existing concepts and methodologies from individual mental models to create coherent interrelations. The extent up to which knowledge integration takes place in a cross-disciplinary environment can be described by the different levels of integration.

Finally, the extent up to which professionals are able to engage in constructive conflict, and as a result, effective knowledge integration, can be described in terms of collaborative pliability. This is the ability of a professional to link routines, concepts or methodologies from the own mental model to those of mental models of other professionals. When two mental models are not similar, conventional rules and logic from both mental models sometimes have to be overlooked to find a synthesis. Numerous factors influence the collaborative pliability of the professionals that can be subdivided into four categories: Personal factors for the factors influencing the professional at the personal level, interpersonal factors regarding the one-on-one relationship between two professionals, group factors regarding the entirety of members from all collaborating disciplines involved in a collaboration and disciplinary factors affecting a discipline as a whole.

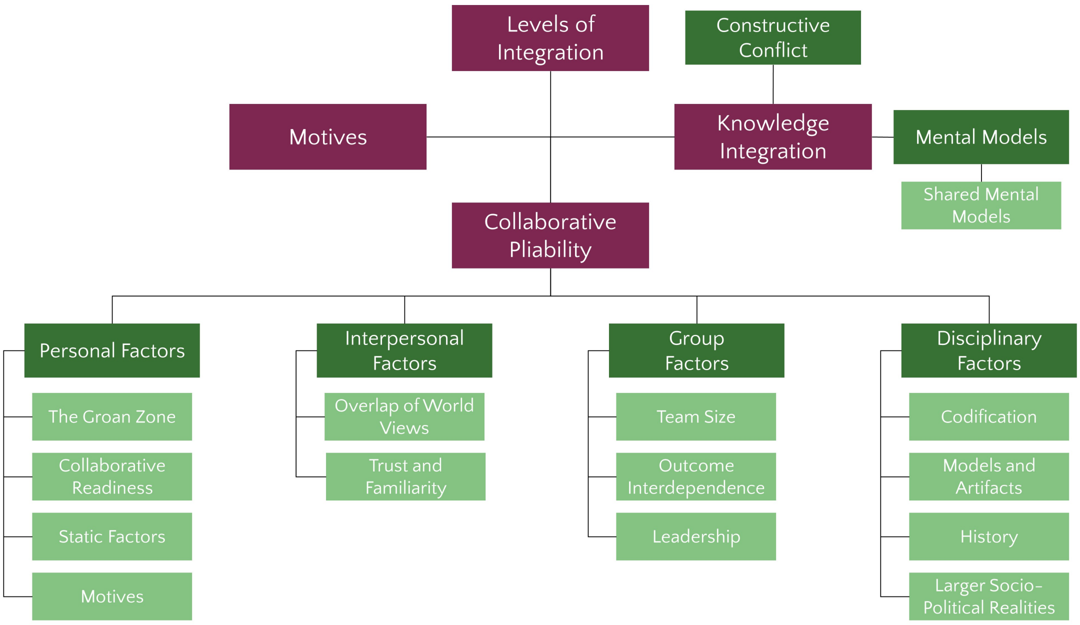

Figure 5.3: Overview of the entire theoretical framework showing the interrelations between the different theories.

Analogy: Overview

A framework has been developed in which dynamics behind cross-disciplinary collaborations are interrelated using relations used within Newtonian dynamics. Forces, positions and systems in the form of stiffness are described in terms of analogous counterparts. The analogies between these concepts are summarised in Figure 5.4.

Position has been defined as the position in mental space: The mental models of professionals entail a position and can be positioned in relation to mental models of other professionals. When professionals try to conceptualise knowledge outside of their mental models, a displacement occurs to an area where knowledge is more abstract to the professional. This is required to effectively integrate knowledge that is not yet common to the professional.

The extent up to which the professional displaces to disciplinary abstraction is defined by the pliability of the professional: A system property with similarities to mechanical compliance, the inverse of mechanical stiffness. Like with stiffness, the compliance of a professional is non-linear, time-varying and can be described by analysing contributions to pliability separately.

All reactions start with an action, and an incentive to move is first needed before professionals are inclined to integrate their knowledge. Incentives are the forces behind cross-disciplinary collaborations.

This interplay between forces, systems and displacements can be used to analyse and distinguish different configurations of collaborations. It can be used to describe the differences between disciplinary, multidisciplinary, interdisciplinary and transdisciplinary collaborations.

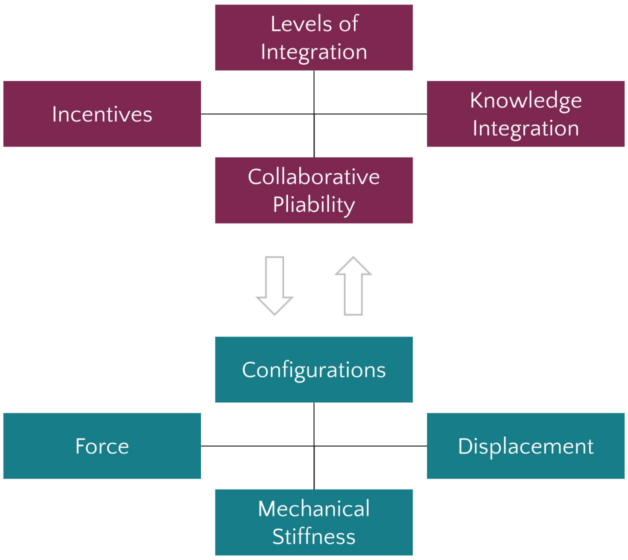

Figure 5.4: Overview of the analogies between the primary concepts of the theoretical framework and their counterparts from mechanical engineering.

6
Model Development

The theoretical framework presented in Chapter 5 uses a collection of theories entailing the dynamics at play within cross-disciplinary collaborations. These theories were linked to mechanical engineering theories using an analogy. In the current chapter, the process is described in which of this analogy is turned into a model that is easily interpretable by mechanical engineers.

Figure 6.1 shows four processes that took place simultaneously in the development of the model. Each section of this chapter discusses one of these processes more elaborately. Section 6.1 describes input from literature that gave clear directions in the development of the theoretical framework. Next, Section 6.2 discusses contributions to the model development based on conversations with four collaboration professionals. Afterwards, Section 6.3 discusses some analogies between mechanical engineering and collaboration theories that did not make it into the final model. Finally, Section 6.4 describes the process of creating a visualisation of the analogy.

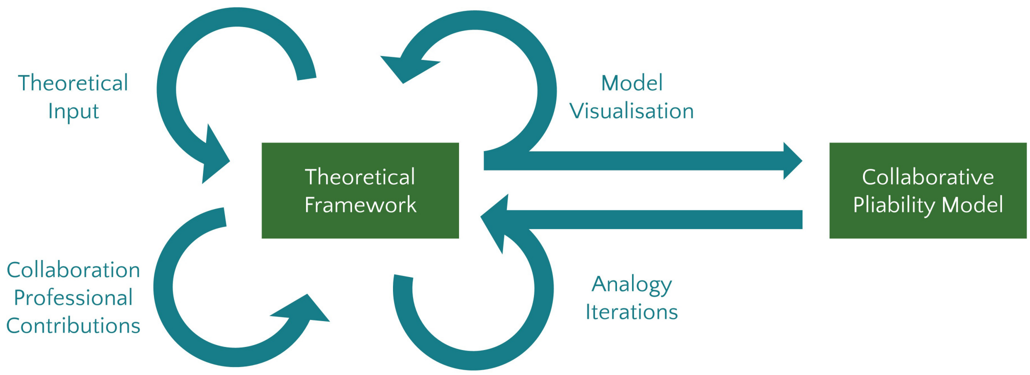

Figure 6.1: Visualisation of the four processes that were undertaken to create the Collaborative Pliability Model. Each process is discussed in a separate section.

6.1 Theoretical Input

Mechanical engineer using the Collaborative Pliability Model are exposed to knowledge on cross-disciplinarity on two levels. The first and most obvious level is the exposure to the content on cross-disciplinarity as part of the shared mental model. The second and slightly less obvious level is the fact that gaining knowledge from another discipline, on its own, is a cross-disciplinary process. Therefore, mechanical engineers that use the Collaborative Pliability Model can immediately reflect on the theories that they are learning within the context that they are learning about it.

These two levels of applying cross-disciplinary knowledge are also present within the development process of the model. The first level is the usage of cross-disciplinary theories as part of the analogy that is created with mechanical engineering. The second level refers to the usage of this knowledge to knowledge to bridge the two epistemological paradigms effectively.

This section will discuss two directions in the development that were based on this theoretical knowledge: Codification in Section 6.1.1 and the different mental model types in Section 6.1.2.

6.1.1 Codification

Professionals having a background in mechanical engineering have identical notions of state-of-the-art formulas such as Newton's second law, the first law of thermodynamics and rules of elasticity. If the notions of these concepts are different, constructive conflict can take place until one of the professionals is proven wrong and the other is proven right. Any newly introduced concept or set of theories has to conform seamlessly to the already existing knowledge. If there is no 'perfect fit' with regards to the framework of the already existing knowledge, the knowledge is deemed untrue. This framework of theories consists of boundary conditions within any disciplinary collaboration and form a set of rules that are always applicable when mechanical engineers tackle challenges.

Within human sciences, this is different. Human dynamics are inherently too complex to be described in a quantitative manner (Wagner et al., 2011). Hence, in comparison to positivist-driven sciences, human sciences have less an aversion with regards to subjective knowledge, uncertainty and qualitative data (Fam et al., 2018). This affects the way constructive conflict takes place as well. Mutual agreement can exist even when there are discrepancies with regards to the perception of reality.

To find common ground between the two epistemologies, this discrepancy between ways of dealing with constructive conflict cannot be overlooked. In particular, to make an analogy between concepts, the conceptual relations that are borrowed from mechanical engineering should be aligned with existing mechanical engineering conceptual relations as seamlessly as possible. If there is a lot of conflict with existing relations, the newly attained knowledge can easily be deemed 'untrue' for a mechanical engineer.

6.1.2 Mental Model Type

Mental models are fundamental to the theoretical framework: They are descriptions of space in the domain of knowledge. However, mental models theories can also be used as a basis for developing a model of shared conception between the two epistemologies. The decisions made with regards to developing a shared mental model are highlighted here.

Three different types of mental models can be distinguished: Declarative, procedural and strategic models (Webber et al., 2000). Declarative models store information, concepts and the relations between these. They are the most concrete mental models and are most easily understood.

Procedural models store information on how challenges are approached and solved. They are more abstract than declarative models, but also more generalisable to different cases. Finally, strategic mental models provide the information that is at the basis of problem-solving from the highest level.

Mechanical engineering as a discipline is relatively codified compared to social sciences. This is translated into a heavy reliance on shared concepts and relations between them. For this reason, the decision was made to develop a shared mental model based on the resemblance between concepts. However, just aligning concepts based on their similarities does not necessarily mean that their meanings will make sense from both epistemological paradigms. To create a coherent product, emphasis also has to be put on procedural similarities: The steps that disciplines take to tackle their challenges, and on strategic similarities: The basis of problem-solving that is part of a discipline, including the action plans to meet the desired goals and what knowledge is required for this implementation.

6.2 Collaboration Professional Contributions

Four collaboration professionals were interviewed during the development process to reflect on the model from different perspectives. Intermediary versions of the model were shown to the professionals and they were consulted to rate the completeness and clearness of the model. Their input was used to redefine the model. The methods of these interviews are described in Section 4.4, the interview protocols are enclosed in Appendix D.1 and summaries of the interviews are enclosed in Appendix D.2. Three considerable points of feedback were gained through these interviews. Each of these points is discussed below.

First of all, at the point at which the interviews were conducted, factors influencing pliability were subdivided into three categories: intrinsic, reflexive and voluntary pliability, as described in Section 6.3.1. Multiple comments mentioned the fact that these categories were ambiguous and that many of the assigned factors did not belong to just one category. A suggestion was made to restructure the pliability categories to the scale at which the factors influence collaborations. Based on this suggestion, the factors were restructured to personal, interpersonal, group and disciplinary factors.

Second of all, one of the professionals made mention of the fact that a greater or lesser amount of codification within a discipline greatly influences the pliability of its consisting professionals. This was a remark that had not been taken into consideration yet but became significant in many of the other development considerations that are described in this chapter.

Third of all, several theoretical contributions were suggested that were added to the theoretical framework in Chapter 5. Two concrete additions of literature were suggested that were directly incorporated into the theoretical framework: the theory on the Groan Zone from Facilitator's Guide to Participatory Decision-Making by Kane et al. (2010) and the theory on leadership affecting team performance from Team Leadership by Zaccaro et al. (2001).

6.3 Analogy Iterations

During the development process, some analogies were created between Newtonian dynamics and collaboration theories that did not make the final cut. In this section, four analogies that had potential but were modified or removed in a later stage are discussed. First, Section 6.3.1 describes a different categorisation of the factors that influence pliability. Next, Section 6.3.2 describes how training pliability is similar to developing muscle stiffness in sports. Afterwards, Section 6.3.3 describes an analogy between doing a system identification experiment to measure joint stiffness and doing a social experiment to measure pliability. Finally, Section 6.3.4 touches on how the analogy can be extended using two extra system properties: mass and damping.

6.3.1 Pliability Categories and Joint Stiffness

One modification that was made during the development process, is how categories influencing pliability (Section 5.4) are grouped. The initial grouping of categories was based on a direct relationship with the way joint stiffness can be decomposed:

- Intrinsic pliability: Intrinsic flexibility to move to disciplinary abstraction, independent of the collaborating discipline. Slowly changes over weeks, months and years. (Related concepts: Collaborative readiness, expectations, reflexivity, motives)
- Reflexive pliability: Flexibility to move to disciplinary abstraction due to the other discipline. (Related concepts: Trust, connectivity, divergence of world views, mutual appreciation)
- Voluntary pliability: Context-dependent flexibility to move to disciplinary abstraction, varying from day to day and dependent on the context-dependent decisions of the professional. (Related concepts: Communication platform, dynamics of the scientific field, team size, leadership/management, based on decisions)

The advantage of this subdivision was that a direct mapping of social and mechanical concepts was possible. However, after discussing this distinction with the collaboration professionals, it soon became clear that there was a lot of ambiguity between the categories. One professional mentioned that a factor like 'Trust', grouped under reflexive pliability, is also influenced by intrinsic pliability. There was also a lot of ambiguity within voluntary pliability: Factors like team size and communication platform are often externally imposed, while the decision-based aspect of voluntary pliability is related to things determined by the professional.

The final categorisation that is presented in chapter 7 is largely based on a suggestion of Collaboration Professional 4, who suggested an alternative subdivision of concepts. This alternative looks at a distinction between concepts based on their scale of intersection: The personal level, interpersonal level, group level and disciplinary level. While this distinction cannot be linearly mapped to technological concepts, the advantage of using this distinction is that communication theories more unambiguously fall under one category.

6.3.2 Training Pliability and Developing Muscle Stiffness

As part of the categorisation of intrinsic, reflexive and voluntary pliability, the analogy between technology and collaboration dynamics was extended by looking at training within sports. Intrinsic, reflexive and voluntary stiffness are three contributions that can be summed linearly to yield the stiffness of a joint. When someone trains to become a better sporter, the subdivision of stiffness often changes from one focus point to another. For example, a beginner in climbing will initially rely more on intrinsic stiffness, while with practice the contribution of voluntary stiffness becomes more dominant. Within the original distinction, one can argue that someone adept at cross-disciplinary collaborations will rely more on intrinsic stiffness as well, while with practice the contributions of voluntary stiffness become more dominant.

While this analogy makes sense, several flaws compromise the ambiguity of the model. First of all, the training example is based on stiffness, while the model is based on pliability, the inverse of stiffness. Describing the training example using pliability is more difficult and makes less sense from both mechanical and social perspectives. Secondly, the training example suggests that there is always a direction of progress in training cross-disciplinarity, which involves a decrease in intrinsic stiffness and an increase in voluntary stiffness. While in many examples this may be the case, this should not be the main message that the model gets across - There should be more freedom in how the model can be used for different cross-disciplinary collaborations. Hence, the training example was dropped.

6.3.3 System Identification Experiment

The principle of the system identification experiment described in Part II is as follows: An input position is applied to the identifiable system and the output force is measured. If a sufficient number of data points is measured, the system can be identified.

In the social domain, such an experiment is not executable, since both 'incentives' and 'displacement to disciplinary abstraction' cannot be measured quantitatively. Also, a set of comparable data points would need to be available, while creating reproducible conditions in such a social situation is difficult. However, thinking about what a social experiment would look like with similar characteristics can be interesting. In the social domain, such an experiment would look as follows: An input incentive is applied to a group of professionals and the resulting displacement to disciplinary abstraction is measured. Based on the intensity of the incentive and the movement of the professional, something can be said about the pliability of the professional.

6.3.4 Differential Equations: Mass and Damping

Within Newtonian dynamics, the concept of stiffness has been used in many different contexts and many additional mathematical relations could be added to increase the complexity of the model. The relation between force and position is often described by the following differential equation:

$$F = m\ddot{u} + b\dot{u} + ku \tag{6.1}$$

in which m is the mass (kg), b is the damping (N/ms) and k is the stiffness (N/m). Mass and damping are similar system properties as stiffness, relating other time derivatives of position to force. One can argue that a similar distinction can be made in the social domain: The incentives (F) that work on the system do not just cause a displacement to disciplinary abstraction (u), but also a velocity to disciplinary abstraction ($\dot{u}$) and an acceleration to disciplinary abstraction ($\ddot{u}$). This analogy makes things unnecessarily complicated, as the focus of this equation is on *how* the professional displaces to abstraction instead of *where* it goes. For this reason, this analogy is not further investigated.

6.4 Model Visualisation

The analogy has to be shaped in a way that is as comprehensible to mechanical engineers as possible. To do this, inspiration is drawn once again from conventional methods to visualise mechanical structures and schematics. A common way of simplifying reality on paper is by drawing schematics such as the one illustrated in Figure 6.2. Schematics of spring mechanisms are common in mechanical engineering and this familiarity can easily be used to describe the analogy with pliability.

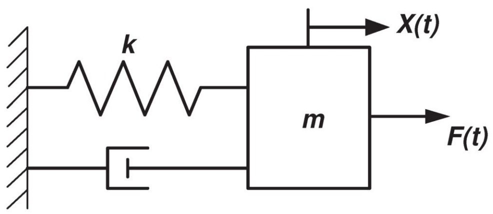

Figure 6.2: Schematic overview of a mass-spring-damper system that is well-known within mechanical engineering. (Image from (Gómez-Aguilar et al., 2015))

A constant question during the development process of the model has been this schematic can be used to describe pliability and its movement to personal abstraction, can be visualised flawlessly. Two intermediary visualisations are illustrated in Section 6.4.1 and 6.4.2.

6.4.1 Visualisation Prototype 1

The movement resulting from a force exerted on a spring is drawn as a displacement in a 2D plane. In our social analogy, the movement occurring is the displacement from personal concreteness to personal abstraction. As a logical result, a 2D plane should be designed with personal concreteness on one end and personal abstraction on the other. One of the first visual representations of this plane is shown in Figure 6.3.

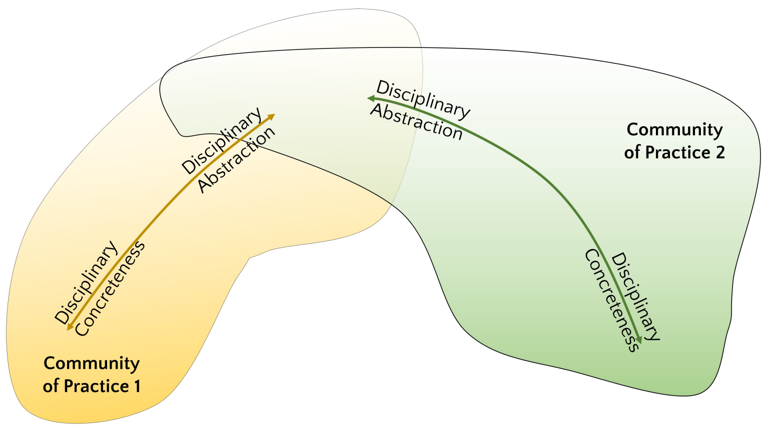

Figure 6.3: First visual iteration of a cross-disciplinary collaboration. Two communities of practice are drawn with a gradient ranging from disciplinary concreteness (darker colour) to disciplinary abstraction (lighter colour). The area of overlap is where the two disciplines can understand each other.

At this stage of the development process, it was presumed that the movement from concreteness to abstraction does not necessarily happen at the personal level but at the level of a community of practice as a whole. Professionals were assumed to be in their community's area of concreteness on one side, and when moving towards the community's side of abstraction, an intersection could be found with the side of abstraction of another community.

6.4.2 Visualisation Prototype 2

It became clear that the area of intersection between some disciplines is easier to find than other disciplines. In other words, the area of intersection is closer to the area of concreteness for some disciplines than others. The best way to visualise this was to modify the visuals to create a 2D gradient as opposed to a 1D gradient. A fixed point of engagement was also added to the gradient that the spring could be attached to. The result is shown in Figure 6.4.

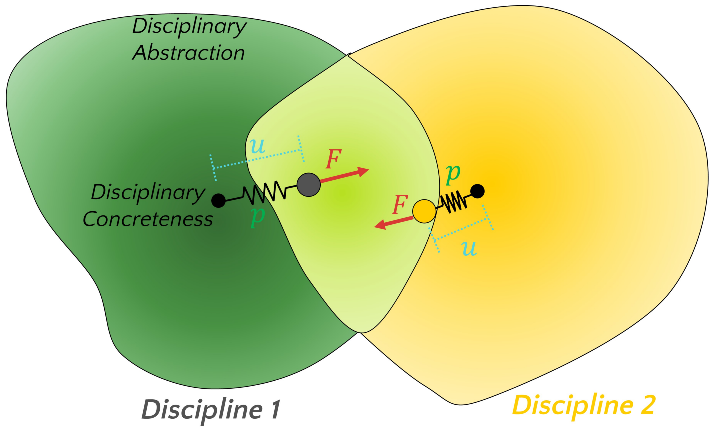

Figure 6.4: Second visual iteration of a cross-disciplinary collaboration. The gradient ranging from disciplinary concreteness to abstraction is changed from 1D to 2D. Two individuals are added that are connected to their respective disciplines with a spring. These springs each have their point of engagement at the centre of the professional's discipline. The incentive F between the two professionals causes displacements to disciplinary abstraction u, dependent on the pliabilities p.

Several things became clear after this visualisation was created. First of all, the non-round shapes of the disciplines imply that moving in one direction requires more force than moving in another direction. However, this dynamic is not supported by the fact that the spring has a single, rigid point of connection, which implies that an equal amount of force is needed to move in any direction. More fitting would be to have different points of connection depending on what direction the professional is moving towards. Second of all, the black border surrounding the edges of a discipline doesn't have a specific meaning. It implies that there is a limit to how abstract a discipline can become and that beyond this level of abstraction, the concreteness of another discipline can be found. This is untrue and for this reason, the black edge was removed.

These insights have been combined to create the final visual design of the model and are explained more thoroughly in Chapter 7. The black dot in the middle of the previous iteration has been changed to a solid shape. When the professional moves to disciplinary abstraction, the spring forces work on the edge of the shape. Hence, the spring force will be bigger if the area of concreteness is further away. The gradient that appeared in the previous iteration has been removed completely. Instead of displaying concreteness and abstraction as properties of a discipline, these properties are modelled as personal properties. A professional always has its own definitions of what is concrete and abstraction and the difference in 'personal concreteness shapes' underlines this.

7 Collaborative Pliability Model

Chapter 5 described a theoretical framework with theories on cross-disciplinary collaborations and their analogy with Newtonian dynamics. In Chapter 6 development process is described in which this framework is developed into a visualised shared mental model. The resulting model, called the Collaborative Pliability Model, is presented in this chapter.

First, Section 7.1 a set of mechanical engineering concepts are briefly introduced that are fundamental to the analogy. Next, in Section 7.2, each of these components are linked to analogous counterparts from collaboration sciences. In Section 7.3, the newly introduced concepts are illustrated using schematic examples. Finally, in Section 7.4, the analogy is used to explain some key configurations within cross-disciplinary collaborations.

7.1 Mechanical Stiffness and Compliance

The displacement of a linearly elastic spring u changes in direct proportion to the force F acting on it. A key characteristic in defining the elasticity of the spring is the spring constant or mechanical stiffness k. The deformation of the spring is then the force F divided by the stiffness k:

$$u = \frac{F}{k}$$

A schematic representation of a spring is shown in Figure 7.1. While the force and displacement working on the system are externally imposed, the stiffness is an internal system property. If the force acting on the spring is twice as big, the displacement will also be twice as big. Similarly, a spring that is twice as stiff will cause a displacement that is twice as small if the same force is applied to it.

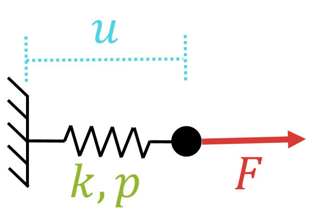

Figure 7.1: Schematic of a spring with stiffness k or compliance p. The spring force F is exerted on the spring, causing a displacement u. The initial length of the spring is assumed to be zero.

Mechanical compliance p is the opposite of mechanical stiffness k and is also a system property. A system being more stiff, so having a higher stiffness, is equivalent to a system being less compliant, so having a lower compliance. The displacement can also be written in terms of the force and compliance.

$$p = \frac{1}{k}$$
$$u = p \cdot F$$

7.2 Analogy with Collaborative Pliability

Synonyms for the word *compliance* are *complaisance*, *deference*, *elasticity*, *flexibility*, *pliability*, *springiness* and *tractability* (Thesaurus.com). Antonyms are *noncomformity*, *refusal* and *resistance*.

The mechanical definition of compliance, as described in the previous section, can figuratively be compared to the definition of collaborative pliability, a concept stemming from collaboration sciences. Collaborative pliability describes a professional's flexibility to move from personal concreteness to personal abstraction. Personal concreteness is the space where conventional rules of problem-solving apply, whereas personal abstraction is the space where conventional reasoning and logic are taken out of context to solve problems that are not in the ordinary scope.

Whereas mechanical compliance (p) describes the system's flexibility to move in the physical space (u) when a force (F) is applied to it, pliability (p) describes a person's flexibility to move from personal concreteness to abstraction (u) when incentives (F) are presented. In other words, a professional's movement to personal abstraction is dependent on a multiplication of two variables: incentives and the professional's pliability.

$$\begin{array}{ccccc} u & = & p & \cdot & F \\ \text{Movement to personal abstraction} & = & \text{Pliability} & \cdot & \text{Incentives} \end{array}$$

In the mechanical as well as the social domain, F and u are contextual, external factors that are related to each other by the system property p. For a given instance of time, p has a set value that unambiguously links u and F together. A more in depth description of the concepts 'movement to personal abstraction', 'pliability' and 'incentives' is given in the following sections.

7.2.1 Movement to Personal Abstraction (u)

Personal concreteness is the professional's concrete application of obtained knowledge. Familiar concepts, methods of problem-solving and disciplinary rules are used within this space. Personal abstraction, on the other hand, is an area containing (partially) unknown, new knowledge, methods of problem-solving or disciplinary rules. Creating logical connections in the area of personal abstraction is more difficult than within the area of concreteness.

In literature, the more general terms 'disciplinary concreteness' and 'disciplinary abstraction are used (Fam et al., 2018). However, when the changes are looked at on the individual level, it can only be concluded that what is perceived as concrete and abstract is different for each individual. Nobody has precisely the same background, past and experiences. Hence, these terms are referred to as 'personal concreteness' and 'personal abstraction'.

The change from personal concreteness to abstraction is not a black-to-white shift and a concrete distinction between what is abstract and what is concrete cannot be made. Instead, some of the professional's knowledge can more concretely be evoked than other knowledge, depending on the previous contact with and application of this knowledge. For example, a college student will develop concrete knowledge during the education program. As the curriculum progresses, knowledge, concepts and relations will become more concrete as the student gets more familiar with how theory can be applied.

Within a collaboration between professionals, be it disciplinary or cross-disciplinary, there will be some exposure to a degree of disciplinary abstraction for everyone involved. The incentives that are presented and pliabilities of the professionals determine up to what extent each professional displaces towards personal abstraction. If the displacements are sufficient, a point of intersection can be found. As a result, professionals can relate familiar knowledge to each other to communicate and share ideas. This intersection point is usually more abstract to one professional than to the other, depending on the previous experience of both professionals with the topic.

7.2.2 Incentives (F)

A movement is always initiated by an inducement. In the physical domain, the movement of the spring is initiated by a force F extending the spring (or pushing the spring inwards). The compliance p relates this force to the displacement u. Likewise, a disciplinary displacement is initiated by an incentive F that triggers the professional to displace to personal abstraction. The pliability p relates this incentive to the resulting disciplinary displacement.

One incentive can trigger a displacement of multiple professionals n. It is an action that can cause multiple reactions:

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} F$$

A distinction between two types of incentives is made: Internal and external incentives. An external incentive for one discipline can be an internal incentive for another discipline. In formula form this distinction will not be elucidated and both types of incentives are referred to as F.

Internal Incentives

Internal incentives are thoughts and actions emerging from professionals themselves. Examples of internal incentives are the intrinsic willingness to collaborate with another scientific team, the personal collection of information that leads to new insights or conversations that were conducted with a cross-disciplinary partner. Internal incentives are often the cause of proactivity.

While internal incentives and pliability are both concepts related to what is happening inside the professional, there is a fundamental difference between these two. Incentives are always the reason that change is occurring. They are actions that induce movements to personal abstraction. Pliability, on the other hand, is merely a system property that translates the incentive to a shift towards personal abstraction. Pliability is a time-varying system property, whereas internal incentives are context-dependent initiators. Both are needed to realise a disciplinary displacement: An infinitely stiff spring will not move no matter how hard you tug on it, but if you do not pull on a spring it will never move, no matter how compliant the spring.

External Incentives

External incentives are induced by something other than the professional. They are the external forces causing the professional to move. Examples are financial motives imposed by the government, investments done by investors to develop a specific cross-disciplinary project or the desire of collaboration partners to work together.

7.2.3 Collaborative Pliability (p)

Collaborative pliability is the system property that determines the magnitude of a displacement to personal abstraction as the result of an incentive. An analogy is made with joint stiffness, which describes the human stiffness of a joint that changes as a result of external factors. Some models approximate the total value of joint stiffness as the sum of the different factors that contribute to stiffness changes (Kearney et al., 1997). These factors are in reality not completely independent: Coupling takes place, which is the effect of stiffnesses mutually influencing one another. The system identification techniques that are heavily elaborated upon in part II make use of this distinction and aim to identify these different types of stiffness. The same principle is used to describe the different factors influencing pliability. The effects of coupling are neglected and it is assumed that the contributions accountable for different parts of the stiffness can be summed linearly:

$$u = (p_p + p_i + p_g + p_d)F$$

In this equation, personal pliability p_p refers to pliability or pliability changes due to personal factors. Interpersonal pliability p_i refers to pliability or pliability changes due to interpersonal factors. Group pliability p_g is impacted by group factors and finally, disciplinary pliability p_d is impacted by disciplinary factors. One discipline is more pliable than the other, just like one team will be more pliable than the other. Also, people's pliability may differ depending on who they are working together with. Finally, some individuals are more pliable than others. Mind that this distinction does not mean that disciplinary pliability is the same for each professional of a discipline, group pliability is the same for everyone in the group and interpersonal pliability is a pliability changing equally for two collaborating partners. Instead, each of these pliabilities represents the contribution of disciplinary, group and interpersonal dynamics to the person's pliability. These changes are different for every professional.

Since one incentive can trigger a displacement of multiple professionals, this equation can be further expanded in the following form:

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} p_{1,p} + p_{1,i} + p_{1,g} + p_{1,d} \\ p_{2,p} + p_{2,i} + p_{2,g} + p_{2,d} \\ \vdots \\ p_{n,p} + p_{n,i} + p_{n,g} + p_{n,d} \end{bmatrix} F$$

with n the total number of professionals impacted by the incentive. In the technical domain, the stiffness of a spring can change due to factors like erosion, material fatigue or a nonlinear position dependency. In the social domain, pliability also changes in time it changes differently per person. The following subsections give examples of how each type of pliability is defined and how it can change.

Personal Pliability (p_p)

Personal pliability generally increases with experience in the long term. This is related to a conjunction of factors that can best be described as collaborative readiness. Moving towards the area of personal abstraction can go paired with discomfort, frustration and confusion. With experience, a professional develops expectation management that eases dealing with these effects.

Apart from these effects, all professionals have a 'baseline' personal pliability depending on their characteristics. This baseline pliability can slowly increase or decrease as a function of time, depending on new experiences and changing worldviews.

There are also swift, volatile processes that change the personal pliability from day to day. However, because it is difficult to grasp the long-term pattern of these effects, only the slower, more robust changes in personal pliability are highlighted.

Interpersonal Pliability (p_i)

Interpersonal pliability is relationship-based and focused around the pliability of collaborating with one other professional specifically. A professional's interpersonal pliability is different depending on the partner that he or she is collaborating with.

A reference point for interpersonal pliability is the difference of worldviews of two professionals. More like-minded professionals are more pliable to collaborate because like-mindedness gives the expectation that other ideas of the collaborating professional are generally also comparable to own ideas.

A more changeable but influential factor influencing interpersonal pliability is trust. Trust between two professionals is something comprehensive that cannot easily be described, but it can have a big impact on how willing two professionals are to collaborate. It is something that can improve quickly over time, but also deteriorate swiftly.

Group Pliability (p_g)

Group pliability is the professional's pliability due to dynamics at the group level. From a policy perspective, group pliability is the easiest to change and often the target of policy interventions. Group pliability does not change equally for every professional part of a group since policy decisions affect each professional differently.

A factor influencing group pliability is the leadership of a team. A leader can actively take a facilitating role within a team to streamline the collaboration process, which can yield pliability commitments. Other factors that indirectly have an impact on the team members' pliability are the outcome interdependence between the team members and the team size. With interdependent goals determined within a team, working together is more of a necessity and team members will be more inclined to pliable thinking. While team size likely impacts the group pliability, it can have mixed effects on the group pliabilities of the team members.

Disciplinary Pliability (p_d)

Finally, disciplinary pliability is the effect of disciplinary dynamics on the professional's pliability. The dynamics at the disciplinary level change slowly if they change at all. It is difficult to modify them, but their importance cannot be neglected.

Disciplinary aspects like the discipline's history, the amount of codification and prominent models and artifacts play a big role in how things are organised and looked at within a discipline. The amount of codification means that there is less freedom to apply disciplinary knowledge pliably. Hence, professionals from disciplines that are more codified will have lower disciplinary pliability.

A more changeable factor influencing disciplinary pliability is what happens on the socio-political level within a discipline. Socio-political dynamics can change the need or openness to other disciplinary worldviews, in turn impacting the disciplinary pliability.

7.3 Schematic Representation

Personal concreteness can be represented in a 2D plane using a different shape for every person, representing the variety in perceptions of personal concreteness. Some examples are shown in Figure 7.2. The area inside the shape is the personal area of concreteness. The area outside of this shape is defined as personal abstraction. Even within what is currently modelled as an area of concreteness, a certain degree of pliability is often required to map knowledge that is more concrete to an area that is relatively abstract but still quite concrete. The hard border at the edges of each area is actually a gradient from more concrete in the centre towards more abstract at the edges.

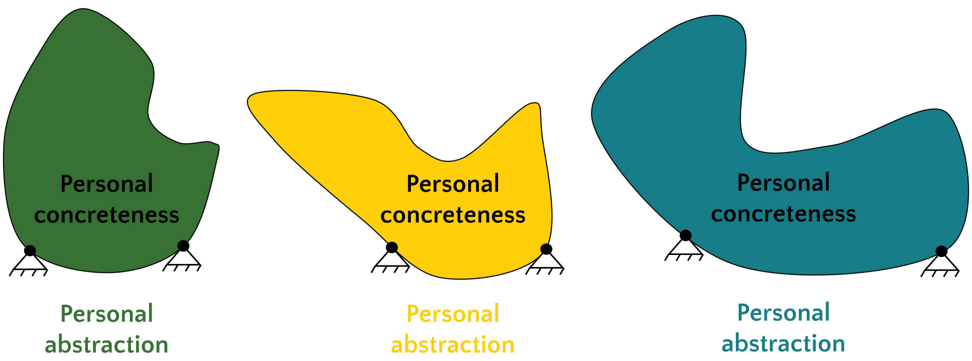

Figure 7.2: Schematic of the difference in shapes in personal concreteness between different individuals. The two ground symbols at the borders of each shape indicate that the shapes themselves do not move. To avoid having cumbersome figures, these symbols are not drawn in the upcoming figures.

Depending on the context of problem-solving and the collaboration partners, professionals can evoke knowledge from their area of personal concreteness with little effort. However, when concepts in a collaboration become more abstract, professionals are compelled to conceptualise knowledge in the area of personal abstraction to find a point of intersection with the collaboration partners. This is where a degree of pliability is required: Depending on the pliability of the professionals they will be able to conceptualise knowledge that is further or less far in the area of personal abstraction.

The left shape in Figure 7.3 represents a situation where the professional conceptualises knowledge in his or her area of personal concreteness. No (or actually, little) incentives are required for the professional to understand concepts, methods and logic inside this area.

The middle and right shapes in Figure 7.3 represent two instances where a professional is exposed to incentives to move towards personal abstraction. The movement from personal concreteness to abstraction can schematically be represented using the spring analogy. The product of incentives and pliability of the professional determines how abstract the knowledge is that the professional can conceptualise:

$$u = p \cdot F$$

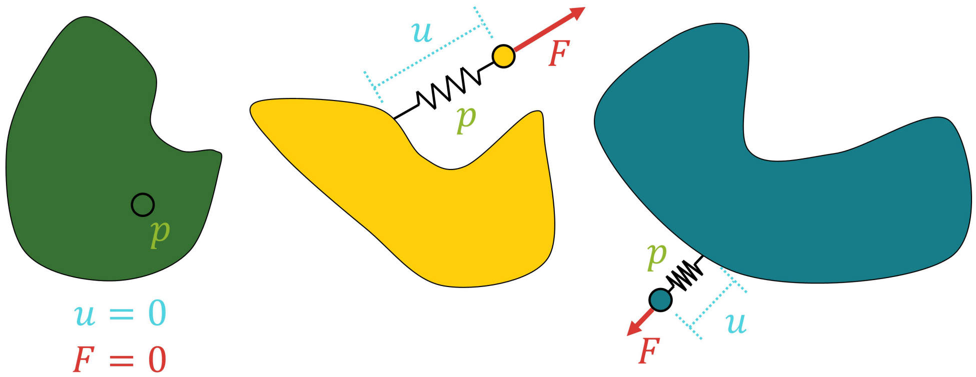

Figure 7.3: Schematic of how individuals can evoke knowledge with respect to their personal concreteness and abstraction, making use of the spring analogy. The circles represent the knowledge that the professional is evoking. In each situation, incentives F present themselves and the person's movement to personal abstraction u can be observed. The magnitude of the movement is dependent on the professional's pliability p.

The areas of personal concreteness are not static: Whenever professionals try to conceptualise knowledge outside of their conventional areas of concreteness, the concepts that were abstract at first start to make more sense. By visiting an area of abstraction repeatedly and frequently, the conceptualisation of this area becomes more concrete as visualised in Figure 7.4.

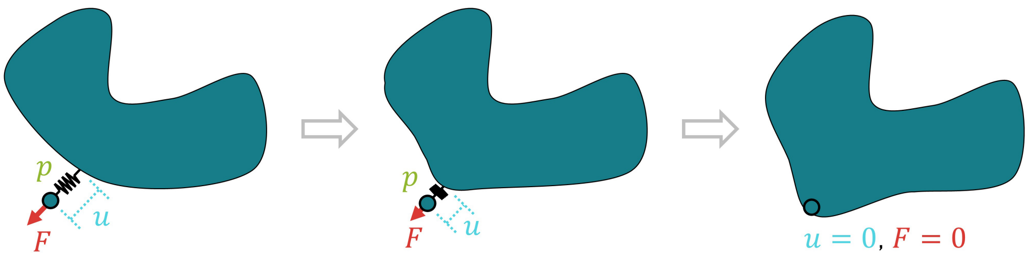

Figure 7.4: Schematic showing how the areas of personal concreteness are constantly changing. By evoking knowledge in the area of disciplinary abstraction, knowledge in this area becomes more concrete and the size of the area of personal concreteness increases.

7.4 Levels of Cross-Disciplinary Integration

Now that the fundamentals of the model are covered, the differences between disciplinarity, multidisciplinarity, interdisciplinarity and transdisciplinarity can be clarified.

Disciplinary Collaboration

In a disciplinary collaboration, the professionals involved in the collaboration have overlapping areas of personal concreteness, see Figure 7.5. This is often because they have similar educational backgrounds or experiences. They are familiar with working with the same concepts, theories and methods to tackle problem-solving and know about the bottlenecks and struggles when solving a problem within this area of concreteness.

Because all professionals have their specialisations, fields of interest and knowledge, there are still parts where not all the areas of concreteness overlap, or none overlap at all. Still, relatively little pliability is needed for the professionals to find an area of intersection and mutual concreteness. Making such a collaboration succeed is easiest compared to the other collaboration types.

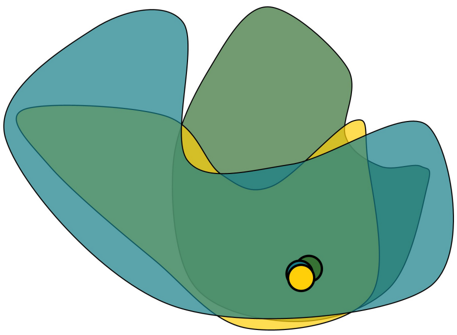

Figure 7.5: Example of the personal areas of concreteness within a disciplinary collaboration. The professionals have overlapping areas of concreteness and little pliability is required to conceptualise shared knowledge.

Multidisciplinary Collaboration

In a multidisciplinary collaboration, clusters of professionals work together that have shared areas of concreteness within the cluster, whereas there is little to no overlap between the areas of concreteness of different clusters, see Figure 7.6. One cluster can be seen as a discipline or a team that has prior experience working together.

Again, the local areas of concreteness will be relatively easy to find, but communicating ideas and concepts from one cluster to another is more difficult because ideas are not shared with a common conceptual basis. As a result, teams work together in a relatively isolated fashion and strip ideas from the majority of their disciplinary context when communicating, anticipating that they are more meaningful by neglecting discipline-specific details and considerations that go into problem-solving.

Multidisciplinary collaborations can be seen as clusters of disciplinary collaborations, in which little pliability is needed to communicate effectively. Because within the transfer of knowledge between clusters problems are stripped of most of their disciplinary complexity, less pliability is needed as compared to a situation where the full scope of complexity is shared with the other cluster. Knowledge is rarely conceptualised at a point of intersection by professionals from different clusters.

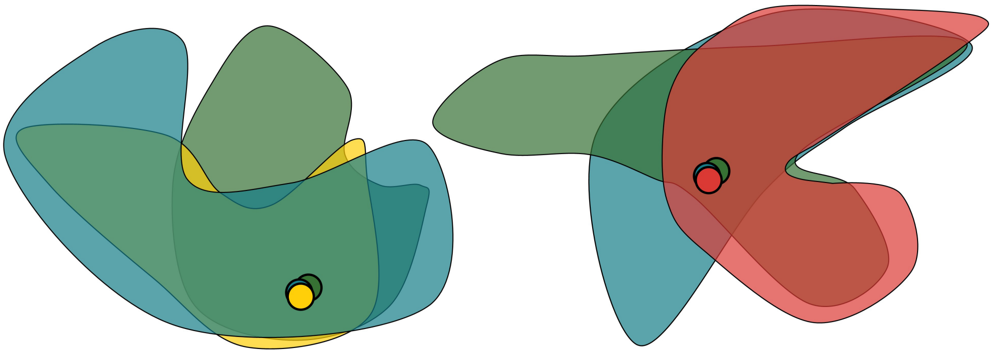

Figure 7.6: Example of the personal areas of concreteness within a multidisciplinary collaboration. Professionals conceptualise shared knowledge in clusters, but a shared conceptualisation of knowledge does not occur within the whole team.

Interdisciplinary Collaboration

Within an interdisciplinary collaboration, professionals from different disciplines move away from their areas of personal concreteness towards abstraction, see Figure 7.7. Somewhere within this space, disciplines find each other to create solutions containing logic and concepts from both disciplines. The point of intersection is closer to the area of concreteness for some professionals than for others, and some professionals need more pliability to understand the logic within this area of intersection than others. The point of intersection can even be within the area of concreteness of some professionals.

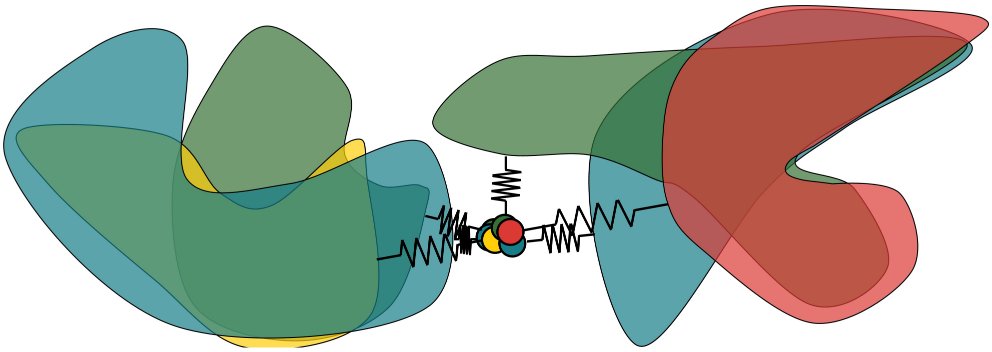

Figure 7.7: Example of the personal areas of concreteness within an interdisciplinary collaboration. The professionals conceptualise knowledge outside of their personal areas of concreteness to find an area of intersection. Doing so requires incentives and a degree of collaborative pliability.

The figure shows that professionals now need to conceptualise knowledge in their domains of personal abstraction to find common ground. To do this, professionals need a degree of pliability to collaborate effectively. Ideas, concepts and problems that are shared within this area of abstraction constantly need to be mirrored back to the area of concreteness of the professional, which takes considerable effort and may take some time to process. Once this process is initiated, a bridge for knowledge transferring is established between two different conceptual models that are normally not related to one another.

Transdisciplinary Collaboration

The final and most integrated form of collaborating is a transdisciplinary collaboration. When shared knowledge is repeatedly and frequently conceptualised in the areas of personal abstraction, professionals will perceive this knowledge as less abstract as time progresses. Eventually, their fields of personal concreteness are expanded in the direction of the newly developed knowledge. The result is shown in Figure 7.8. A new area of concreteness is developed that contains methods, concepts and tools from multiple disciplines that participated in the collaboration.

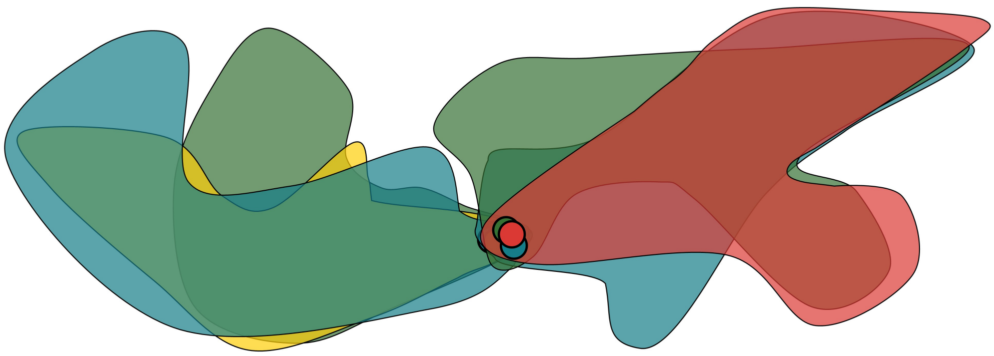

Figure 7.8: Example of the personal areas of concreteness within a transdisciplinary collaboration. The professionals intensively sought to find common ground by repeatedly trying to conceptualise knowledge in a domain abstract to them. As a result, their areas of personal concreteness have morphed and a shared area of concreteness has been developed.

Creating a truly transdisciplinary collaboration needs professionals to work together in an integrated and interwoven manner. A great deal of pliability is required to constantly re-evaluate collaboration problems and mirror these to knowledge within personal concreteness. In the initial stage of a transdisciplinary collaboration, where knowledge integration still has to unfold, the areas of personal concreteness resemble the ones sketched in Figure 7.7. Repeatedly scouring through the area of personal abstraction can be a resourceful process. However, with due time, the mental models of the professionals are permanently broadened, creating new knowledge that the professional can comfortably use to tackle problems as shown in Figure 7.8.

8

Model Assessment

Chapter 7 introduced the Collaborative Pliability Model, a shared mental model that is based on an analogy between cross-disciplinary collaboration dynamics and Newtonian dynamics. The model is visualised using schematics that are commonly used within mechanical engineering so that mechanical engineers can more easily link the discussed content to existing knowledge. In this chapter, the model is tested by presenting it to a group of mechanical engineers and determining how it is perceived by them.

The methods of this assessment are discussed more elaborately in Section 4.5 and are repeated briefly. An assessment is conducted with a group of six mechanical engineering students that consists of three phases. In phase 1 the participants fill in a questionnaire on a cross-disciplinary collaboration project that they participated in and on their perceptions on the success of that collaboration. In phase 2, the Collaborative Pliability Model is presented to the participants in presentation form. In phase 3, the participants fill in another questionnaire on the collaboration that they participated in using the insights attained from the presentation. In this round, they are also asked their opinions on the model.

First, Section 8.1 elaborates on how the Collaborative Pliability Model is presented to the participants. Next, the results of the assessment are highlighted. In Section 8.2, participants' perceptions of the success of their collaborations are shown. In Section 8.3 the insights that participants attained from the presentation are then discussed. Finally, Section 8.4 shows the opinions of the participants of the Collaborative Pliability Model from phase 3 of the assessment.

8.1 Presentation

The Collaborative Pliability Model is presented to the participants in a 30-minute presentation in which the contents are illustrated using 21 slides in Microsoft PowerPoint. The presentation is structured in the same order that is used to introduce the model in Chapter 7. The presentation slides and transcript are enclosed in Appendices E.3 and E.4.

Slides 2 to 3 are used to go through the theory on mechanical stiffness and compliance that is relevant for understanding the analogy. This theory is not covered in-depth, as mechanical engineers are expected to have a lot of knowledge on these topics already. Next, slides 4 to 6 are used to explain the analogy between mechanical compliance and collaborative pliability. Collaborative pliability is introduced as a concept, and similarities with mechanical compliance are explained using the schematic of a spring. Slide 7 is then used to describe the movement to personal abstraction u by going through definitions of personal concreteness and personal abstraction. In slide 8, the concept of incentives F is further explained by giving a few examples of what incentives could be. Slides 9 to 13 are then used to go in depth into collaborative pliability and by what it is influenced. The main assumption is that the pliability of any professional is influenced by factors that can be categorised using four categories: Personal, interpersonal, group and disciplinary factors. Personal factors are defined as factors that affect the professional alone, group factors affect the group as a whole, et cetera. For each category, the same examples that were discussed in Chapter 7 are given. Slides 14 to 20 are then used to illustrate the different types of collaborations using the analogy: Disciplinary, interdisciplinary, multidisciplinary and transdisciplinary collaborations. Slide 21, shown in Figure 8.1, is a summary slide in which all components of the model are repeated. This slide is shown to the participants during the third phase of the assessment.

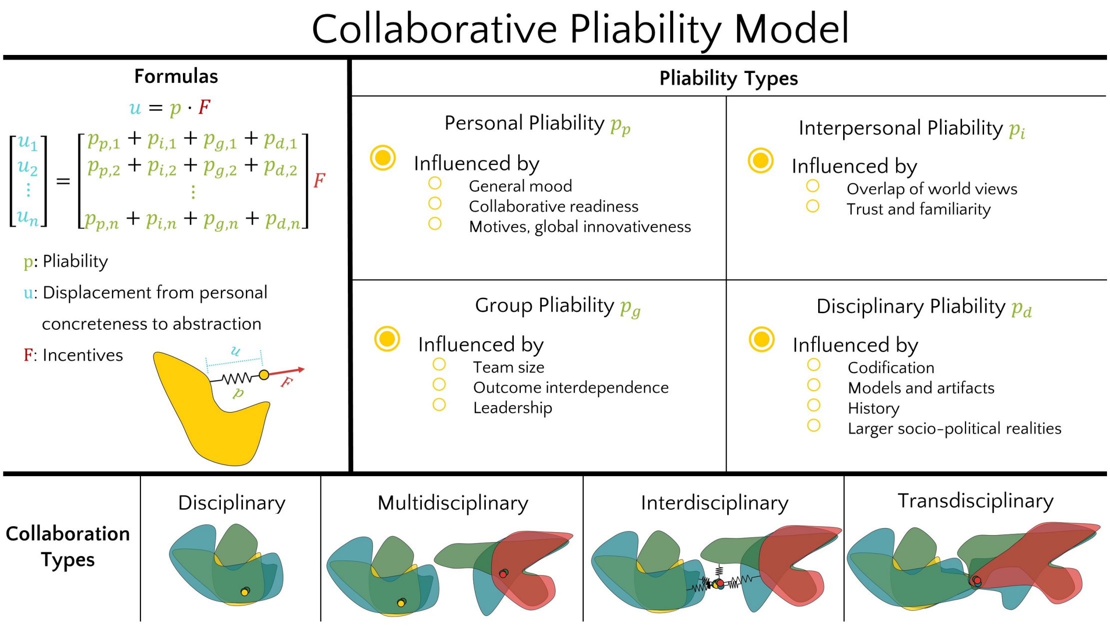

Figure 8.1: Summary slide that is shown to the participants during the third phase of the assessment.

8.2 On the Collaboration

Before conducting the presentation, participants are asked to give their opinion of how well the cross-disciplinary projects that they participated in went in their perception. This is done because participants that had a negative experience might be less inclined to analyse their collaboration openly. Figure 8.2 shows that every member of the assessment group was positive about their collaboration process, rating the collaboration as either a good experience or a very good experience.

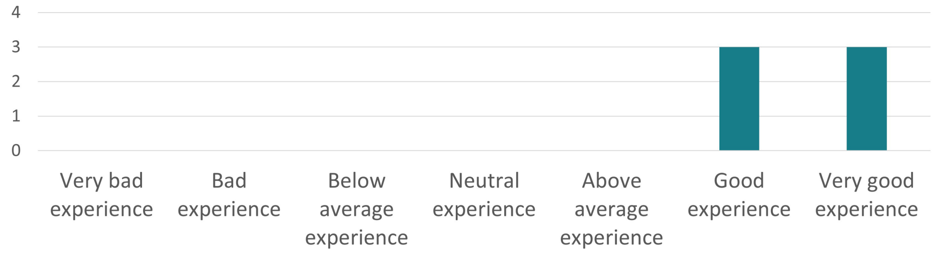

Figure 8.2: Answers to the question "*What is your overall experience of the collaborative process? Choose one option.*" using a seven-point Likert scale.

In the third phase of the assessment, the participants are asked to rate if their collaboration was mainly disciplinary, multidisciplinary, interdisciplinary or transdisciplinary. This question serves as a check to see if the participants could make sense of these concepts and link them to their collaboration. In Figure 8.3, it is shown that every participant labelled their collaboration as interdisciplinary, whereas one participant also included 'multidisciplinary' as an answer and one participant categorised his or her collaboration as both disciplinary, multidisciplinary and interdisciplinary. No participants saw their collaboration as mainly transdisciplinary.

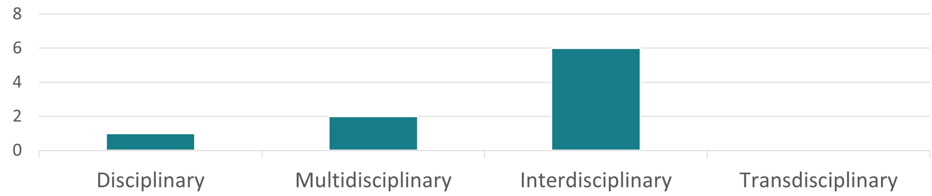

Figure 8.3: Answers to the question "*Was your collaboration mainly disciplinary, multidisciplinary, interdisciplinary or transdisciplinary?*" Multiple answers could be given.

8.3 Factors Influencing the Collaboration

In the first phase of the questionnaire, before seeing the presentation, the participants are asked to list a series of factors that influenced their collaboration. In the third phase, after the presentation, the participants are asked to determine whether the factors that they listed belonged to personal, interpersonal, group or disciplinary pliability. Afterwards, they are asked to come up with new factors that influenced their collaboration and list at least one factor per category. The slide from Figure 8.1 was shown to the participants during the answering of these questions and they were allowed to discuss among each other how they would categorise certain factors or ask questions.

The distinction between personal, interpersonal, group and disciplinary pliability is used as a way to let the participants analyse their collaborative process from a different angle. It serves as a tool to give new impulses to the thought process of the professionals. The professionals make the distinction themselves by interpreting the concepts that were introduced in the presentation and giving meaning to them in light of their collaborations. Factors are devised by the participants by thinking about the different types of pliability, by discussion among the group of participants and by asking questions.

Figure 8.4 shows how many factors were thought up before the presentation and after the presentation by each participant. It is shown that on average, participants list as many new factors after the presentation as they listed original factors before the presentation. This suggests that seeing the presentation gave new input to revisit their collaboration and come up with new factors.

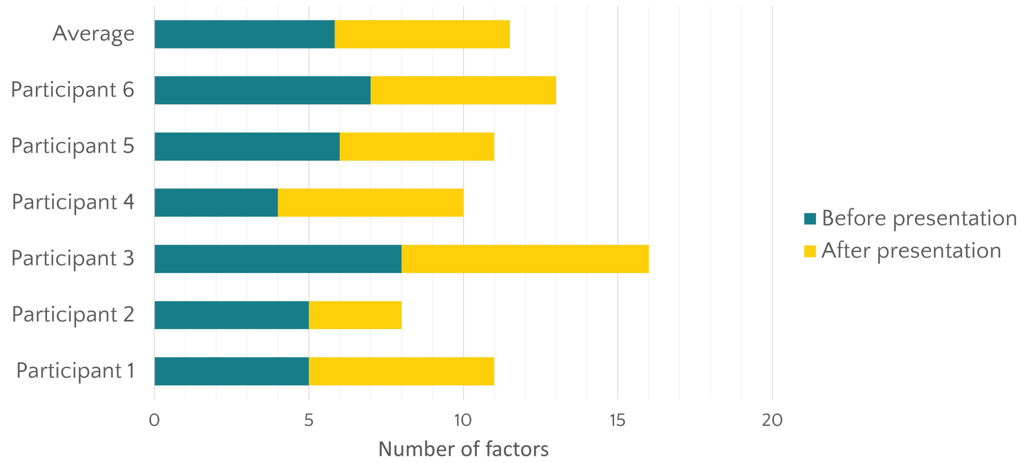

Figure 8.4: Overview of the number of factors influencing the pliability of the collaboration that was thought up per participant. On average, 49% of the factors were thought up before the presentation and 51% were thought up after the presentation.

The number of factors that the participants labelled as personal, interpersonal, group or disciplinary factors is shown in Figure 8.5. Participants came up with more personal pliability (22.5) and group pliability (23.5) factors as opposed to interpersonal pliability (13) and disciplinary pliability (10) factors. The pliability categories for which the fewest factors were written down before the presentation have the biggest relative increase: The number of interpersonal pliability factors increases by a factor 2.6 and the number of disciplinary pliability factors increases by a factor 3.3.

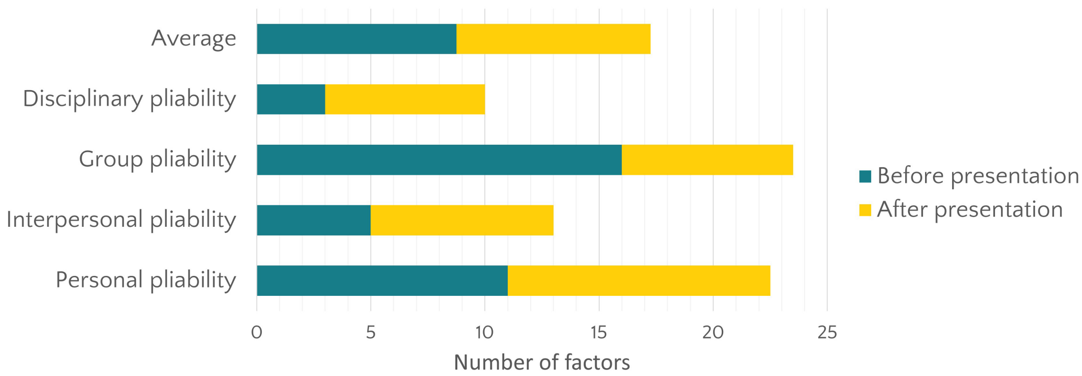

Figure 8.5: Number of personal, interpersonal, group and disciplinary pliability factors that were mentioned in total in each stage of the questionnaire. The numbers that are shown are summed over all participants.

8.3.1 Impactful and Easily Changeable Factors

After writing down all factors that the participants could come up with, they are asked to mark which of the factors that they devised had an impact on the success of the collaboration. Similarly, they are asked to mark the easily changeable factors. This is done because impactful and easily changeable factors are assumed to be more relevant than other factors. Figure 8.6 shows the number of impactful factors and Figure 8.7 shows the number of easily changeable factors the participants wrote down before and after seeing the presentation. The relative number of impactful factors (33%) and easily changeable factors (44%) written down after the presentation is slightly smaller compared to the overall number of factors written down after the presentation (49%). Still, a significant number of impactful and easily changeable factors was added after seeing the presentation, which implies that the presentation gave the participants new useful insights.

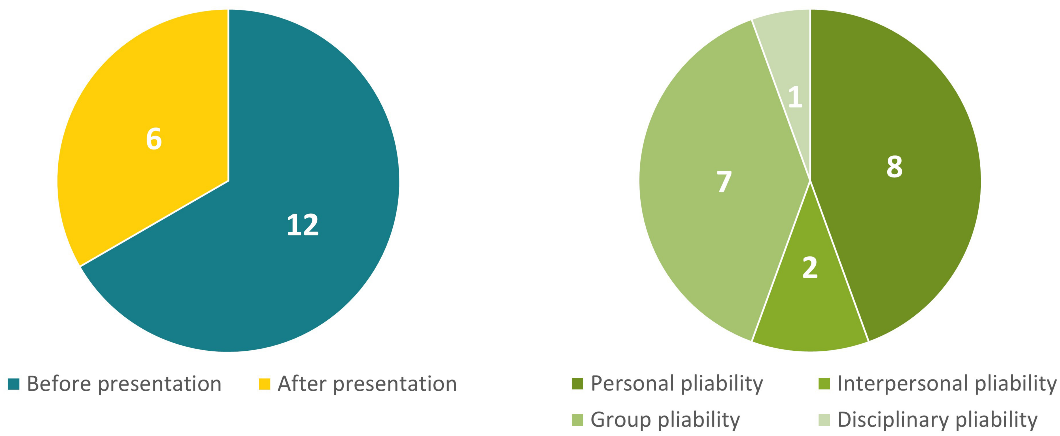

Figure 8.6: Overview of the total number of factors that were marked as 'impactful' by the participants. All participant data is taken together. 33% of the factors that the participants marked as impactful were thought up after seeing the presentation.

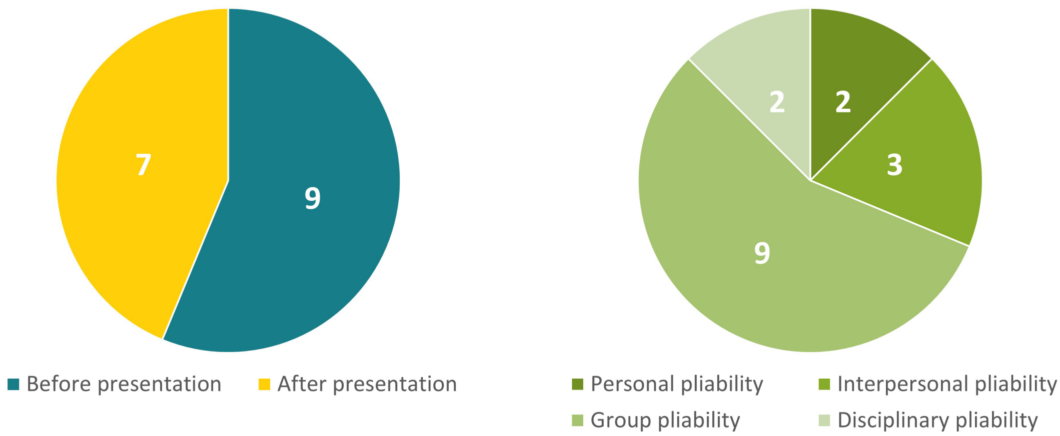

Figure 8.7: Overview of the total number of factors that were marked as 'easily changeable' by the participants. All participant data is taken together. 44% of the factors that the participants marked as easily changeable were thought up after seeing the presentation.

	Positive factors	**Negative factors**
Personal pliability	• People were motivated to get everything out of the project • Different passions of team members complemented each other	! Intrinsic personalities of colleagues made it difficult to work together Δ Frequent interruptions from work by people having non-urgent questions
Interpersonal pliability	Δ Supervisors were approachable, since they were co-students Δ Conducted a DISK personality test to understand each other's personalities	! Lack of confidence in some fellow group members
Group pliability	Δ! Skill level of the group leader Δ Changed offices depending on the phase of the project	• Large group, which resulted in a lack of a group feeling Δ Lack of personal overview of the course of the project
Disciplinary pliability	• Different disciplinary backgrounds	• Uniform team resulting in a lack of different viewpoints Δ It was difficult to get everyone aboard on quality control

Figure 8.8: Factors that were filled in before conducting the presentation. The factors have been reframed so that each factor is presented in a similar, concise form. Factors that are marked as 'impactful' are labelled with an exclamation point (!). Factors that are marked as 'easily changeable' are labelled with a delta symbol (Δ).

	Positive factors	**Negative factors**
Personal pliability	• Curiosity of team members to learn about other disciplines • Positive effect of the weather	• Stubborn supervisor that did not like to take risks ! Not everyone had the same goal
Interpersonal pliability	• Increase of trust as the project progressed Δ Each week, retrospectives were held to clear the air between team members	• Small interpersonal issues became bigger over time when not addressed • Feeling that someone often did not listen
Group pliability	Δ Small team size resulted in better cooperation ! Outcome interdependence between departments	• Lack of a long-term vision Δ! Working in shifts meant that the whole team was not always together
Disciplinary pliability	! Great vibe in the building with other project teams Δ All collaborators were TU Delft/Engineering students	• Difficulties between the 'tech' team and the 'non-tech' team • An all-technology team meant having a lack of skills in sales, HR, etc.

Figure 8.9: Factors that were filled in after conducting the presentation. The factors have been reframed so that each factor is presented in a similar, concise form. Factors that are marked as 'impactful' are labelled with an exclamation point (!). Factors that are marked as 'easily changeable' are labelled with a delta symbol (Δ).

8.3.2 Examples of Factors

The purpose of the assessment is to see if the Collaborative Pliability Model yielded the participant new insights and what factors the participants came up with is subordinate to this. Still, to give an idea of what kind of factors were written down, examples of factors that were listed before conducting the presentation are listed in Figure 8.8 and after conducting the presentation in Figure 8.9. Some factors that were marked as 'impactful' and 'easily changeable' are also included in these figures. Determining what category each factor belongs to is done by the participants themselves and is not always adequate with the description of the pliability categories. For example, 'Great vibe in the building with other project teams' is labelled as disciplinary pliability, while this factor does not change the pliability of the discipline as a whole, but that of the group working together. However, the primary goal of using the Collaborative Pliability Model is to serve as a workbench for participants to shed new light on their collaborative process, regardless of how they use the model.

8.4 Model Opinions

One question asked if the conceptualisation of collaboration theories in the form of a mechanical stiffness model helped with the understanding of the concepts that were explained. 5 out of 6 participants state that the mechanical stiffness model helped with the understanding of the concepts. The other participant stated that the model did not help this participant personally, but supposes that the model could help others. Three of the answers that were given are shown in figure 8.10. Also in response to the question if discussing the collaboration model yielded new insights, the participants were generally positive. Two answers are shown in figure 8.11.

*"Yes, in this case I can **imagine the problem**. I like that the spring needs to become longer and that therefore more force is needed. I think that this is a good representation of the real world visualized in an **easy to understand way**."*

*"Yes, most definitely. I think this is a good analogy, because it is a **very familiar concept** for us. Therefore, it is well within our personal concreteness."*

*"YES, yes definitely !! Especially **everyday examples help** with understanding the theory. Very interesting!"*
(Translated from Dutch)

Figure 8.10: Answers to the question: "Did the conceptualization of collaboration theories in the form of a mechanical stiffness model help with the understanding of the concepts that were explained?"

*"It was **very interesting** to see the different factors that make up pliability, **it could help to see how you could improve collaboration** with a new team member by for example focusing on their interpersonal and group pliability."*

*"Everyone has heard of the terms multidisciplinary, interdisciplinary & transdisciplinary but the exact differences between the three never stuck with me. [...] **The concepts have changed from being something I have to really remember to something I can derive myself**."*

Figure 8.11: Answers to the question: "Did discussing the collaboration model yield you new insights?"

9 Discussion

This research investigated a way to bring together the epistemological paradigms of collaboration sciences and mechanical engineering. This is done by creating a shared mental model using a tailor-made analogy. The following research question was central to this research: "*How can cross-disciplinary collaboration dynamics be described in a way meaningful to mechanical engineers?*".

A theoretical framework was constructed that describes the processes behind cross-disciplinary collaborations. At the same time, an analogy between parts of the theoretical framework and fundamental concepts from Newtonian dynamics was developed. As a result, a framework of collaboration theories is created using connections and principles that are well-known to engineers. The framework is used to develop a visual model using schematics that are commonly known within mechanical engineering. The model, called the Collaborative Pliability Model, is assessed by presenting it to a group of six mechanical engineering students and determining how it is perceived by them. The students came up with numerous new insights based on input from the model and were positive with regards to its usability. In this chapter, these results are discussed.

First, the relevance of the model is discussed in a societal and scientific context in Section 9.1. Next, Section 9.2 elaborates on how the model can be used in practice. Afterwards, in Section 9.3 two points of attention with regard to the development process are discussed. Next, the difficulties and limitations of this research are discussed in Section 9.4. Finally, recommendations for future research are given in Section 9.5.

9.1 Relevance

In this section, the relevance of the current research is described. Section 9.1.1 describes the primary role that the developed model has in enhancing cross-disciplinary collaborations. The importance of cross-disciplinarity in tackling today's grand challenges is then stressed in Section 9.1.2. Afterwards, the scientific relevance of the research is discussed in Section 9.1.3. Finally, Section 9.1.4 compares the developed model with tools that have previously been developed.

9.1.1 Role of the Collaborative Pliability Model

The Collaborative Pliability Model is developed as a tool to enhance the understanding of cross-disciplinary collaboration theories by mechanical engineers. It serves as a way to broaden the view of the mechanical engineers that use it. In a way, it updates the mental model of the users of the model by introducing new concepts that extend the representation of reality that the engineers already have.

The gap between the epistemological paradigms of collaboration sciences and mechanical engineering is reduced by creating a shared mental model between these paradigms. Concepts from collaboration sciences are put in relation to concepts from mechanical engineering using an analogy. As a result, mechanical engineers can use the model to link these collaboration sciences concepts to existing knowledge, making them more meaningful than in their original context. Therefore, mechanical engineering professionals need less collaborative pliability to make sense of the concepts.

The goal of making these concepts meaningful to mechanical engineers is to improve their success in cross-disciplinary projects. Learning about the processes behind cross-disciplinary collaborations is a form of metacognition. Spending time on the metacognitive process behind cross-disciplinarity improves the professional's ability to be successful in a cross-disciplinary environment (Keestra, 2017).

The model assessment conducted for this research showed that participants liked the Collaborative Pliability Model as a tool for sense-making and that using the model helped them to categorize new knowledge in a way that was familiar to them. Numerous new insights were attained by seeing the presentation. The personal opinions of the participants concerning the model also underline that the model was deemed likeable as a tool for learning.

9.1.2 Need for Cross-Disciplinarity

Grand challenges, sometimes called wicked problems, are complex, unique and interconnected problems that cannot be definitively described (Rittel and Webber, 1973; Courtney, 2001). Linear solutions are not available and state-of-the-art theories are inadequate for fully describing the scope of the problem. Many of the grand challenges that have a great impact on today's society require input from technical scientists to be dealt with accordingly. For example, technical input is required to battle climate change, to ensure food security and to keep in pace with technology.

Nowadays professionals are educated in a highly hyperspecialised manner. This means that they are specialised in solving smaller problems, existing in a chain of multiple small problems that together entail a bigger problem. However, this method overlooks the fact that the full scope of many of today's grand challenges is not addressed when they are subdivided into smaller separate sub-problems. These challenges require a more holistic problem analysis to be solved (Fam et al., 2018). Grand challenges are fundamentally indeterminant when they are not viewed in coherence with the larger whole that they are a part of (Buchanan, 1992). Instead, cross-disciplinary approaches are required to grasp the full nature of today's grand challenges (Mitchell, 2009; O'Rourke et al., 2016).

9.1.3 Scientific Relevance

This research relies on creating an analogy between the concepts of two specific disciplines. Analogies are often used to draw parallels with concepts or examples that are meaningful to the general public, when for example the process of photosynthesis is explained by comparing a plant to a little factory that uses water and light as fuel. An advantage of using analogies is that new knowledge on a topic can be linked to existing knowledge, creating more cohesion with the newly learned topic.

This research applies analogous reasoning differently: Specific concepts and their relations are put in conjunction with a topic that is fundamental to another discipline. As a result, new content is presented tailor-made to a specific target group. Within conventional analogies, an analogy is drawn with a general topic that everyone is assumed to have some, but not intensive knowledge of. By making an analogy with a topic that is fundamental to a discipline, professionals from this discipline can link newly attained knowledge to the wide understanding that they already have of the fundamental topic of their discipline.

This new way of bridging two epistemological paradigms is used to enhance the knowledge of engineers on cross-disciplinarity to improve their knowledge on cross-disciplinary collaborations and as a result their cognitive awareness. As a result, theories on collaboration dynamics are taught in a way that is interwoven with the primary discipline. These theories no longer have to be perceived as a standalone framework of theories but are integrated and interpreted with respect to the primary discipline. Mechanical engineers can use their own concepts to conceptualize cross-disciplinary collaborations and an improved perception of concepts related to mechanical stiffness can also improve their perceptions of cross-disciplinary collaborations.

9.1.4 Comparison to Other Models

Another model that is focused on improving metacognitive awareness to enhance the collaborative process is Insights Discovery (Insights). This model has been developed into a tool and is designed specifically to improve team collaborations. After filling in a questionnaire about their personality, collaborators receive a personal profile with ratings on their collaboration style. Within the group, the profiles are put in perspective to one another and concrete tips are given on how to collaborate with co-collaborators specifically. This method contributes to self-understanding and gives practical tips on how to improve collaboration. A similar model focused on improving metacognition is DISC (DISC Factor B.V.). This model divides professionals among four 'personality styles' that each has its strengths and weaknesses.

A difference with the Collaborative Pliability Model is that Insights Discovery and DISC are more generic and are targeted at professionals from any discipline. The Collaborative Pliability Model, in contrast, targets mechanical engineers specifically to raise metacognitive awareness. It makes use of a set of concepts that mechanical engineers are familiar with to improve the cohesion with the newly introduced concepts.

9.2 Application

In this section, an outlook of future usage of the model is given. Two ways in which the Collaborative Pliability Model can be used as a tool are first proposed in Section 9.2.1. Next, ways of applying this tool in practice are discussed in Section 9.2.2.

9.2.1 Tool

Two ways are proposed in which the Collaborative Pliability Model can be used as a tool: As a standalone tool and as an interactive tool.

Standalone Tool

The Collaborative Pliability Model has been developed and tested in the form of a presentation. In its current form, it can readily be used to help mechanical engineers to improve their metacognitive awareness. Because it is desirable to not be solely reliant on someone familiar with the model to conduct a presentation, the slides and text of the presentation have also been printed and are enclosed with this master thesis. Mechanical engineers can read this presentation as a standalone document. Chapter 7 has also been written as a standalone chapter and contains the same content as the presentation.

An advantage of using the model this way is that using it is not very time and resource-demanding. However, the risk of only reading through the model contents without readily applying the newly attained knowledge is that the knowledge is not actively integrated with existing knowledge. There is a chance that some concepts are not fully understood or that constructive conflict is not fully resolved. To maximally integrate the knowledge from the model with the already existing knowledge, a more interactive way of using the Collaborative Pliability Model is preferred. In the next section, a way for doing so is discussed.

Interactive Tool

A more interactive way of interpreting the new material is in the form of an interactive workshop. Two-hour workshops can be conducted with groups of mechanical engineers, sizes ranging from 3 to 30 participants. Before participating in the workshop, participants have to think about a cross-disciplinary collaboration that they previously participated in. During the workshop, participants first fill in a questionnaire regarding this collaboration, enclosed in Appendix E.2. Afterwards, the model is presented to the participants. After conducting the presentation, the participants fill in a second questionnaire with regards to their collaboration using the concepts attained from the presentation.

A major advantage of the standalone application is that professionals can engage in constructive conflict with the presenter and with one another. This elicits critical thinking and lets professionals learn about the concepts interactively, deepening their understanding of the new theories. A disadvantage compared to the standalone tool is that the interactive tool requires a bigger investment of time and resources.

9.2.2 Tool Usage

In the previous subsection, a description was given of two ways in which the Collaborative Pliability Model can be used as a tool. In this section, several examples are given in which a tool can help mechanical engineers with their metacognitive process to improve cross-disciplinary collaborations.

Accelerating the System Identification Development Process

In Chapter 1 the situation between medical and technical researchers concerning system identification solutions to analyse movement disorders is described. It is argued that a more interdisciplinary approach, as opposed to a multidisciplinary approach, can help in accelerating the implementation of these solutions. This thesis proposes that a catalyst to accelerate the transition to a more integrated approach is to equip collaborators with the knowledge on the differences between these types of collaborations and what factors play a role in changing a collaboration from one type to the other. With this knowledge, collaborators are more likely to identify what factors are most relevant to pay attention to. The impact of this method on the development cycle was shown schematically in Figure 1.2 and is repeated in Figure 9.1.

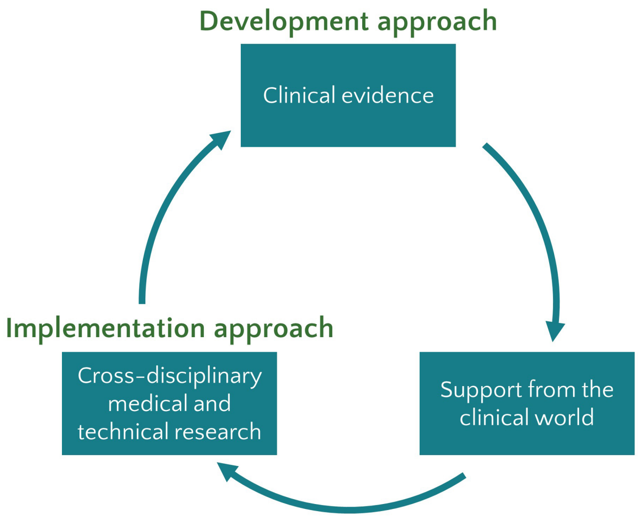

Figure 9.1: Repetition of Figure 1.2 showing the positive feedback loop between support from the clinical world, leading to more cross-disciplinary medical and technical research, boosting the development of clinical evidence. This cycle is created based on interviews with medical and technical professionals.

If the Collaborative Pliability Model is then used as a tool to improve the metacognitive process, the challenge remains for mechanical engineers to use this newly attained knowledge to develop interdisciplinary collaborations with medical researchers. Proposing a tailor-made step-by-step program that guarantees a more interdisciplinary collaboration is difficult due to the unique nature of each specific instance of collaboration, each with different professionals that have different pliabilities. However, dedicating time to the metacognitive process can help professionals to cope with cross-disciplinary processes (Keestra, 2017). Therefore, a more accentuated effort to learn about metacognition can help mechanical engineers to involve medical researchers in the development process of system identification solutions.

The virtuous circle as shown in Figure 9.1 was described by one of the medical researchers interviewed for this thesis. It shows that clinical evidence showing the added value of system identification techniques can boost support from the clinical world for these techniques. Support from the clinical world can then boost the development of more clinical evidence. If medical researchers can be engaged to collaborate in developing clinical evidence at an earlier stage, this positive feedback loop can be accelerated at an earlier stage, rather than relying on the first clinical evidence coming from solutions that are primarily disciplinary.

Education

Jantsch proposes to fundamentally restructure education systems to better tackle societal challenges (Jantsch, 1970). Jantsch proposes four levels of education: A level on positivist logic, a level on human sciences logic, an level on integration between these two to solve societal challenges and a level looking to extrapolate the first three factors to look at long-term human development. He describes a system in which professionals are educated in more transdisciplinary ways so that they are better equipped to address today's grand challenges. In alignment with this vision, the Collaborative Pliability Model can be implemented as part of Bachelor's or Master's programmes for engineers. Less effort is required to learn about collaboration sciences when the theories are aligned with the knowledge that is already part of the curriculum.

Similarly, for companies that would like to improve their cross-disciplinary engagement or output, the model can be used in the form of an interactive tool to help mechanical engineers in a one-day workshop.

9.3 Model Development

In this section, two points concerning the development of the Collaborative Pliability Model are discussed. First, difficulties in trying to bring the two paradigms together are discussed in Section 9.3.1. Next, Section 9.3.2 talks about the multi-interpretability of the pliability categories.

9.3.1 Difficulties

Analogy-making is based around the categorisation of concepts (Hofstadter and Sander, 2013) and concepts from both conceptual worlds were re-categorized so that they could be aligned. The different categorisations of concepts are perhaps what is the most different between the positivist and social sciences paradigms. Bringing these two paradigms together went paired with some difficulties. Fundamental rules from both paradigms had to be neglected to find common ground. For instance, the human sciences paradigm does not assume linear relationships between its concepts. Collaborative pliability is normally not mapped out as an unambiguous relation between two factors. However, to find common ground with the positivist paradigm, it is modelled as a linear relationship between incentives and displacement to disciplinary abstraction. Similarly, the positivist paradigm exclusively connects concepts using formulas when there is a quantitative connection between them. Yet, the Collaborative Pliability Model makes use of non-quantifiable concepts.

Perhaps the most difficult part about bridging these two paradigms was to consider up to what extent formulas and connections can be put in formula form. By trying to put social concepts in a context where everything is too quantifiable, the concepts will lose a lot of the complexity that is fundamental to their understanding. However, refraining from formulas and more unambiguous connections between the concepts means that their descriptions are more divergent from the positivist paradigm.

9.3.2 Ambiguity

As a result of finding a balance between the positivist and human sciences paradigms, a categorisation of pliability categories is made that is not completely unambiguous. Making such a categorisation completely unambiguous is difficult, if not impossible, but categorising pliability factors as a distinct set of factors is done because such an alignment fits with the positivist paradigm. Some factors influencing collaborative pliability could be attributed to multiple pliability categories at the same time. This is unavoidable - Collaboration dynamics are inherently complex and so is devising groups of independent factors that have no mutual influence over one another.

The ambiguity of the categories recurs in the results as well. Some factors were categorised by the participants with a different pliability category than would be logical at first sight. For instance, *"Frequent interruptions from work by people having non-urgent questions"* was labelled as personal pliability. If the fact that many interruptions by a colleague resulted in a decrease in inclination to work together with this person, this factor belongs more to interpersonal pliability. On the other hand, if one of the collaborators gets irritated by frequent interruptions, and as a result becomes impatient to work together with any one of the team, it should be attributed to personal pliability. Another named factor is *"Different disciplinary backgrounds"*, which is labelled as disciplinary pliability. However, if a group is deliberately put together by leadership to consist of different disciplinary backgrounds, this factor belongs to group pliability instead of disciplinary pliability.

These examples demonstrate that there are many angles at which one can look at these factors. It might be that one professional considers one factor to be a part of a different category than another professional. In the end, what is most important is that the model serves as a tool to put important factors into a framework so that new factors can be thought of. It serves as an opportunity to look at collaboration from a different angle: The generalisability and reproducibility of the categorisation of the factors are subordinate to clearing the way for a new kind of thinking.

9.4 Research Limitations

Two limitations with regard to this research are discussed: Limitations concerning model content in Section 9.4.1 and limitations concerning model testing in Section 9.4.2.

9.4.1 Model Content

The research limitation concerning model content has to do with reliability of the research. A narrative literature review is conducted on cross-disciplinary collaboration dynamics. Because of the broad range of concepts and topics related to cross-disciplinary collaborations, this way of finding literature is the preferred method for this research. The alternative, which is conducting a systematic literature research, would mean having to narrow down to a specific topic, such as *integration* or *mental models*, which would neglect important theories on cross-disciplinary collaborations. Otherwise, the literature survey would be too cumbersome within the scope of this project to be executed.

The risk of performing a narrative literature review is the lack of systematic scouring of literature. As a result, theories might be neglected that could be beneficial to the structure, coherence and value of the model. To account for this, four collaboration professionals were consulted. Their input was used to validate if the model was solid from a theoretical perspective and to see if relevant theories were overlooked. There is a good chance that the theoretical framework is still not all-encompassing since only four collaboration professionals were interviewed. However, an all-encompassing theoretical framework was never sought in the first place, since this was not a realistic objective to meet within the broad range of theories that is covered.

9.4.2 Model Testing

The research limitations concerning model testing have to do with validity and reliability of the research. Two limitations are discussed: The group of participants that was used for model testing and the fact that new tests constantly yield new improvements to the model.

It should be noted that the participants that were used to conduct tests are all from the same niche. They are all highly educated mechanical engineering students, below their thirties, that participated in ambitious cross-disciplinary collaboration projects. People with this background are generally viewed as more pliable than people that are less ambitious, less highly educated or of higher age. Therefore, conclusions about the generalizability of the effectivity of the Collaborative Pliability Model cannot be drawn based on this research.

Apart from that, most interviews and presentation sessions, up to and including the final presentation session presented in Chapter 8, gave new input that was used to restructure and redefine the model to make the relations more unambiguous and clear. Part of the development process is that the model is never finished and new discussions can always yield new insights. This also means that new tests could still result in significant improvements.

9.5 Recommendations for Future Research

The fact that using the Collaborative Pliability Model to transfer knowledge on collaboration dynamics is deemed an effective method for the tested target group gives a promising outlook for the future. First and foremost, we are interested in finding out if mechanical engineers, in general, are receptive of using the Collaborative Pliability Model. A test should be conducted with a group should involving more diversely represented mechanical engineers, including people of higher age and people that are less highly educated.

Secondly, even though the model is developed specifically for mechanical engineers, the structure and reductionist view might also make sense for professionals from other engineering disciplines or even from completely different fields. Therefore, the Collaborative Pliability Model should also be tested on professionals from different disciplines like medical researchers. Based on their input, the model can then be adjusted to create a version of the model that is more aligned with the worldview of the target discipline specifically.

Thirdly, the concept of pliability is specifically assigned to the flexibility of a professional to collaborate in a cross-disciplinary environment. This concept could also be panned out to be applicable to collaborations in which there are other fundamental differences, like different age groups or professionals from different cultures.

Finally, knowledge transferring from one discipline to the other using an analogy with specific concepts from both epistemologies has proven to be promising. This way of bridging conceptual worlds should further be investigated. Other target groups, like medical scientists or physicists, can be targeted to transfer knowledge on cross-disciplinary collaboration dynamics. Similarly, theoretical frameworks on other topics, such as decision-making or marketing, should be translated to other epistemologies using an analogy and their effectivity should be measured.

10 Conclusion

This research aimed to gain insights into the effectiveness of transferring knowledge on cross-disciplinary collaborations to engineers by creating a shared mental model using an analogy. After developing this model and testing its effectiveness on a group of mechanical engineers, this chapter draws conclusions. This is done by answering the main research question: *"How can cross-disciplinary collaboration dynamics be described in a way meaningful to mechanical engineers?"*. First, the accessory sub-questions are answered, after which the main research question is addressed.

10.1 Answers to the Research Sub-Questions

10.1.1 Cross-Disciplinary Collaborations in a Theoretical Framework

Cross-disciplinary collaborations, a collective term used to describe any collaboration that is not between people of the same discipline, can be described using numerous theories.

As an answer to the sub-question *SQ1: "How can cross-disciplinary collaboration dynamics be described within a theoretical framework?"*, these theories are combined and interrelated to each other in a theoretical framework revolving around three concepts. The first concept, mental models, describes the thought processes, worldviews and methodologies of professionals. The second concept, knowledge integration, describes the process that takes place when different mental models are integrated into a shared mental model. Finally, collaborative pliability describes the extent up to which a professional is able to engage in knowledge integration to develop a shared mental model. The factors that influence pliability are grouped into four categories: Personal, interpersonal, group and disciplinary factors.

10.1.2 Shared Mental Model Creation

The theoretical framework that is created by answering sub-question 1 served two purposes. First of all, it creates a solid foundation of knowledge that is to be shared with mechanical engineers. Second of all, it creates an overview of the factors that are important to take into account when creating a shared mental model.

The sub-question *SQ2: "How can this framework be presented in a way that is aligned with the conceptual world of mechanical engineers?"* is answered by creating an analogy between concepts from the theoretical framework and concepts fundamental to mechanical engineering as a discipline. The analogy is based around similarities between *mechanical stiffness* and *collaborative* *pliability*. In the technical domain, mechanical stiffness represents the relation between the force acting on a system and the resulting displacement. In the social domain, collaborative pliability can similarly be described as the relation between incentives inciting a professional and the resulting displacement from personal concreteness to abstraction. Pliability can be seen as a system property, where the system is the professional, that is influenced by personal, interpersonal, group and disciplinary factors. This way of representing collaborative pliability can be used to explain the differences between multidisciplinary, interdisciplinary and transdisciplinary collaborations.

A strong reliance on concepts and their relations is used as the basis for the analogy since the epistemological world of engineers strongly revolves around the relations between concepts as well. By using this analogy, collaborative pliability and the accessory concepts from the theoretical framework can be described using relations that are already well-known by mechanical engineers. Concepts and their relations that are widely used within mechanical engineering can then be used as well to digest the new information. As a result, less collaborative pliability is needed to integrate new knowledge with existing knowledge. Collaboration dynamics become integrated with primary knowledge stemming from the discipline instead of being taught as a standalone discipline.

10.1.3 Changing the Views of Engineers

The Collaborative Pliability Model that is created by answering sub-question 2 is tested by exploring to what extent it is an effective way of transferring knowledge on cross-disciplinary collaborations to mechanical engineers.

To answer the sub-question *SQ3: "Is this framework meaningful to mechanical engineers?"*, the model is assessed by six mechanical engineering students that are asked to analyse a cross-disciplinary project that they previously participated in. The students fill in two questionnaires and the Collaborative Pliability Model is presented in between the questionnaires. Before and after the presentation, the students are asked to write down what factors influenced the success of their collaboration. After the presentation of the Collaborative Pliability Model, the engineers came up with numerous new factors that affected the success of their collaborative process. The engineers themselves considered the model an effective tool for learning about cross-disciplinary collaborations.

10.2 Answer to the Main Research Question

The Collaborative Pliability Model provides the answer to the main research question *"How can cross-disciplinary collaboration dynamics be described in a way meaningful to mechanical engineers?"*.

The Collaborative Pliability Model proposes a new way of transferring knowledge on cross-disciplinary collaboration dynamics. It is based around creating an analogy between mechanical stiffness and collaborative pliability. These conceptual similarities make it possible to link theories on cross-disciplinary collaborations to concepts that are fundamental to mechanical engineering as a discipline. Learning about cross-disciplinary collaboration theories using this analogy creates a connection between the newly attained knowledge and concepts that are already familiar to mechanical engineers. Instead of treating newly acquired theories as standalone pieces of knowledge, the theories are immersed with the existing mental models of the engineers and the extensive conceptual knowledge of mechanical stiffness can be used to put the new concepts in relation with one another. As a result, new knowledge can be applied by resorting to the same framework of connections that is used to apply the primary discipline. Using the model was deemed an effective way of knowledge sharing by conducting a test on a group of six mechanical engineers. This gives a promising outlook for the future and opens the door for new applications for using an analogy to transfer knowledge between specific target groups.

Part IV

Reflection

11
Reflection

To close off this master thesis, a reflection on the produced work is given in this chapter. First, a reflection on the process is given in Section 11.1. Next, Section 11.2 reflects on how the integrated research process went.

11.1 On the Process

After having dedicated most of my time to this project for almost a year, it feels surreal that it is coming to an end. Conducting a solo project of this magnitude is among others a process of self-discovery. I would like to reflect on one particular part of the process that influenced the way in which the project was conducted.

A pitfall while conducting this project was that I was not always aware of the fact that I was making important decisions on the direction of the project until the decisions had already been made. At times, when I had a new hunch of inspiration, I would pursue this hunch without realizing that this potentially meant excluding alternative ways of moving forwards. For the mechanical engineering project, I think that this way of problem-solving is not necessarily negative. It resulted in a direction of the project that was aligned with what I was naturally comfortable with and allowed me to develop a solution that was most aligned with the skills that I already attained as an engineer. For science communication, I may have made project decisions too soon at times, which could be part of the reason why the two projects diverged.

11.2 On Integrating the Research Projects

I conducted two research projects simultaneously, with two supervisors for the mechanical engineering project and two supervisors for the communication design for innovation project. No requirements on how the two projects had to be integrated were given prior to conduction. Guidance in this process was given along the way, but decisions on the integration were in the end up to me.

At the start, both projects did not have a clear direction yet. For Mechanical Engineering, I knew that I was going to work on developing a system identification method, although it was not clear yet what exactly my contribution to this process would be and what kind of method I would develop. For science communication, my initial idea was to look at the communication process between medical researchers and mechanical engineers with regard to these system identification methods to see if an interesting research project could be extracted based on this process. Soon after starting the project, I assumed that the best way to turn this into a research goal was to look at developing a shared language between these disciplines. Not much later, I shifted the focus to developing a shared language between mechanical engineers and communication scientists, since these are two languages that I am familiar with myself. In a way, the entire science communication part of this thesis has been looking at ways in which these two languages intersect and how common ground can be found.

The research goals that I ended up with for both projects were farther apart than I had originally intended. While I would have preferred to have conducted a project of a truly transdisciplinary nature, the diverging paths that the two projects took resulted in a research project of an interdisciplinary nature. With a focus on system identification techniques for the mechanical engineering project, finding a truly transdisciplinary counterpart for science communication was difficult.

Because of the interdisciplinary way that this project was conducted, my understanding and appreciation of interdisciplinarity have improved. By continuously switching between two projects that made use of such different research methodologies, I was constantly exposed by different ways of approaching problems. This sparked my creativity in general and made it accessible to come up with interdisciplinary input for both projects.

All in all, it was a refreshing process to work on two projects at the same time that were so different in approach and field. The projects demanded different skillsets and required thinking about solutions in different ways. Conducting them simultaneously has been a pleasure.

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Appendices

A

Variance Accounted For (%VAF)

Table I shows all %VAF values for the simulation and experimental studies. The simulation study is conducted with 8 conditions: Intrinsic stiffness alone (i) versus intrinsic and reflexive stiffness (i+r), open-loop (OL) versus closed-loop (CL) and sampling frequency f_{s1} versus f_{s2}.

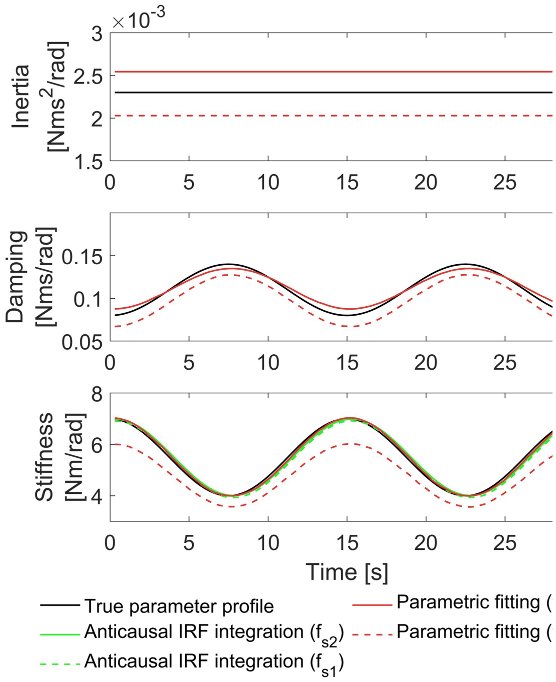
	$\%VAF_{np}$	$\%VAF_{np,i}$	$\%VAF_{np,r}$	$\%VAF_p$
Simulation $i, \quad OL, f_{s1}$	99.997	99.996	-	99.96
Simulation $i, \quad CL, f_{s1}$	99.99	99.99	-	99.9
Simulation $i+r, OL, f_{s1}$	99.0	72.0	30.2	72.1
Simulation $i+r, CL, f_{s1}$	98.6	73.5	29.1	72.9
Simulation $i, \quad OL, f_{s2}$	99.95	99.9	-	86.2
Simulation $i, \quad CL, f_{s2}$	99.95	99.9	-	87.8
Simulation $i+r, OL, f_{s2}$	98.9	74.7	25.6	58.4
Simulation $i+r, CL, f_{s2}$	98.4	75.9	25.4	64.1
Subject 1	92.4	92.0	3.8	5.6
Subject 2	95.9	95.2	4.1	53.8
Subject 3	92.6	91.6	3.7	20.5

Table I: All %VAF values for simulation and experimental studies. $\%VAF_{np}$: %VAF of the nonparametric estimate, $\%VAF_{np,i}$: Intrinsic contribution to $\%VAF_{np}$, $\%VAF_{np,r}$: Reflexive contribution to $\%VAF_{np}$, $\%VAF_p$: $\%VAF$ of the parametric estimate. These values are shown visually in Part II, Figure 10.

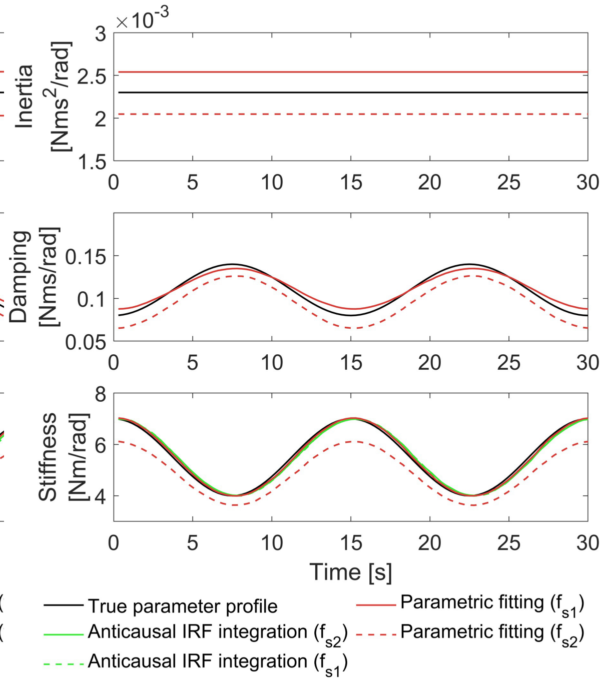
B
Parameter Estimations

B.1 Simulation Study

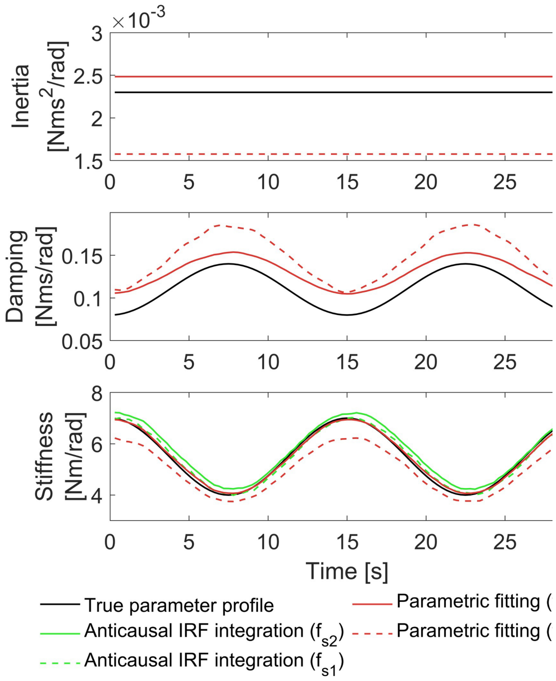
See next page.



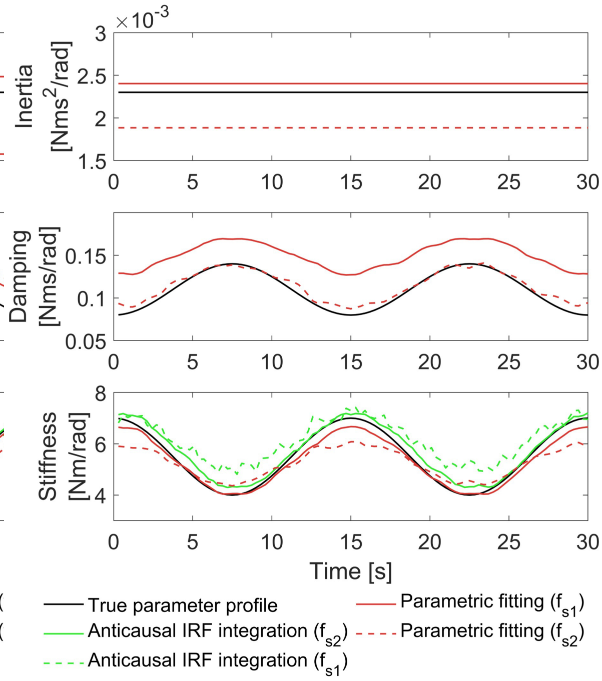
(a) Simulation conditions with just an intrinsic pathway in open-loop.



(b) Simulation conditions with just an intrinsic pathway in closed-loop.



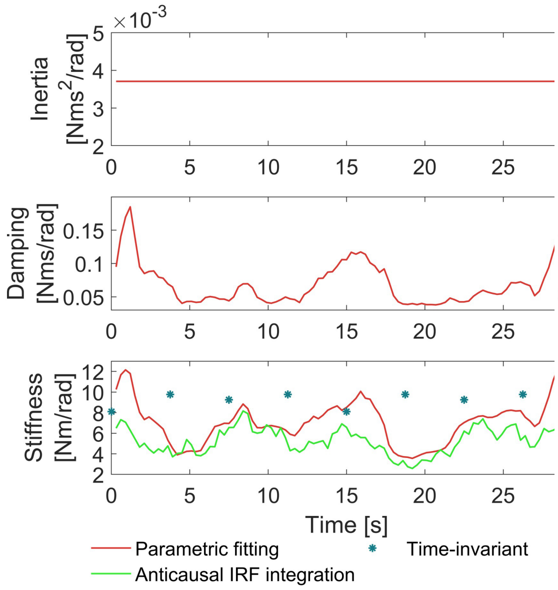
(c) Simulation conditions with an intrinsic and reflexive pathway in open-loop.



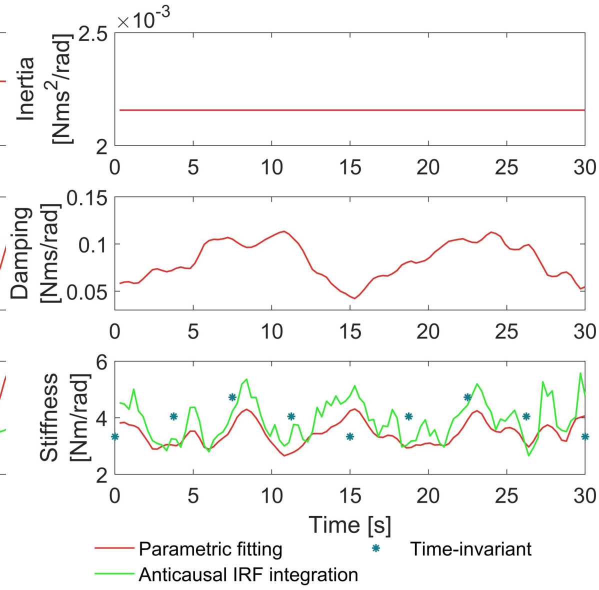
(d) Simulation conditions with an intrinsic and reflexive pathway in closed-loop.

Figure B.1: Time-varying parameter estimates for all simulation conditions. Estimates using both parametric fitting and anticausal IRF are shown. Even with decimation, anticausal IRF fitting gives a good estimate for stiffness, whereas parametric fitting on decimated data introduces biases.

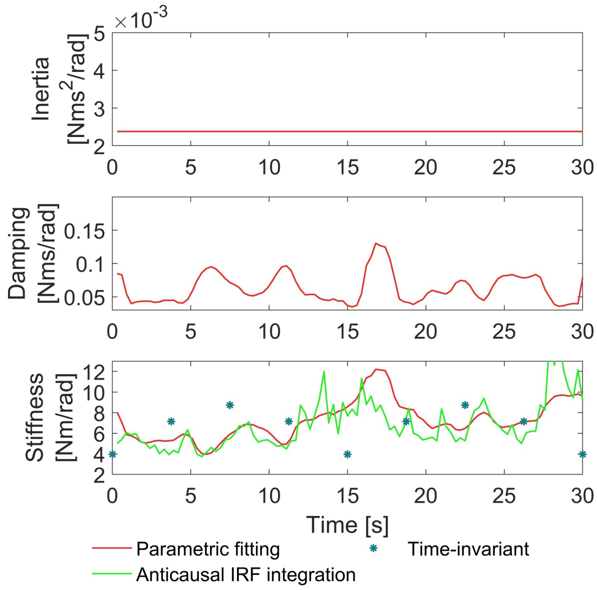
B.2 Experimental Study



(a) Subject 1.



(b) Subject 2.



(c) Subject 3.

Figure B.2: Parameter estimation for all subjects. The time-invariant estimations of stiffness for angles $\theta = -0.15, 0$ and 0.15 rad are plotted for the time points where the time-varying trajectory reaches these points. The stiffness profiles appear to be driven by movement, as it is highest at the peaks of the trajectory where there is no movement and lower during the transition from one peak to another.

C

Interviews Medical and Technical Researchers

C.1 Interview Aide-Mémoires

Three interviews that were conducted with medical and technical researchers that all had a slightly different focus. The following aide-mémoires were used for each interview. The last two interviews have aide-mémoires that more closely resemble an interview protocol of a semi-structured interview. However, the questions in the protocol were not asked literally and served as talking points to discuss during the interviews.

C.1.1 Interview 1

In hoeverre hebben, in uw ervaring, de volgende facetten een rol gespeeld in de soms lastige samenwerking tussen medische en technische onderzoekers?

- Verschil van culturen
- Verschil in taalgebruik / terminologie
- Bereidwilligheid om samen te werken
- Ego
- Onduidelijkheid
- Wederzijds begrip / Openheid voor de motieven van de ander
- Belangenverschillen
- Gebrek aan connectiviteit, gezamenlijke evenementen en gevoel van een gezamenlijk doel
- Conservativiteit / terughoudendheid om als discipline te veranderen

C.1.2 Interview 2

- Kunt u een voorbeeld geven van een techniek die al langer bestond voordat er in de medische wereld gebruik van werd gemaakt?
- Wat voor factoren zorgden ervoor dat de implementatie langzaam ging?
- Wat voor factoren zorgden ervoor dat het uiteindelijk wel lukte om de techniek te implementeren?
- Was u betrokken bij dit proces?
- Kunt u de verschillende factoren beschrijven die invloed hebben op of een techniek wel of niet wordt opgepakt?

C.1.3 Interview 3

Vragen – Over uzelf

- Kunt u me wat vertellen over uw achtergrond en vakgebied?

Vragen – Over spierziekten

- Kunt u wat vertellen over spierziekten in het algemeen, vanuit uw perspectief?
- Is de diagnose van spierziekten moeilijk?
- Waar liggen de huidige uitdagingen in het diagnosticeren van spierziekten?

Vragen – Over het integreren van systeemidentificatie in de diagnose

- Wordt er al weleens gebruik gemaakt van 'systeemidentificatie' technieken voor het diagnisticeren van neuromusculaire aandoeningen?
- Heeft u in het verleden samengewerkt met werktuigbouwers om deze technieken te implementeren?
- Ervaarde u de samenwerking als effectief?
- Heeft u ook op andere vlakken wel eens samengewerkt met werktuigbouwkundigen?
- Waar lagen de grootste knooppunten in het implementeren van deze technieken?

C.2 Interview Summaries

C.2.1 Summary Interview 1

De geïnterviewde heeft de volgende factoren gerangschikt op een schaal van 1 tot 10, waarin 1 betekent dat de factor over het algemeen weinig impact heeft op de samenwerking tussen doktoren en technici en een 10 betekent dat de factor veel impact heeft:

- Verschil van culturen: 8
- Verschil in taalgebruik / terminologie: 9
- Bereidwilligheid om samen te werken: 5
- Ego: 5
- Onduidelijkheid: 8
- Wederzijds begrip / Openheid voor de motieven van de ander: 4
- Belangenverschillen: 3-7
- Gebrek aan connectiviteit, gezamenlijke evenementen en gevoel van een gezamenlijk doel: 6
- Conservativiteit / terughoudendheid om als discipline te veranderen: 7

C.2.2 Summary Interview 2

In the past 20 years, system identification techniques have been developed and collaborations with medical researchers were initiated, but much of what has been developed is not yet used in hospitals. Some collaborations have been successful and are now readily applied.

What an orthopedic surgeon needs to know about biomechanics is similar to what a neurologist needs to know about control technology. The laws of control are also applicable to the human body. Unfortunately, doctors do not understand when a control system loses its stability, what the effect is of increasing a gain and what the effect is of time delays. Doctors sometimes mention that they do not exactly need to know why certain things happen.

In some cases, research is ahead of what the market wants. It can take years before a technique is implemented, even though the technique has existed for years. We have been able to find some doctors that are enthousiastic. It is up to us to prove that the techniques work. These techniques are so far away from the reality of doctors that we have to show the effect that it has on therapy and diagnostics. And we have not been able to prove that yet. We can see and understand many connections, but the world doesn't think yet that these are methods of the future.

In meetings with medical researchers, concepts have to be explained in a simple way with one-liners. But you should not think that they understand the formulas that you show to them. We have to skip the formulas and go back to concepts, and find parameters with these concepts. The frequency domain is a concept that is difficult to explain to medical researchers. Doctors are very interested in outcome metrics, but we are more interested in the underlying metrics. Certain gains, to better understand how the system works.

C.2.3 Summary Interview 3

Over spierstoornissen:

- Neurologische aandoeningen gaan vaak gepaard met spierstoornissen.
- Klinisch gezien zijn deze goed uit elkaar te houden. Onderliggend gezien is dit lastiger, daar is systeemidentificatie goed voor.
- In de praktijk wordt dit soms gedaan, maar soms is het lastig om de klinische kant te overtuigen omdat systeemidentificatie ingewikkeld uit te leggen is.

Over de potentie van systeemidentificatie:

- De volgende beperkingen hebben de huidige technieken:
  - Een manipulandum heeft in de praktijk beperkte beweegvrijheid.
  - Een taak vragen van een patient is lastig.
  - Een diagnose duurt vaak lang (ongeveer 2 uur)
- Een golden demo ontbreekt – Wat levert zo'n systeemidentificatie-experiment op? Dus: Een concrete methode die de meerwaarde van systeemidentificatie laat zien.
- Als je kunt uitleggen wat de meerwaarde is, kan er meer samenwerking gecreeerd worden.

Over huidige projecten met systeemidentificatie:

- Balansstoornissen. Er kan gemeten worden of een afwijking wordt veroorzaakt door proprioceptische aandoeningen, visuele aandoeningen of aandoeningen door het evenwichtsoorgaan. Meettijd is nog wel lang.
- Wrist manipulandum. Kan worden gebruikt op patienten die een beroerte hebben gekregen. Voor een spasme in de pols kan worden ontdekt of dit een neurale of biomechanische oorsprong heeft. Volgende stap: In een keuzeboom de diagnose veranderen, hier zijn we nog niet.

We zitten in een lastig pakket: Doordat er geen golden demo is, zien doktoren niet de meerwaarde in van systeemidentificatietechnieken. Hierdoor gaat er beperkte aandacht naar de ontwikkeling van de technieken en wordt er beperkt samengewerkt tussen doktoren en engineers. Toch is juist die samenwerking nodig om intensief samen pilot-experimenten te verrichten en een juiste methode de ontwikkelen die in ziekenhuizen gebruikt kan worden, en kan dienen als golden demo.

Er moet nagedacht worden over waar de diagnostiek beter gaat worden. Wat levert het de patiënt op? De behandeltechnieken van zo'n systeemidentificatietechniek liggen zo ver in de toekomst, dat het lastiger is om op zo'n korte termijn er de vruchten van te plukken. Zijn die behandelmethoden er wel? Hoe zouden die eruit moeten zien? Voor een business case heb je best wel wat nodig. Het beste om mee te beginnen, is om met een patiënt in een ruimte te zitten om te bepalen waar een behandelmethode aan moet voldoen.

D

Interviews Collaboration Professionals

D.1 Interview Protocol

The questions formulated in this interview protocol were asked while giving a presentation. The presentation that was used was a draft version of the final presentation enclosed in Appendix E.3 and E.4. Between each round of questions, the slide numbers of the final presentation that are based on the slides presented are indicated.

Presentation part 1 (Part roughly became slides 1 - 5 and 14 - 20 in the final presentation)

- Is this part of the model clear to you?
- Do you feel like this interaction between two professionals from different disciplines gives an accurate representation of what is happening in practice?
- Do you think that this way of representing a collaboration can give new insights?
  - What kind of insights does the model give you on first view?
- What existing theories does this model remind you of?
- Do you know of any theories that could be a great addition to what is already presented here?
- Are there any (important/prominent) theories that are clearly overlooked in this model?

Presentation part 2 (Part roughly became slides 6 - 13 in the final presentation)

- Do you feel like this categorisation gives an accurate representation of what is happening in practice?
  - Is the distinction of three categories accurate?
  - Do you feel like some category is missing?
- Do you think that this way of categorising can give new insights?

  - What kind of insights does the model give you on first view?

- What existing theories does this model remind you of? Do you know of any existing, similar categorisations?
- Do you know of any theories that could be a great addition to what is already presented here?
- Are there any (important/prominent) theories that are clearly overlooked in this model?

Presentation part 3 - Part is removed in the final presentation

- What do you think of this observation of how stiffnesses change when time evolves?
- Do you know of any literature that supports this? Has the evolving of factors influencing collaborative capacity been discussed in literature that you know?

D.2 Interview Summaries

D.2.1 Collaboration Professional 1

The model has many resemblances with the model called ‘the groan zone’ from the book *A facilitator’s guide to participatory decision making* by Sam Kaner. The groan zone is a place that people don’t always like being in. Discomfort is a concept that is linked to the groan zone, because this is part of what people experience when they go towards personal abstraction. The model in the thesis is written from a team science perspective, while Kaner’s model is written from the perspective of conflict.

Something that has not been included in the model is power, which is part of individuals and institutions. But in social sciences, power is difficult to model so consider if it would be effective to add this to the model or not.

The shapes and size of disciplinary concreteness for individuals, but also the shape and size of the intersection area, will constantly change. At some point one discipline might be bigger than the other, and at another point it might be smaller. The end goal could be to let both disciplines be big and represented.

An analogy to moving towards disciplinary abstraction is fishing. You’re trying to catch something in the area of disciplinary abstraction and when you’re trying to heal it back, it is going to take a lot of force to pull it back to your disciplinary concreteness. Another option would be to just let go of your abstract idea, which is what a lot of people do. The fish might dart and shake around when being pulled back.

Think about how the different types of pliabilities influence each other. For instance, a change in the leadership, which is now part of context-dependent pliability, can greatly affect the trust, which is part of relationship-based pliability.

Factors that have not been included, but could be a great factor, are mission and vision of a team. Having these can have a lot of impact on the collaborative proficiency of a team. Also consider pointing out how these different types of pliabilities evolve during a collaboration.

D.2.2 Collaboration Professional 2

For any discipline, a distinction between disciplinary concreteness and disciplinary abstraction can be made.

There are many ways of talking about collaborations between disciplines and influential factors, that do not use a mechanical viewpoint. Make sure that the added value of using the mechanical angle is stressed. If this analogy helps a certain target group to understand collaboration dynamics, that is useful.

Grouping the factors influencing pliablities into different categories is something that should be looked at carefully. Trust, for instance, does not necessarily just fall under relationship-based pliability, but could also be viewed as intrinsic pliability, because cultural factors can determine how trustful certain cultures are to others. It’s also easier to establish trust during a video conference than during a text-based conversation, linking it to context-dependent pliability.

Be aware that this model can mislead people into thinking that all these pliability factors can be quantitatively measured and combined in a linear fashion.

Some things part of context-dependent pliability are not easily changeable. Sometimes things like the leadership or team size of a team are fixed on an organisational level.

D.2.3 Collaboration Professional 3

The concepts within mechanical engineering itself are actually not very pliable. The formulas that are applied within the discipline, like the stiffness formula, have linear solutions and within the discipline they cannot be interpreted differently. Social scientists can often be satisfied with having many answers to a problem, while mechanical scientists are often satisfied with having just one answer to a problem. Their worldviews originate in different epistemologies and this might be part of the core problem of this thesis. Is it possible to link these worlds together and what are the key points in doing this? It can be good to look at literature on shared mental models. Steven Zaccaro has work that can be relevant for this thesis.

How integrated do you want the stakeholders to be? Something that could be interesting, is the measurement of disciplinary integration. The assumption in the mental model in the middle is that some how, human collaborative theories and the mathematics of engineering need to somehow be integrated. An author that might be helpful in this area is Michael Oworke University of Michigan, he has done work in an area of testing integration across disciplinaries.

The conceptual model is not just a step from collaboration theories to engineers, but there is actually dynamic behaviour from engineers back to the shared mental model and the collaboration theories also. This is constantly changing, because people are never going to become the other person. Constant learning of the other is part of the team construct, creating new cognitive awarenesses. Also, 'collaboration theories' and 'engineers' are not on the same level. Perhaps 'collaboration theories' should be substituted with something similar to 'social scientists'.

As for the different factors contributing to pliability from a social perspective: Michelle Bennett explains about the different degrees of trust, in a similar way that this project talks about different pliability factors. That literature can be interesting to look at. On methodologic flexibility, Gaetano Lotrecchiano published some work. Collaborative readiness is a broad category: There is the cognitive level, the emotional level, and this has to be defined tighter. On team size there is a lot of literature coming out of the management community, but is somewhat controversial, because there is never the right size. On complexity leadership Mary Uhl-Bien published work that could be interesting. There is work in all of the areas, like collaborative readiness, in science of team science research. There is a mendeley database of the team science community that is kept up with many related articles. The 2008 special issue on team science for the journal of preventative medicine is also a go-to collection on these different factors.

This analysis is done on the individual level. Look out that individuals do not become a mirror of their disciplines. Obviously everyone is a product of their training, but because of people's world views and personalities, pliabilities can be different for each individual. Be very clear on how to stay on the individual level. Perhaps it would even be easier to do the analysis on the disciplinary level, but give that some thought.

D.2.4 Collaboration Professional 4

How are you going to measure these things? I am not looking at ways of measuring these pliabilities, but hoping that a shared mental model is going to make it easier to understand these concepts from a mechanical engineering perspective.

Literature on 'team creativity' focuses on analogous reasoning, where transdisciplinary or interdisciplinary design teams use analogies to bring ideas from their disciplines together. Applying analogous reasoning in a sporadic manner could be seen as an interdisciplinary collaboration, while applying it continuously could be seen as starting a transdisciplinary collaboraton.

Looking at literature on knowledge networks could be a helpful addition. Within this literature, a distinction is made between knowledge creation, knowledge transfer/learning and knowledge adoption/implementation. Multidisciplinary collaborations could solely be focused on knowledge creation, but interdisciplinary or transdisciplinary collaborations also consist partially of the transfer, learning, adoption and implementation of knowledge. This literature also talks about the absorptive capacity of nodes, which increases its ability to receive knowledge from its network contacts. This can be related to pliability and the factors that influence it.

The model currently focuses on the pliability of individuals, but it should be taken into account that the collective pliability of a team is not the same as the sum of individual pliabilities. For instance, a team can be more pliable when operating together than when team members are operating alone.

The current categories that influence pliability aligns very well with categories presented in theories on knowledge networks. Intrinsic pliability is similar to factors related to nodes. Relationship-based pliability is related to factors influential between nodes. Another level that is incorporated in knowledge networks, but is not present in my model, is the structural level that deals with dynamics happening in the group or disciplinary level. Some of these factors are currently grouped as 'Context-dependent pliability' but this does not cover all of it.

Some factors that are currently grouped as 'Context-dependent pliability' are actually external factors that incline professionals to move out of their comfort zone. For the model to make better sense, it could be good to model these factors as external forces rather than pliability contributions.

An article by Hoffman & Henn called 'Barriers to Grain Building' also discusses different forces that discourage people to innovate, and talks about three different levels. It could be interesting to look at.

There are reciprocal ties between the different levels influencing pliability. Collaboration professional 4 will send some slides with theory on this.

E
Interactive Model Assessment

E.1 Participant Information and Informed Consent Form

See next pages.

Participant Information Letter

Concerning the research on using a shared conceptual model to teach cross-disciplinary collaboration dynamics to engineers

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Date 23-03-2020, Version 1.0

Dear participant,

You have been asked to participate in a study on using a shared conceptual model to teach cross-disciplinary collaboration dynamics to engineers. In this letter you will find information about the research. If you have any questions, please contact the person listed at the bottom of this letter. Thank you for your cooperation.

<u>Background of the research</u>
Implementing a truly interdisciplinary development process between doctors and engineers is difficult. In practice, professionals often remain conceptually and methodically anchored in their own fields. Realizing a more interdisciplinary approach during the development process could bring great benefits in terms of problem solving, funding and efficiency. Rather than trying to identify the main bottlenecks at a distance, professionals can be given the tools to analyse their collaborations themselves and find solutions that could improve them.

Theories on cross-disciplinary collaborations are often written from a social perspective, to be interpreted by other social scientists. A well-known method for building a bridge between two disciplinary worlds is by creating an analogy between concepts of each world. For this research an analogy is constructed between collaboration dynamics and a framework within mechanical engineering that has been validated, expanded and established over and over: Newtonian dynamics. More specifically, the analogy will be centred around stiffness, a dominant concept within mechanical engineering.

<u>Goal of the research</u>
The goal of this project is to measure how effective using a shared conceptual model is to make cross-disciplinary collaboration dynamics understandable to engineers.

<u>What does participation in the research involve?</u>
The experiment consists of three phases: A first questionnaire phase, a presentation phase and a second questionnaire phase.

1. **First questionnaire phase**: You are instructed to fill in a questionnaire regarding a cross-disciplinary collaboration that you participated in.
2. **Presentation phase**: A presentation on cross-disciplinary collaboration dynamics is given.
3. **Second questionnaire phase**: You are instructed to fill in a second questionnaire based on the insights gained from the presentation.

Participating in this experiment happens simultaneously with 4 to 8 fellow participants. The experiment will take 60 to 90 minutes.

<u>Risks</u>
Participants will not be exposed to unusual risks when participating in this study.

Voluntary participation

Your cooperation in this research is voluntary. If you give your consent to this research, you have the freedom at all times to come back on this decision (also during the experiment). You do not have to give an explanation for your decision.

Confidentiality of data

This investigation requires that the following data is collected and used: Your study background, the study background of your co-collaborators and your personal analysis of the collaboration. Your data will be collected using a participant number only. Your participant number will never be shared on publications about the research.

The results will be published in a master thesis report and possible future scientific publications.

Contact Information

J. (Jorik) van Koppen
Master student Science Communication and Mechanical Engineering
E:
T:

If you have any complaints regarding confidentiality of your data, you can contact the TU Delft Data Protection Officer (Erik van Leeuwen) via .

Science Education & Communication

Consent Form

Concerning the research on using a shared conceptual model to teach cross-disciplinary collaboration dynamics to engineers

Date 23-03-2020, Version 1.0

Participant number:

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the participant information letter dated 23-03-2020. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
Use of the data in the study		
I understand that data I provide will be used for a master thesis report and possible future scientific publications.	○	○
I understand that personal information collected about me that can identify me will only be reported in an anonymous form.	○	○
Future use and reuse of the data by others		
I give permission for the measured data and to be archived in TU Delft project storage so it can be used for future research and education. All data will be processed confidentially and anonymously.	○	○

Signatures

______________________	______________________	________
Name of participant	Signature	Date

To the best of my ability, I have ensured that the participant understands to what they are freely consenting.

Jorik van Koppen	___________________	________
Researcher name	Signature	Date

E.2 Questionnaires

See next pages. Part I and II belong to questionnaire 1 and part III and IV belong to questionnaire 2.

Participant questionnaire – Cross-disciplinary collaboration dynamics

Participant number: ____________

Lines have been added in each answer box to indicate where the answers should be given. You are free to remove the lines. Double click on a text field, or click above the text field, to select all the lines. This removes the lines once you start typing.

Part I: Basic information on the collaboration

1) Describe the project that you worked on (name, aim, etc.).

____

____

____

____

2) How long did the collaboration last?

____

    a. How many hours did you spend on the collaboration per week?

    ____

    b. How much of the time was spent alone on average?

    ____

3) How many people worked together (including yourself)?

____

4) Describe your own background and the background of each collaborator in a few words. This can be a study background or the field that the person was working in. If there were more than 10 collaborators participating in the collaboration, pick the persons that you worked most closely together with.

Yourself: ____

Collaborator 1: ____

Collaborator 2: ____

Collaborator 3: ____

Collaborator 4: ____

Collaborator 5: ____

Collaborator 6: ____

Collaborator 7: ____

Collaborator 8: ____

Collaborator 9: ____

Collaborator 10: ____

Part II: Rating the quality of the collaboration

5) What is your overall experience of the collaborative process? Choose one option.

☐	☐	☐	☐	☐	☐	☐
Very bad experience	Bad experience	Below average experience	Neutral experience	Above average experience	Good experience	Very good experience

For questions 6 and 7, you can give multiple answers per question. Separate your answers using dashes (-). Try to give at least one answer per question.

6) What went well in the collaborative process? What circumstances influenced the collaboration in a positive way?

____

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7) What could have been improved in the collaborative process? What circumstances influenced the collaboration in a negative way?

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____

8) How easy was it for you to collaborate with each co-collaborator? Choose one option per collaborator. Add comments if necessary.

	Very difficult	Difficult	Pretty difficult	Neutral	Pretty easy	Easy	Very easy	Not applicable
Collaborator 1	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 2	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 3	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 4	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 5	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 6	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 7	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 8	☐	☐	☐	☐	☐	☐	☐	☐
	___							
Collaborator 9	☐	☐	☐	☐	☐	☐	☐	☐
	___							

Collaborator 10	☐	☐	☐	☐	☐	☐	☐	☐

Participant questionnaire – Cross-disciplinary collaboration dynamics

Participant number: ____________

Lines have been added in each answer box to indicate where the answers should be given. You are free to remove the lines. Double click on a text field, or click above the text field, to select all the lines. This removes the lines once you start typing.

Part III: Rating the quality of the collaboration based on the shared mental model input

1) Was your collaboration mainly disciplinary, multidisciplinary, interdisciplinary or transdisciplinary? Motivate your answer.

   Kies een item.

____

____

____

____

2) Write down each of the factors mentioned in part II, questions 6 and 7 and label if the factor is part of personal pliability, interpersonal pliability, group pliability or disciplinary pliability.

   Question 6 factors:

____

____

____

____

____

____

____

____

____

   Question 7 factors:

____

____

3) Try to come up with new factors that influenced your collaboration from another pliability category. Label whether these factors are part of personal pliability, interpersonal pliability, group pliability or disciplinary pliability. Try to come up with at least one negative and one positive factor per pliability group.

Question 6 factors:

Question 7 factors:

____

____

____

4) Of the influential factors listed under questions 2) and 3), what factors do you think had the most impact on the collaboration? Write an exclamation point (!) left of these factors.

5) Of the influential factors listed under questions 2) and 3), what factors do you think are most easily changeable? Write a caret (^) left of these factors.

6) In continuing your collaboration or in participating in a new cross-disciplinary collaboration, what factor(s) would you focus on to improve the collaboration?

____

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Part IV: Feedback on the model presentation

7) Did the conceptualization of collaboration theories in the form of a mechanical stiffness model help with the understanding of the concepts that were explained?

____

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8) Did discussing the collaboration model yield you new insights?

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E.3 Presentation Transcript

The following text is used as a guidance during the presentation phase of the interactive model assessment. Therefore, the text is not a word-by-word transcript, but contains the essence of what was explained. The presentation is given in Dutch, because Dutch is the mother tongue of all the participants.

Transcript

1) Als er vragen zijn tijdens de presentatie, wees dan vrij om me te onderbreken en die te stellen. Eerst ga ik aan de hand van 21 slides het model toelichten. Daarna krijgen jullie de tweede vragenlijst toegestuurd.

2) Het model is gecentreerd rondom het begrip stijfheid, een begrip dat vanuit de werktuigbouwkunde veel gebruikt wordt. Stijfheid k is de relatie tussen de kracht F die op een object werkt, en de resulterende verplaatsing u. In deze presentatie wordt deze formule steeds uitgedrukt met u als output, en F en k als input. F is hierbij dus de opgelegde kracht, k is de systeemeigenschap en u is de resulterende verplaatsing.

3) Een ander gangbaar begrip is compliance, de inverse van stijfheid, dus 1 gedeeld door k. Als u uitgedrukt kan worden als F gedeeld door k, is u ook F maal p.

Feitelijk is dit alle werktuigbouwkundige theorie waar het model op gebaseerd is. We gaan nu kijken naar een begrip in de samenwerkingsliteratuur dat veel lijkt op compliance: pliability.

4) 'Pliability' is vertaald 'plooibaarheid'. De Engelse synoniemen staan op de slide, maar andere Nederlandse synoniemen zijn buigzaamheid, coulantheid, flexibiliteit, meegaandheid, . . .

Pliability wordt hier gepresenteerd als 'The professional's flexibility to move from personal concreteness to abstraction as a result of incentives.'

5) Deze begrippen kunnen worden gekoppeld aan de stijfheidsformule: De pliability is p, de stimulansen zijn F en de beweging van persoonlijke concreetheid naar abstractie is u.

6) Dit kan natuurlijk weer worden uitgedrukt in de stijfheidsformule. Er bestaat geen kwantitatief verband tussen deze drie parameters, kwalitatief kan wel gezegd worden dat de verplaatsing van concreetheid naar abstractie groter wordt als de plooibaarheid van de professional groter is, maar ook als de incentives groter worden.

Deze begrippen zijn waarschijnlijk nog vrij abstract, dus ik zal ze een voor een bespreken.

7) Persoonlijke concreetheid en abstractie zijn twee 'manieren van denken'. Persoonlijke concreetheid is de ruimte waarin je de kennis die je hebt geleerd concreet kan toepassen. Hier ken je de begrippen en methoden om problemen op de lossen goed. Als werktuigbouwer in een dreamteam zou persoonlijke concreetheid bijvoorbeeld direct toegepaste kennis uit de vakken zijn die je hebt geleerd.

Maar in de praktijk is de benodigde kennis niet 'perfect concreet', maar is er een shift naar 'persoonlijke abstractie nodig'. Daarbij kom je in aanraking met (deels) nieuwe kennis om toe te passen en te 'linken' aan je al bestaande kennis. Deze shift naar abstractie kan op veel verschillende niveaus gebeuren: Er is geen zwart-witte scheiding tussen wat concreet en abstract is. Als je bijvoorbeeld in je dreamteam verantwoordelijk wordt voor een ander technisch aspect met raakvlakken aan de werktuigbouwkunde, zal dit als minder abstract worden ervaren dan bijvoorbeeld deze presentatie over communicatie.

8) Een ander begrip uit de stijfheidsformule zijn 'Incentives', of 'Stimulansen'. Een stimulans is dus de actie die ervoor zorgt dat professionals geneigd zijn om naar hun persoonlijke abstractie te denken. Vervolgens bepaalt de plooibaarheid van de professional dan dus hoe erg de professional reageert op zo'n stimulans en bereid is om naar persoonlijke abstractie te bewegen.

Er zijn veel soorten stimulansen denkbaar. Ik zal kort ingaan op een onderscheiding tussen interne en externe stimulansen. Externe stimulansen zijn bijvoorbeeld de projectleider die je de opdracht geeft om aan een bepaald project te werken, een handreiking van een collega om samen te werken of financiële prikkels vanuit een investeerder om een project te starten. Interne stimulansen komen vanuit de proactiviteit van de professional zelf: De professional kan ook zelf op het idee komen om zijn kennis toe te passen op onbekend gebied.

9) Tot slot is er plooibaarheid, of pliability. Dit is de systeemeigenschap die bepaald in welke mate er een displacement plaatsvindt door de gepresenteerde stimulans. Elke professional heeft zijn eigen plooibaarheid die constant verandert als functie van de tijd. De plooibaarheid kan zelfs compleet verschillen tussen het begin en het einde van een overleg.

Er kunnen vier factoren worden onderscheiden die de plooibaarheid van een professional beïnvloeden: persoonlijke, interpersoonlijke, groeps- en disciplinaire factoren. Ik ga zo al deze factoren kort af. Wiskundig gezien zou je kunnen veronderstellen dat de plooibaarheid een som is van deze vier componenten. In de werkelijkheid zal er een bepaalde onderlinge afhankelijkheid zijn tussen de factoren en zijn ze niet volledig onafhankelijk zoals dat hier gepresenteerd wordt, maar voor het begrip is het wellicht handig.

10) Persoonlijke plooibaarheid slaat op persoonlijke processen die op de professional zelf slaan. Er zijn vluchtige persoonlijke processen die van dag tot dag veranderen en de plooibaarheid beïnvloeden, zoals de stemming van de professional, of hij of zij goed heeft geslapen bijvoorbeeld. Maar ik ga liever in op langzamere, meer robuste veranderingen in persoonlijke plooibaarheid als functie van de tijd.

Een professional wordt over het algemeen meer plooibaar met ervaring. Dit heeft te maken met factoren die het best beschreven kunnen worden als 'collaborative readiness', of 'bereidheid tot samenwerking'. Een interdisciplinair project doorlopen gaat gepaard met veel onzekerheden, aanpassingen en juist het onderling afstemmen vergt meer energie en toewijding dan bij een disciplinair project. Daarom zorgt een juiste verwachting ervoor dat de professional met de juiste instelling aan het project begint.

Een andere factor, global innovativeness, zegt wat over de persoonlijke normen en waarden die de professional heeft. Een hoge global innovativeness betekent dat de professional meer open staat voor nieuwe ideeen en innovaties.

11) Dan interpersonele plooibaarheid: Dit slaat op de relatie tussen de professional en zijn samenwerkingspartner specifiek. Deze plooibaarheid is voor beide professionals natuurlijk an-

ders en de factoren die hier genoemd worden hebben een eigen effect op elke plooibaarheid.

Een soort 'baseline' van interpersonele plooibaarheid is de algemene overlap van wereldbeelden. Meer gelijkgestemde professionals zullen sneller geloven dat de ideeen van de ander aansluiten bij de eigen ideeen, en dus plooibaarder zijn om zich te verplaatsen in het denkbeeld van de ander.

Ook vertrouwen en bekendheid spelen een grote rol. Vertrouwen kan binnen een collaboratie snel groeien en ook de interpersonele plooibaarheid ten goede doen.

12) Dan groepsplooibaarheid: Dit zijn de factoren die de plooibaarheid van alle professionals uit de groep beïnvloeden. Ook hier hebben de factoren allemaal een ander effect op de groepsplooibaarheid van elke professional. De factoren die hier genoemd worden, zijn factoren die vaak in beleidsplannen staan: Teamgrootte, onderlinge afhankelijkheid van uitkomsten en leiderschap zijn alle drie factoren die vanaf de zijlijn makkelijk te veranderen zijn. Ik ga er kort overheen.

In een team kan iemand leiderschap vertonen door een faciliterende rol op zich te nemen en actief te zoeken naar een gedeelde oplossingsruimte. Ook door een wederzijdse afhankelijkheid van uitkomsten te creeeren, zorg je ervoor dat mensen afhankelijk van elkaar worden en plooibaarder zullen zijn omdat het succesvol afronden van projecten erop berust. Het effect van teamgrootte op plooibaarheid specifiek is niet onderzocht, maar de effecten op het succes van een collaboratie zijn gemixt. Wel is iedereen het erover eens dat het effect heeft.

13) Disciplinaire plooibaarheid, tot slot, heeft invloed op iedereen uit de deelnemende discipline. Dit zijn veelal robuuste factoren die amper veranderen. Ik ga hier alleen in op codificatie, omdat het effect daarvan duidelijk te koppelen is aan de plooibaarheid: De mate waarin een discipline gecodificeerd is, heeft grote impact op de plooibaarheid. Veel beta-disciplines hebben een hoge mate van codificatie. Dat betekent dat formules en methodes eenduidig ondubbelzinnig te interpreteren zijn. Dit maakt het moeilijker om bekende concepten toe te passen op een probleem waar het pallet aan bekende regels niet direct op toepasbaar is. Zoals normaal gesproken het geval is bij het maken van een analogie zoals in deze presentatie.

14+15) Ik ga nu deze drie concepten schematisch weergeven en een paar voorbeelden laten zien. We beginnen met de weergave van persoonlijke concreetheid en abstractie. Omdat elke professional anders geschoold is en andere ervaringen heeft, ziet iedereens concreetheidsoppervlak er anders uit.

16) Hier zijn drie voorbeelden van professionals in een bepaalde samenwerking. De eerste professional bevindt zich in zijn concreetheidsruimte, waarin er dus geen verplaatsing naar persoonlijke abstractie nodig is. Dit is waar de professional alles begrijpt van wat er gebeurt. In de andere twee voorbeelden bevindt de professional zich buiten deze ruimte. Hier zijn stimulansen nodig die de professional reden geven om zich buiten de persoonlijke concreetheid te begeven.

De harde grenzen zijn nu wel als harde grenzen gemodelleerd. Dit is gedaan omdat stijfheid zoals wij het kennen een aangrijpingspunt nodig heeft. Maar in werkelijkheid is er hier dus een gradiënt, en zal er al 'wat' stijfheid nodig zijn om ook binnen die vormen van concreetheid te bewegen.

17) Tot slot volgen vier voorbeelden van verschillende soorten samenwerkingen: disciplinair, multidisciplinair, interdisciplinair en transdisciplinair. Dit zijn vier begrippen die allemaal wat anders betekenen. Het een is niet per se beter dan het ander, maar heeft andere voordelen.

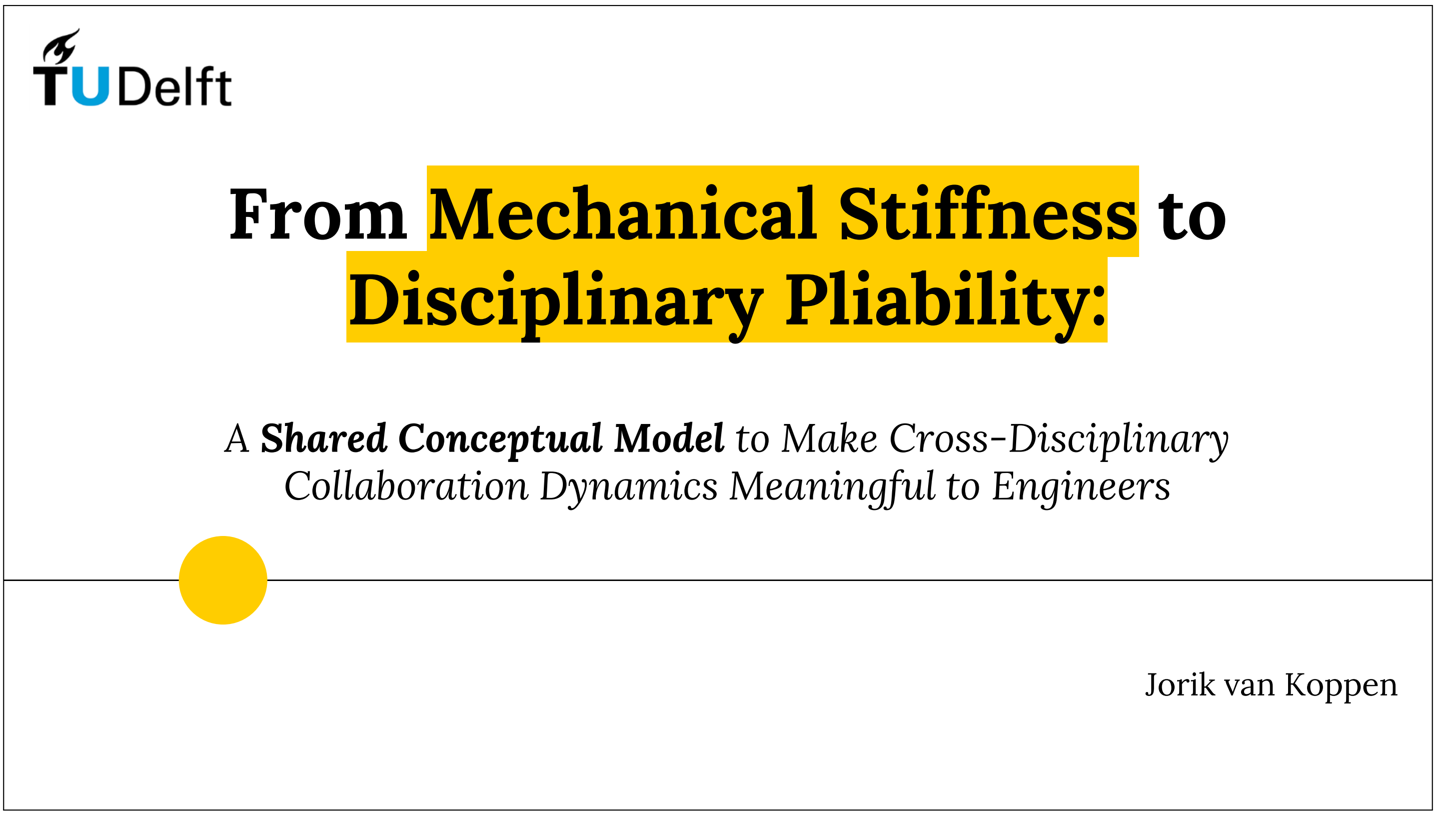
Een disciplinaire samenwerking betekent dat de concreetheidsruimtes elkaar overlappen. De professionals kunnen elkaar dus makkelijk vinden in een taal die door hen allemaal gesproken wordt.

18) Een multidisciplinaire samenwerking bestaat tussen groepjes professionals die in die subgroepen wel dezelfde taal spreken, bijvoorbeeld mensen van de technische afdeling en marketingafdeling, maar samen niet dezelfde taal spreken en niet echt elkaars problemen begrijpen. Ideeën worden niet vertaald naar een ruimte die echt door de ander begrepen wordt, en ondanks dat er wel samengewerkt wordt blijven professionals geankerd in hun eigen disciplinaire regels en methodes. Er wordt dus op een standalone manier aan problemen gewerkt. Iedereen keert na een meeting terug naar zijn eigen eilandje.

19) Bij een interdisciplinaire samenwerking wordt dat contact wel gezocht. Daarbij zoeken de professionals actief hun persoonlijke abstractie op om dus tot een begrip van het ‘probleem’ of het ‘project’ te komen waarbij iedereen de problemen begrijpt waar alle professionals mee dealen en deze kunnen relateren aan hun eigen vakgebied. Hier wordt dus wel geintegreerd aan problemen gewerkt.

20) Tot slot, een transdisciplinaire samenwerking is een samenwerking die nog intenser is, waarbij de professionals door intensieve samenwerking een nieuw begrip van het probleem ontwikkelen – een soort gezamenlijk uitgangspunt van soms nieuwe concepten of methodes, die losstaand aan mensen geleerd zouden kunnen worden. Deze vorm vergt het meeste tijd en de meeste inspanning. Hierbij wordt er op een volledig immersieve manier naar problemen gekeken en samen aan oplossingen gewerkt.

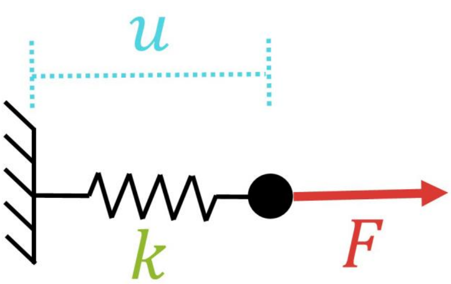
E.4 Presentation Slides



Mechanical Stiffness

- k: Mechanical stiffness
- u: Displacement
- F: Force

$$u = \frac{F}{k}$$



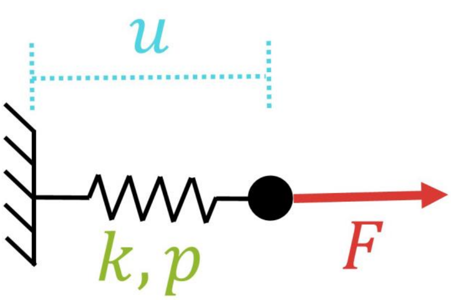
Mechanical Stiffness – Disciplinary Pliability – Displacement – Incentives – Pliability – Schematic Representation

Mechanical Compliance

$$p = \frac{1}{k}$$

- p: Mechanical compliance
- u: Displacement
- F: Force

$$u = \frac{F}{k} = F \cdot p$$



Disciplinary Pliability

- Pliability:
  - Synonyms: 'compliance', 'deference', 'elasticity', flexibility', 'springiness' (Cambridge dictionary)

"The professional's flexibility to move from personal concreteness to abstraction as a result of incentives."

Mechanical Stiffness – **Disciplinary Pliability** – Displacement – Incentives – Pliability – Schematic Representation

Disciplinary Pliability

- Pliability:
  - Synonyms: 'compliance', 'deference', 'elasticity', flexibility', 'springiness' (Cambridge dictionary)

"The professional's flexibility to move from personal concreteness to abstraction as a result of incentives."

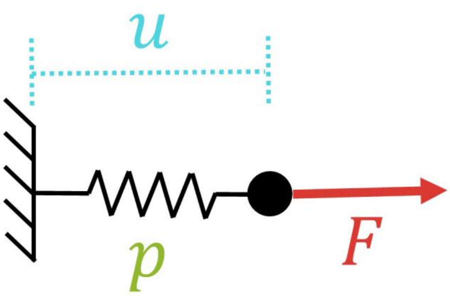
p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Disciplinary Pliability

$$u = F \cdot p$$



p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Displacement from personal concreteness to abstraction (u)

- **Personal concreteness**:
  - Concrete application of obtained knowledge
  - Familiar concepts, methods of problem solving and disciplinary rules
- **Personal abstraction**:
  - (Partially) unknown, new knowledge, methods of problem solving or disciplinary rules
- Gradient between what is ‘concrete’ and ‘abstract’

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Incentives (F)

- One incentive → Multiple displacements

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} F$$

- Internal incentives
  - Intrinsic motivation, proactivity, ...
- External incentives
  - Financial motives, initiative of a colleague, ...

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Pliability (p)

- Four factors:
  - Personal factors p_p
  - Interpersonal factors p_i
  - Group factors p_g
  - Disciplinary factors p_d

$$p = p_p + p_i + p_g + p_d \qquad u = F(p_p + p_i + p_g + p_d)$$

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Personal Pliability (p_p)

*"Flexibility to move to disciplinary abstraction due to **personal dependencies**."*

- Influenced by
  - General mood
  - Collaborative readiness
  - Global innovativeness

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Interpersonal Pliability (p_i)

*"Flexibility to move to disciplinary abstraction due to factors regarding the relation with the **collaborating individual**."*

- Influenced by
  - Overlap of world views
  - Trust and familiarity

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Group Pliability (p_g)

"Flexibility to move to disciplinary abstraction due to factors influencing the ***group as a whole****."*

- Influenced by
  - Team size
  - Outcome interdependence
  - Leadership

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives

Mechanical Stiffness – Disciplinary Pliability – Displacement – Incentives – **Pliability** – Schematic Representation

Disciplinary Pliability (p_d)

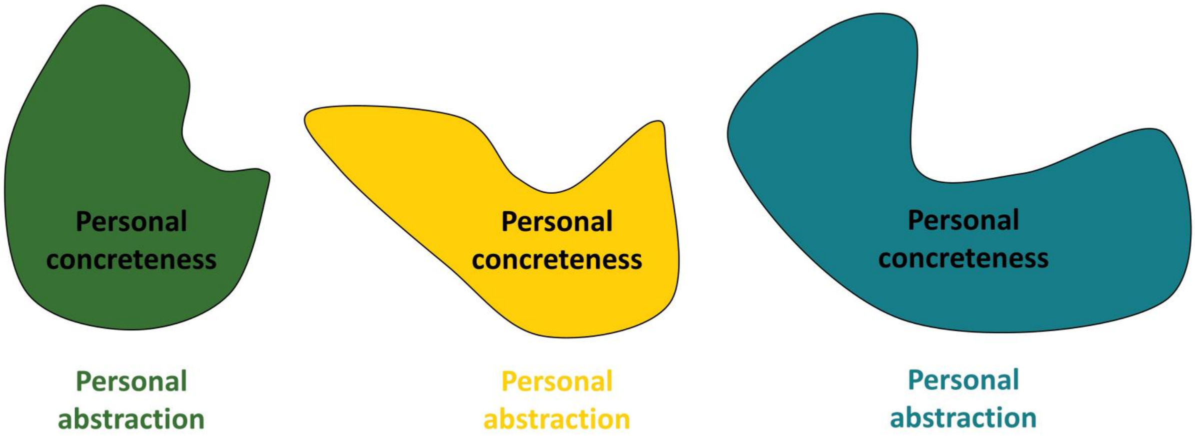
"Flexibility to move to disciplinary abstraction due to factors influencing the ***discipline as a whole****."*

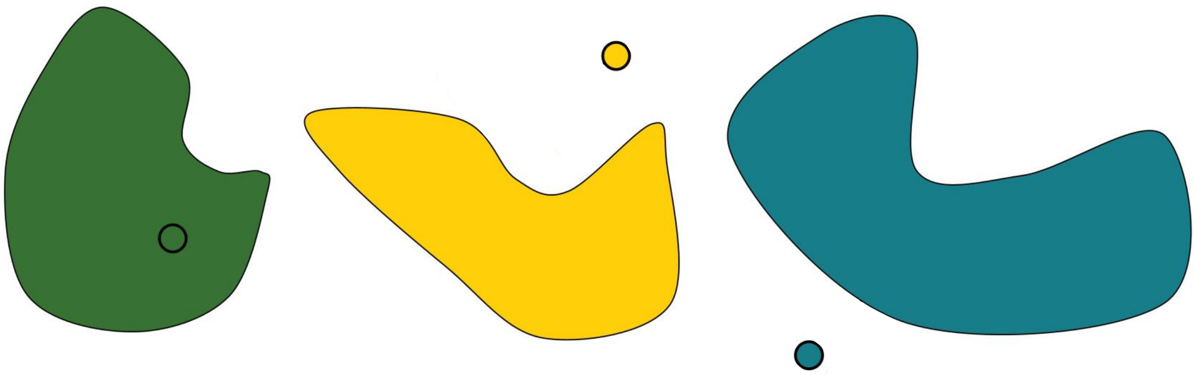
- Influenced by
  - Codification
  - Models and artifacts
  - History
  - Larger socio-political realities

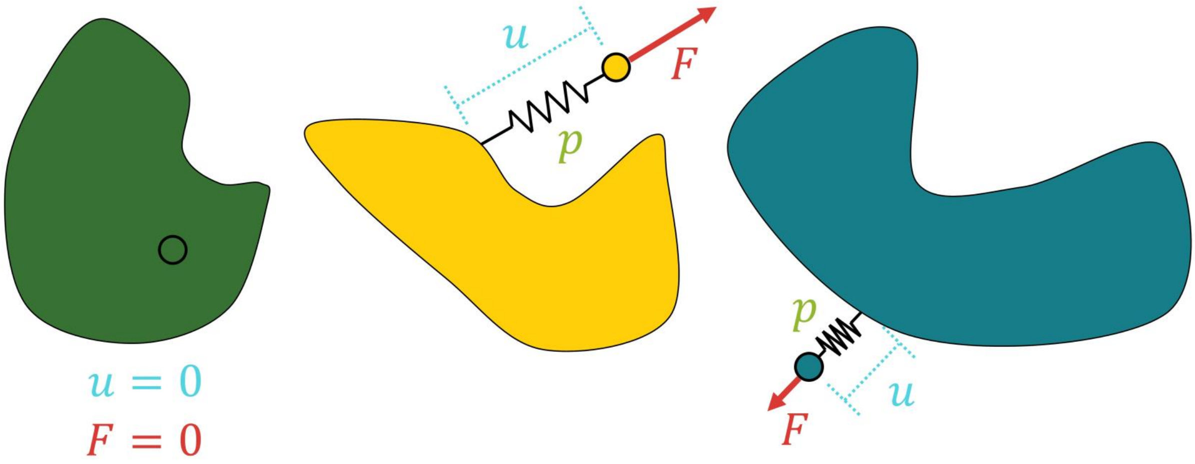
p: Pliability

u: Displacement from personal concreteness to abstraction

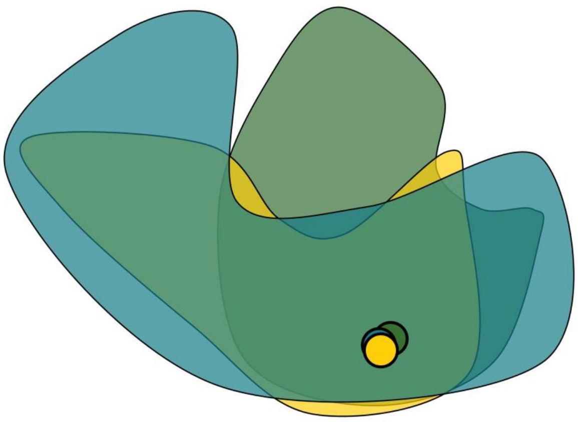
F: Incentives


Personal
concreteness
Personal
concreteness
Personal
concreteness
Personal
abstraction
Personal
abstraction
Personal
abstraction

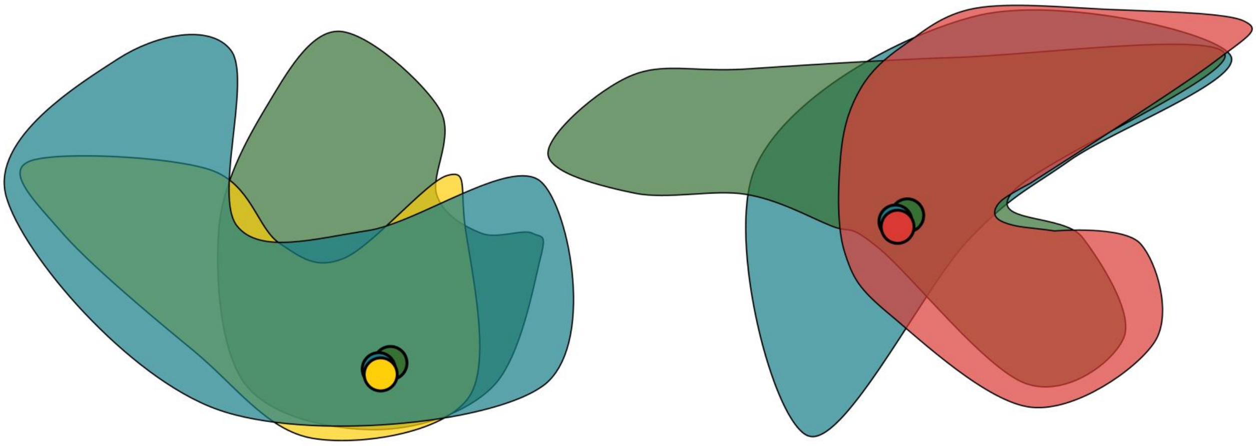




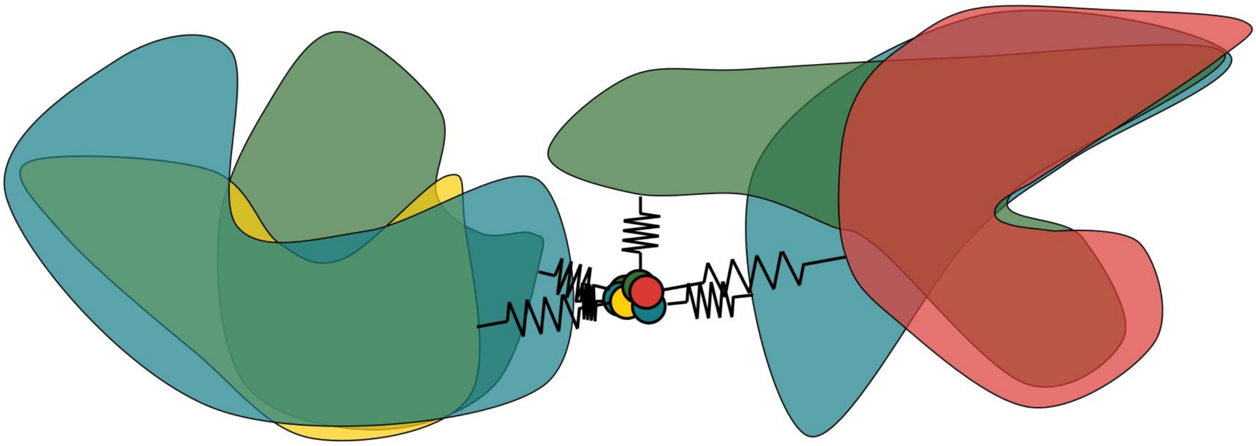
Disciplinary Collaboration



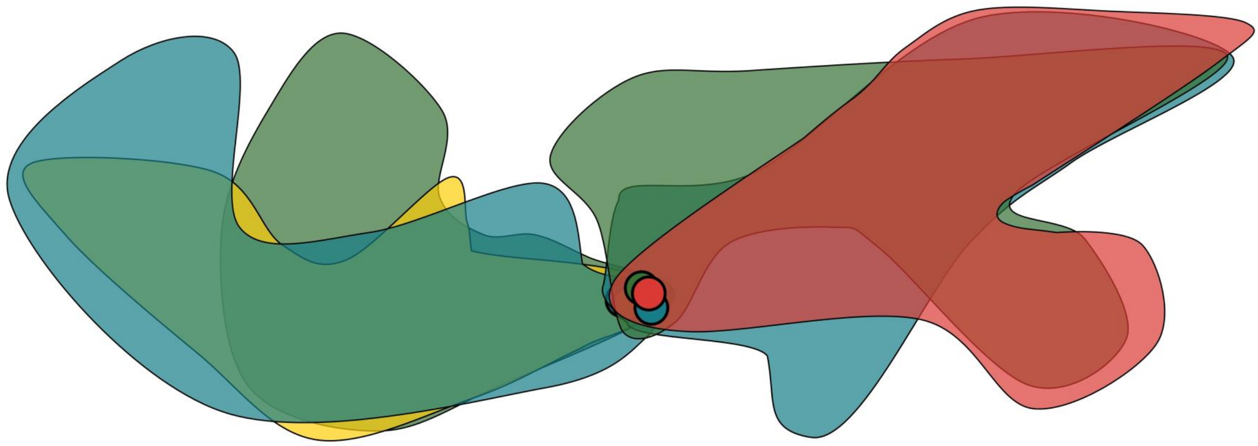
Multidisciplinary Collaboration



Interdisciplinary Collaboration



Transdisciplinary Collaboration



Collaborative Pliability Model

Formulas

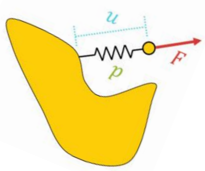
$$u = p \cdot F$$

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} p_{p,1} + p_{i,1} + p_{g,1} + p_{d,1} \\ p_{p,2} + p_{i,2} + p_{g,2} + p_{d,2} \\ \vdots \\ p_{p,n} + p_{i,n} + p_{g,n} + p_{d,n} \end{bmatrix} F$$

p: Pliability

u: Displacement from personal concreteness to abstraction

F: Incentives



Pliability Types

Personal Pliability p_p

- Influenced by
  - General mood
  - Collaborative readiness
  - Motives, global innovativeness

Interpersonal Pliability p_i

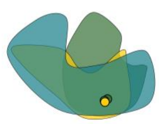
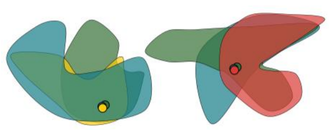
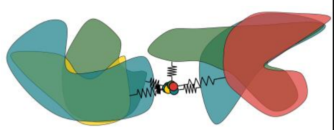
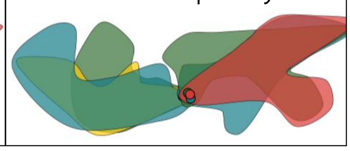
- Influenced by
  - Overlap of world views
  - Trust and familiarity

Group Pliability p_g

- Influenced by
  - Team size
  - Outcome interdependence
  - Leadership

Disciplinary Pliability p_d

- Influenced by
  - Codification
  - Models and artifacts
  - History
  - Larger socio-political realities

Collaboration Types	Disciplinary	Multidisciplinary	Interdisciplinary	Transdisciplinary
				

$$u = p * F$$