Trade-offs in Design

A Theory Building Qualitative Study on the Role of Problem
Formulation and Framing in Resolving Trade-offs in Design

by

Jordan Nickel

A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Management Engineering

Waterloo, Ontario, Canada, 2021

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Jordan Nickel was the sole author for Chapters 1, 3, 4, 5, and 6 which were written under the supervision of Dr. Ada Hurst and Dr. Rob Duimering and were not written for publication.

This thesis contains in part of one manuscript written for publication. The exceptions to sole authorship of material are as follows:

Research presented in Chapter 2:

This research was conducted at the University of Waterloo by Jordan Nickel under the supervision of Dr. Ada Hurst and Dr. Rob Duimering. The theoretical framework was developed by Jordan Nickel with contributions in the form of intellectual input from Dr. Ada Hurst and Dr. Rob Duimering, the co-authors. Jordan Nickel drafted the manuscript, and both co-authors provided intellectual input on the manuscript drafts.

Nickel, J., Hurst, A., & Duimering, P.R. (2021, August 16-20). *Modelling Design Trade-offs Using a Set Theory Approach: Alternative Paths for Navigating Trade-off Situations* [Paper presentation]. 23rd International Conference on Engineering Design (ICED21), Gothenburg, Sweden.

Abstract

Design projects are complex problem-solving endeavors that can involve many goals that are often conflicting. These trade-offs between goals have been primarily studied through the lens of optimization, attempting to create the best possible solution under the constraints of the conflicting goals. However, the broader design literature indicates that design problems are characterized by being ill-defined. As a result, designers need to interpret, formulate, and frame the problem they are attempting to solve, and they must do this without a well-defined set of constraints and requirements. To this end, designers use solutions concepts to explore their problem, and this causes the design problem and solution to coevolve. This research explores the ways that designers formulate and frame trade-offs, how they can manipulate their formulation and framings of the problem to resolve trade-offs, and the aspects of their design situations that influence how challenging these reformulation and reframing processes are.

A theoretical framework was derived using set theory to model and describe a designer's formulation and framing of their problem and solution, which is labeled the design space. The framework also utilizes the concept of Pareto optimality to formally define design trade-offs within a design space. An intensionally defined set of possible manipulations to this design space was identified using this theoretical framework, which informs how those manipulations can be used to resolve trade-offs. This framework also models how a designer's perceptions and expectations of their design spaces can differ from the real performance of their solutions due to inherent cognitive limitations, information availability, and biases.

A semi-structured interview approach was used to explore how practicing designers framed and formulated their initial trade-off situation, and how they manipulated those aspects in their resolution of the trade-off, if at all. Additionally, an echo interview process was used to investigate what influences the designers perceived as affecting how challenging their trade-off situations were to resolve.

Seven different approaches to resolving trade-offs were identified in the dataset through a case study analysis, which were classified by how they manipulated the design space. Four of these approaches actively manipulated the designer's perceived design space to resolve the trade-off, two altering the boundaries of the space and two altering the parameters that comprised the space. These manipulations allowed the designers to restructure their design space and the trade-offs therein to make them easier to resolve. In some of the cases studied, the manipulations also allowed the derivation of solutions that dominated the Pareto frontier of the original design space.

In addition to the case study analysis, a thematic analysis was used to identify the aspects of the situation that made manipulating design spaces and resolving trade-offs either easier or more challenging. From this nine codes were identified, sorted into three themes. The three themes were how the design space was initially structured, how well a designer's expectations aligned with the real outcomes of decisions, and how previous decisions impacted the options available to a designer.

The results showed that designers can and do manipulate their problem formulation and framing to resolve trade-offs. This indicates that optimization approaches in design need to account for the dynamic structure of the problem, and that designers should be aware that results of an optimization approach reflect the structure they impose on their design problems. Overall, this research contributes to understanding how designers perceive and frame trade-offs, what tools they have at their disposal to resolve them, and what challenges they encounter while resolving them.

Acknowledgements

I would like to express my extensive gratitude to all the people who have supported and guided me over the entire course of this thesis. To start, I want to extend my sincerest thanks to my supervisors and mentors, Ada Hurst and Rob Duimering. From the very beginning you have believed in me and this work, encouraged me to think rigorously and creatively, and helped me become a better researcher, thinker, and writer.

To my fellow graduate students Meagan Flus and Greg Litster, I want to thank you for all of the support, camaraderie, and intellectual stimulation you have provided me during these trying times. I know the changes brought upon us by COVID-19 have been challenging for all of us, and I appreciate your contributions to maintaining a collaborative and collegial intellectual environment.

To my long-time mentor and friend, Oscar Nespoli, I want to thank you for introducing me to design and sparking my passion for the study of its nature and purposes in this world of ours.

The labours of research require sacrifice and commitment, and I want to thank my partner, family, and friends for believing in me and supporting me throughout this journey. My partner, Chloe Jenkins, has been the foundation upon which I built. She has helped minimize life's distractions and kept me on track, yet still ensured I did not completely forget to relax and enjoy life as I live it.

Lastly, I would like to extend my thanks to all of the participants who so graciously shared their time, experiences, and insights so openly with us. Without them this work would not have been possible.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CAD – Computer Aided Design

CDA – Communicative Disorder Assistant

CEO – Chief Executive Officer

COVID-19 – Coronavirus Disease 2019

DfS – Design for Sustainability

GPS – Global Positioning System

hp – Horsepower

HVAC – Heating, Ventilation, and Air Conditioning

IC – Internal Combustion

ISO – International Organization for Standardization

MBH – 1000 British Thermal Units/Hour (Unit of Power)

MTBF – Mean Time Between Failures

MVP – Minimum Viable Product

OEM – Original Equipment Manufacturer

PCB – Printed Circuit Board

PPM – Parts Per Million

ROI – Return On Investment

RQ – Research Question

SLP – Speech Language Pathologist

TIPS – Theory of Inventive Problem Solving (English abbreviation for TRIZ)

TRIZ – (Russian) теория решения изобретательских задач, Teoriya Resheniya Izobretatelskikh Zadatch. Literal translation "theory of the resolution of invention-related tasks"

UI – User Interface

UX – User Experience

ZF – Zermelo-Frank set theory

Chapter 1 – Introduction and Background

Design is a complex decision-making process that takes a need, transforms it into a problem to solve, and develops a solution to that problem. This process involves many stakeholders, often with diverse and conflicting goals, and myriad constraints both imposed and inherent. In this complexity, trade-offs between goals are frequent and challenging situations that designers must deal with. Trade-offs are situations in the design process where two or more goals of the project are in conflict, and to attain performance gains on one goal, sacrifices must be made on the performance of at least one other goal.

The study of design trade-offs and how to manage them grows more important as the impacts of design trade-offs in areas like sustainability, equity, and safety are increasingly evident (Gibson, 2013; Hahn et al., 2010). As most design occurs in profit-motivated enterprises, these designs must meet market demands on functionality and cost, among other market driven demands. Under these pressures, there is a risk that factors typically classified as "externalities" will not be prioritized when they come into conflict with the market driven goals (de Koeijer et al., 2017; Gibson, 2013).

However, the very complexity of design problems, and their ill-structured nature, allow designers to manipulate not only their solutions, but the way they formulate and frame their problems. By formulating their design problem differently, or by reframing their perspective of the problem, designers introduce flexibility into their problems that may allow them to restructure and resolve trade-offs, or even avoid them altogether.

1.1. Design

To study trade-offs in the context of design problems, that design context must first be defined. Herbert Simon classically defined the process of design as the transformation of existing situations into preferred ones (Simon, 1969). Another common definition of

design is that it is a purposeful, goal-directed, constrained, decision-making activity which occurs within a context (Gero, 1990). Johansson-Sköldberg et al. (2013) identified five primary theoretical perspectives on the nature of design and designerly thinking in the literature: design as the creation of artifacts (Simon, 1969), design as a reflexive practice (Schön, 1983), design as a problem-solving activity (Buchanan, 1992), design as a way of reasoning/making sense of things (Cross, 2006, 2011; Lawson, 2005), and design as creation of meaning (Krippendorff, 2006).

Design trade-offs are best discussed in the design as a problem-solving activity paradigm, since trade-offs are the result of conflicting goals or preferences, although the reflexive practice view informs the framing and reframing process introduced later in this section (Schön, 1983). However, design is not a simple case of problem-solving with well-defined goals, constraints, and permissible actions. Designing involves finding appropriate problems and substantial activity in problem structuring and formulating (Cross, 2001). Indeed, design problems may be among the most ill-defined problem-solving tasks as the requirements, constraints and even goals are typically loosely specified in a design brief, or simply absent altogether (Ball & Christensen, 2019). Research has shown that design problems are initially ill-structured, with ill-defined goals and decision paths to reach those goals (Goel & Pirolli, 1992). These problems often start with specifications that are incomplete, contradictory, or infeasible (Reich, 1995).

In these ill-defined and ill-structured problems, the designer must initially determine what the problem is and how to structure it, and in so doing make initial assumptions about requirements and constraints, a process Cross (2001) defined as "problem formulation". In this vein, Ullman, Dietterich, and Stauffer (1988) found that expert mechanical engineering designers would introduce numerous constraints early on based on their existing domain knowledge, while other constraints were identified as the designers explored solution concepts. Cross (2001) also notes that designers will even treat nominally well-defined problems as if they were ill-defined, relaxing and

2

redefining constraints and adjusting or supplementing goals (e.g., Thomas & Carroll, 1979).

Cross (2001) also found that designers act in a solution solution-oriented, not problem-oriented manner, moving rapidly to early solution conjectures that allow them to impose order on the ill-defined problem situation. It is these solution ideas that allow the designers to clarify their understanding of the problem and its facets, and check whether these initial solutions meet the requirements and constraints of the problem.

Since designers use their solution conjectures to develop an understanding of a problem, and then leverage that new understanding of the problem to inform new solutions, Maher and Poon (1996; 1997) theorized that the design problem and solution "co-evolve". This process of problem-solution co-evolution models the design process as the exploration of two conceptual knowledge spaces: a "problem space" that contains the problem requirements and constraints which are used to evaluate solutions, and a "solution space" that contains all of the attributes that describe the design and provides a foundation for evaluating the appropriateness of requirements (Dorst & Cross, 2001).

From the reflexive practice perspective of design, Schön (1983) proposed the concept of a "problem frame", which is that designers actively select features of the problem to attend to. Schön (1988, p. 182) suggests that: *In order to formulate a design problem to be solved, the designer must frame a problematic design situation: set its boundaries, select particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves.* The process of framing is the designer imposing a viewpoint onto the problem, a selection of aspects that they seek to attend to. Designers may construct a frame meticulously with an awareness of what they are choosing to include in the frame, or they may frame the problem more passively, relying on past experience, norms and other heuristics and guidelines (Cross & Clayburn Cross, 1998; Lawson, 2005, p. 276). The success of a design project depends on the designer effectively constructing a frame that allows sufficient "room" for creativity while still providing enough constraint to focus the solution and enable progress (Ball & Christensen, 2019;

3

McDonnell, 2018). This problem framing is rarely done all at the beginning of the problem, and designers revisit their problem structuring periodically throughout the design process (Goel & Pirolli, 1992; Schön, 1983).

1.2.   Trade-offs and Requirement Conflicts

As introduced above, design problems are inherently ill-structured and designers need to impose a structure and coherence on those problem by formulating and framing it to solve it. These ill-structured problems often have multiple goals, and these goals can come into conflict where trade-offs must be made between them (Jonassen et al., 2006). Trade-offs are often a result of how a designer has formulated and framed the problem situation (Stacey & Eckert, 2010), but we know very little about how designers restructure design problems to resolve trade-offs in practice. The literature bodies pertaining to this issue, namely design creativity and cognition, optimization, problem formulation, and problem framing all cover the issue of constraints on design. Constraints are the limitations on designs, either imposed or inherent, that prevent design solutions from attaining a level of performance on some measure (Biskjaer et al., 2014). Trade-offs represent a specific type of constraint which results from a specific type of interaction between two or more goals of the project, where gains made towards one goal come at the cost of losses towards at least one other goal (Byggeth & Hochschorner, 2006).

The design creativity literature and the history of technology present many examples of instances where innovative solutions were developed that were able to bypass perceived constraints of a problem, ranging from the simple but hidden solution to the 9-dot problem used in Gestalt problem-solving research (Akin & Akin, 1996) to highly complex design problems (Crilly & Moroşanu Firth, 2019). These instances have been colloquially referred to as "eureka!" or "aha!" moments, strokes of creative genius, innovative solutions, or sudden mental insights (Akin & Akin, 1996; Chandrasekera et al., 2013).

Another label that is occasionally applied is "outside the box creativity" or "outside the box thinking", but Stacey and Eckert (2010) believed this to be inherently misleading terminology in their study of constraint management and creativity. Instead, the creativity is still "within the box", but the box is defined by the designer actively constructing a framing of the problem to solve (Stacey & Eckert, 2010). Akin & Akin (1996) argue that to invoke a sudden mental insight, designers must first recognise restrictive frames of reference and construct new frames that are more conducive to solving the problem. It is this very notion that this present study hopes to apply to the study of trade-offs within design.

Designers routinely encounter trade-offs in their design practice, limiting their options and forcing decisions to be made about priorities (Byggeth & Hochschorner, 2006). These decisions are typically complex, involving multiple competing criteria and stakeholders (ibid.). Trade-offs occur when the designers have an overall preference function for the design outcome that they desire to maximize (i.e., solutions get ranked according to some internal preference function, which can be subjective or objective) (Otto & Antonsson, 1991). Design engineers frequently need to manage trade-offs between parameters of many different types to find a solution that maximizes that overall preference function for the design (ibid.).

Fischer (2018) argues that design trade-offs are one of the most basic characteristics of design because of the huge variety of 1) different objectives, 2) greatly varying problems, 3) different value systems, and 4) different people's needs and preferences. Fischer (2018) also posits that viewing design through a trade-off framework is beneficial as it avoids oversimplifying solutions and ignoring important facets of complex problems and uncovers unknown alternatives and identifies the truly limiting factors that underlie problems.

1.2.1. Approaches to Managing Trade-offs in Design

One of the purposes of this thesis was to study the ways designers conceptualize and manage trade-offs between goals and preferences in their design process. Trade-offs in design are discussed primarily in the context of design optimization, although some alternatives like the Theory of Inventive Problem Solving exist. However, despite all of the findings in the general design literature about the nature of problem reformulation and reframing, the study of trade-offs in design does not consider the role of problem reformulation and reframing (Bate, 2008; Belecheanu et al., 2005; Byggeth & Hochschorner, 2006; Carnahan & Thurston, 1998; Schulz et al., 2018).

1.2.1.1. Optimization

Design optimization attempts to identify the "best" possible solution to a design problem, given a series of goals and constraints that bind these goals. It has been described as "the process of repetitively refining a set of often-conflicting criteria to achieve the best compromise" (Hall et al., 2013). This approach relies on the assumption of an overall preference function that distinguishes which design solutions are more preferred and which are less.

Optimizing within design is the state of accepting trade-offs as inevitable and attempting to make the best decision within those dynamics, whereas "good design" seeks to resolve the contradictions driving the trade-offs (Hall et al., 2013). In the context of trade-offs, two or more of the goals that are being optimized for are antagonistically related (i.e., any gain in one of the goals in the conflict is associated with a loss in one or more of the other goals in conflict).

Optimization of this relationship would result in a Pareto optimal set, where the members of that set are all equally optimal on the overall preference function but vary in performance on individual evaluative parameters (Rafiq, 2000). Trade-offs can be defined formally using this concept of Pareto optimality (Schulz et al., 2018). Pareto optimality and its associated concept of Pareto frontiers were originally developed by

Vilfredo Pareto to describe a notion of economic optimality (Ekelund & Hebert, 2007) but have since been applied to a broad variety of optimization problems, including design optimization (Gero & Kazakov, 2000; Malak & Paredis, 2010; Mattson et al., 2019; Rafiq, 2000).

Identification of Pareto optimal sets of solutions is recognized as being important to characterizing the trade-offs that are being optimized (Mastroddi & Gemma, 2013; Rafiq, 2000), and methods have been proposed to identify these Pareto optimal sets in a computationally tractable manner (Kaliszewski et al., 2016).

Katz (2014) found that design optimization frequently causes some of the parameters values to be near "cliffs" in their performance. These cliffs are areas where the performance function of a parameter is highly sensitive to perturbations, such that small changes in the value of the parameter have large impacts. Mathematically, these cliffs are where the partial derivatives of the evaluative parameters' performance with respect to non-evaluative parameters that define the design are very large. Katz's (2014) findings show that optimization on parameters that have a degree of uncertainty, without accounting for that uncertainty through margins of safety or evaluation, can result in an "optimized" design solution providing insufficient performance because it is further along the rapidly changing slope than predicted.

While optimization approaches can be capable of identifying a Pareto optimal set within an explicitly defined design space, they are limited by the requirement that the evaluation function and the constraints of the design must not vary in form, only in value. However, the co-evolution of problem and solution within design can cause the criteria by which the design is judged or the constraints that restrict the feasible region to change (Dorst & Cross, 2001). This would mean that an optimization process must be restarted to reflect these changes every time they occur, costing time and project resources.

A further limitation to the design optimization approaches identified was that they could only optimize the parameters that the designer had explicitly identified and included. Since design problems are complex and ill-structured, not all of the influences on the performance of the design are explicit or well-understood over the course of the design project, and many may only be identified after the design is completed and is operating in its intended functional environment (Goel & Pirolli, 1992).

Furthermore, if a design parameter is not originally included in the optimization model but has a large influence on the performance, it can be discovered during the design process and potentially result in solutions that dominate the original Pareto optimal set. This would indicate that optimization approaches in the context of design can only verifiably identify locally optimal solutions, unless the set of all possible solutions is fully characterized and understood. If the set of every possible solution is fully understood, then a design process is unnecessary, since a solution already exists (Hatchuel & Weil, 2009). This is not to say that optimization has no role in design, but that optimization relies on constraints and requirements, which in design are subjectively and dynamically defined. Optimization can produce solutions that outperform other solutions in a given formulation or frame, but the designer must ensure that the formulation and frame used reflect to the underlying goals appropriately.

1.2.1.2. TRIZ

The Theory of Inventive Problem Solving (TIPS), more commonly known by the original Russian acronym TRIZ, is a design method focused on bypassing requirement conflicts and trade-offs. One of the primary purposes of TRIZ as a design tool is to overcome the need for a compromise or trade-off between two technical parameters, which are called contradictions in the TRIZ terminology. TRIZ was the result of Altshuller and his team's (1984) survey of global patent literature, in which they identified 40 different generalized "inventive principles" that designers and engineers used to resolve contradictions.

These "inventive principles" are a set of conceptual solutions to contradictions, examples of which include making a solution "asymmetric", "using composite materials", "substituting mechanical systems" with electromagnetic equivalents, and "improving the local quality" of portions of the design. Since the principles are derived from the patent literature, they tend to be very engineering focused, and only consider the design of physical artifacts, and not the design of services and systems (Ilevbare et al., 2013).

The TRIZ methodology attempts to reduce a specific technical problem to a single essential contradiction, stated in an abstracted conceptual form. This conceptual problem is then matched to one of the 40 conceptual solutions, or "inventive principles", and then translated back into a concrete solution using that principle.

As an example of how TRIZ is applied to resolve technical trade-offs, consider the design of a train. The contradiction in this example is that goal of the design is to increase the top speed of the train but doing so increases the energy required to move it, and the amount of energy available to the train is limited. TRIZ provides four suggested "inventive principles" for this form of contradiction: periodic action, mechanics substitution, parameter changes, and strong oxidants. Selecting mechanics substitution for further elaboration, the designer could swap the mechanical wheels that support the train with electromagnetic levitation to support the train. In doing so, the rolling friction on the rails is eliminated, and the train can attain higher top speeds without increasing the amount of energy required relative to a rolling train.

However, TRIZ has several limitations as an approach to modeling and understanding trade-offs. The first is that TRIZ is only structured to manage a single contradiction at a time, while the design of complex systems can involve many simultaneous, interconnected contradictions (Chakrabarti & Blessing, 2014). Expanding further, because TRIZ focuses on a single contradiction between two conflicting parameters, it

does not facilitate the identification of potential mediating parameters that affect the performance of the two conflicting parameters.

TRIZ defines the possible solution approaches, or "inventive principles", and the parameter contradiction pairs extensionally (i.e., defining by exhaustively listing everything within the set that is being defined). This is a result of how TRIZ was derived, where each new principle and contradiction discovered in the patent database was added to the set of possible solutions or problems. This definition approach has two primary drawbacks for modeling and explaining trade-offs. The first is that if a problem cannot be abstracted into a contradiction that matches one of the problem structures that are defined extensionally, then TRIZ cannot match it with a solution structure. The other is that while an extensionally defined set can be expanded when novel approach is identified, it cannot itself predict what those novel approaches are.

Lastly, TRIZ does not capture reformulation of the design problem, as it focuses on altering the solutions to mitigate or avoid contradictions. As discussed above, design problems co-evolve with the solutions as the designers explore their problems and develop new insights from the solutions they develop (Dorst & Cross, 2001).

Together, all of these limitations point to the need for a more generalized model of trade-offs that defines the approaches to managing a conflict intensionally (i.e., defining by specifying conditions or properties that make something a member of that set) and captures multi-dimensional conflicts and the parameters that mediate and influence those conflicts.

1.2.1.3. Enlarging State-Spaces

In the model of design problem solving as state-space search established by Simon and Newell (1971) the boundaries of the solution space are known and fixed. The design process is modeled as a branch-and-bound search of a state-space of all possible permutations of solution concepts within a problem space to identify a suitable solution concept to a given problem (Simon & Newell, 1971). As the search proceeds, the

designer moves from one "knowledge state" to another, until their current knowledge state includes an acceptable solution (Simon & Newell, 1971). A criticism of this assumption is that it precludes truly creative and novel designing, since the solution must come from an underlying set that is static (Kazakçi & Tsoukias, 2005).

However, this critique does not apply to all later developments of the branch-and-bound state-space search model of design processes initially proposed by Simon and Newell (1971). Namely, Gero (1990) operationally defines creative design as the result of new parameters being introduced into the definition of the state-space, and innovative design as the manipulation of the possible value ranges of the existing parameters, both of which alter the boundaries of the underlying solution space. These are distinct from what they defined as routine design, which is design that proceeds within a pre-emptively defined state space of potential designs, which is what Kazakçi and Tsoukias (2005) were critiquing.

Gero and Kumar (1993) expanded upon Gero's (1990) definition of creative design to propose guidelines for which parameters to use to expand the solution space. Further work explored using genetic algorithms to enlarge the solution state-space and identify solutions that dominate the Pareto frontier of the original solution space (Gero & Kazakov, 1999, 2000).

However, none of the models proposed by Gero and his colleagues above, or their implementations, capture the influence of a problem structure that dynamically changes through problem-solution co-evolution (Poon & Maher, 1997). In these models it is assumed that the criteria used to evaluate solution performance are fixed and predetermined (Kazakçi & Tsoukias, 2005).

Furthermore, the formulation of the spaces presented by Gero and Kumar (1993) lacks two features necessary to model Pareto frontiers and trade-offs. The first is that the evaluation criteria, which are part of the problem space in their definition, are not included in the model of expanding state-spaces, since the state-space being expanded

11

is the solution space, and therefore it cannot capture problem reformulation. Their model only considers adding new parameters that describe the solution concept, but not parameters that describe the problem goals and constraints. The second is that the interactions between the parameters that comprise the solution space, and performance parameters in the problem space are not made explicit.

1.3.   Literature Overview

The point of departure for this study is to connect concepts from the design cognition and creativity literature to a practical application in resolving design trade-offs. Prior work has considered problem formulation, framing and co-evolution in the context of design cognition and creativity, but it has not connected these concepts to their practical application in the context of design trade-offs. The design optimization literature on the other hand is explicit in its treatment of trade-offs, and how to identify and design to the Pareto optimal set within a problem frame. However, it does not account for the fact that design problems are formulated and actively framed by the designer, and as such the problem structure being optimized is dynamic and can be actively altered by the designer in pursuit of better designs.

1.4.   Research Questions

Considering the gaps identified above, this thesis investigates how designers resolve the trade-offs they encounter in practice and the role problem reformulation and framing in resolving design trade-offs. Furthermore, since design is a situated endeavor (Gero, 2002), identifying the perceived influences on the designer's decision making in trade-off situations is important to gain a picture of why they responded to the trade-offs in the manner that they did. These aims have been formulated into the following four research questions:

> *RQ1 - How can a designer's formulation and framing of a design trade-off be modeled?*

RQ2 - Do designers use reformulation and reframing to resolve trade-offs between their design goals?

RQ3 - What situational influences do designers perceive as making it easier to resolve a trade-off?

RQ4 - What situational influences do designers perceive as making it more difficult to resolve a trade-off?

A theoretical framework that builds upon the ideas of Gero and Kumar (1993) was derived using set theory concepts prior to the exploratory study. This framework models a designer's formulation and framing of their design problem, allowing trade-off situations and designers' responses to them to be modeled and understood, answering RQ1. This framework also provided a lens through which the exploration and analysis required by RQ2, RQ3, and RQ4 occurred.

1.5.   Organization

The remainder of this thesis is organized into five chapters, following the structure outlined below:

Chapter 2 presents the theoretical framework developed by the author from the existing literature to model a designer's formulation and framing of trade-offs and what approaches they use to resolve them, answering RQ1. The model description is divided into three sections: describing the mathematical concepts and modelling design using these mathematical concepts, describing how human processes and limitations are captured in the model, and formalizing the trade-off situations and the possible approaches to resolving them within the model.

Chapter 3 describes the methodology used to acquire the dataset. The selection criteria for interview participants and the semi-structured interview protocol are both described in this chapter.

Chapter 4 and Chapter 5 present the results of a case study analysis and a thematic analysis, respectively. Both chapters begin by describing the specific analytical methodology used for each approach.

The case study methodology was used to explore the approaches used to resolve trade-offs in response to RQ2. Eleven cases from nine interviews were analyzed, and the resulting classification scheme for the responses is presented in Chapter 4.

The remaining two research questions, RQ3 and RQ4, were approached using a thematic analysis. A coding scheme was developed from the transcripts that classifies the helpful and unhelpful influences identified by the designers. Both Chapter 4 and Chapter 5 discuss the limitations of their respective analytical approaches and discuss the findings derived from their analysis.

Chapter 6 connects the general findings of the studies to the literature, discusses the benefits and limitations of the theoretical model and data collection approach, presents prospective avenues for future work, and summarizes the studies and their results.

Chapter 2 – Theoretical Framework

The concept of a design space introduced in this chapter builds on Gero and Kumar's (1993) ideas of altering and expanding the solution space by formalizing a structure to model the designer's formulation and framing of the design problem using the concepts of parameters, membership criteria and elements from naïve set theory (Halmos, 1974). Naïve set theory is a branch of set theory that is defined in natural language, making it distinct from axiomatic set theories, such as Zermelo-Frank set theory (ZF set theory), which are defined using formal logical axioms. Despite this, naïve set theory suffices to develop the theoretical framework presented in this thesis, since the sets described are mathematical abstractions of the natural language descriptions of design problems. By applying a naïve set theory approach, an underlying design space structure can be described and with it the mechanisms by which this structure permits discovery and manipulation of that set's boundaries.

However, it should be noted that the framework presented in this chapter is not a model of design reasoning, unlike the state-space branch-and-bound search paradigm of Simon and Newell (1971) that informed Gero and Kumar's (1993) model. Instead, this framework is a descriptive model of both the structure of the problem and the performance of solution concepts relative to the goals of that problem at a given instance in time during the design process. This representation combines the elements of the problem space and solution space into a single "design space". This approach allows the initial trade-offs and the consequences of the decisions designers take in their attempts to resolve these trade-offs to be modeled. However, it does not model the cognitive process by which designers arrive at an initial solution concept, move from concept to concept, or from problem to solution.

2.1. Modeling the Design Space Using Naïve Set Theory

A mathematical set is defined by its elements and its membership criteria (Halmos, 1974). The elements of the set are the types of entities that comprise that set, and the membership criteria of a set determine which elements are included in the set and which elements are excluded. In addition to the elements of the set and the membership criteria, one other component is required to use naïve set theory to describe trade-off situations in design: the parameters used to characterize and differentiate elements (i.e., designs) from each other. A parameter is any attribute or characteristic that can be used to describe an element or to differentiate two different elements from each other.

The design space itself is a parametric model, wherein every design solution is an element that is characterized by the values it holds on a set of parameters. These parameters describe the attributes and functionality of a design, and different design solutions are distinguished from each other by their differences on those parameters. This section provides a detailed overview of how a design situation and the trade-offs therein are modeled using the mathematical concepts presented in the previous section.

2.1.1. Elements

The elements of the design space are designs, in the noun usage of the term: the output of the design process. Elements are characterized by parameters, and these parameters are what differentiates individual designs from one another. The inclusion of these elements into the design space is determined by the membership criteria, but designs can exist outside of the design space. Elements that are included in the design space can also be called solutions to the design problem, as they are viable solutions to the problem as currently framed.

2.1.2. Membership Criteria

In the context of the design space, the membership criteria determine the viability of a design as a solution to the problem at hand. Viability in this model is defined to be the

logical status (e.g., true versus false) of a design instance relative to meeting the goal(s) and constraint(s) of the design problem as it is currently formulated.

The boundaries of the design space can originate from a variety of sources, as anything that affects the viability of a design as a solution imposes a boundary. Examples include but are not limited to boundaries imposed by natural laws and constraints; the requirements, constraints and criteria of the design brief; regulations, laws and societal expectations; project resources allocated for design, production, distribution, recovery/disposal, etc.; and limits of currently available technology. Boundaries to viability can also be imposed and altered by the decisions the designer makes during the design process, such as the selection of structures or approaches to solving the problem. Furthermore, membership criteria in design can have differing degrees of negotiability (Goel & Pirolli, 1992), from entirely non-negotiable constraints like the speed of light, through constraints like legal regulations that are non-negotiable on the scale of a design project, to completely negotiable and arbitrarily imposed bounds like colour preferences.

The mathematical intersection of the boundaries created by the membership criteria is the viable design space and contains all of the viable design solutions given those membership criteria.

2.1.2.1. Goals

The goals of a design can take varying forms, and each of these forms influences how parameters behave and how boundaries are formed. Classical Pareto optimality, the mathematical concept used to model trade-offs, relies on monotonically ordered parameters, either increasing or decreasing (Malak & Paredis, 2010). Goals in design can take this form when the designer has a preference for maximizing or minimizing a parameter. Monotonic goals can be operationalized onto parameters that are measured at a continuous level down to a discrete ordinal level, so long as the preference is consistently ordered in either an increasing or decreasing direction.

17

However, goals in design are not necessarily monotonic, and that drives the need for Pareto optimality criteria that can accommodate these goals. Malak and Paredis (2010) derived a "parameterized" Pareto criteria that allows for non-monotonic goals to be incorporated into trade-off models, which is outlined later in Section 2.1.4 along with the Pareto frontier's role in the design space. A goal may simply be a nominal threshold of performance that must be achieved, but after it is achieved any further performance does not affect the preference of the solution. Alternatively, the goal may be to keep the performance within a certain range, where it is less preferred as the value diverges from the target in either direction. Regardless, for this model it suffices to note that goals are not always operationalized monotonically, and therefore a parameterized Pareto criterion is necessary.

2.1.3. Parameters

Design goals often begin as ill-defined, common-language descriptions of the intended functionality of the design outcomes (Goel & Pirolli, 1992). Parameters in this model operationalize the goal(s) of the design problem, differentiate individual elements from one another through comparison of the elements' values along the parameter, and allow preference order to be assigned along that parameter.

A goal can potentially be operationalized using different parameters and membership criteria, resulting in different design spaces. For example, a design goal to "move people efficiently from point A to point B" may be operationalized using the parameters speed and fuel efficiency; or it may be operationalized using the parameters average journey time and passenger capacity. The first operationalization may direct a designer towards more efficient single occupancy vehicles as a solution, while the latter may hint at multimodal mass transit.

Parameters can be operationalized at different levels of precision, ranging from binary qualitative parameters to continuous parameters (Stevens, 1946). At the lowest end of the scale are binary parameters, which have two possible values. In the context of

design, these may represent the presence or absence of a design feature, which is given the special label of a "feature parameter". An example of a feature parameter is whether a design solution has wireless internet capabilities or not. The other possibilities in increasing order of refinement and precision are categorical, ordinal, and continuous parameters. Categorical parameters have discrete values that have no inherent order, such as the names of cities. Ordinal parameters are also discrete, but the values have some order to them, either inherent or imposed by designer preference. Standardized component sizes, such as valve sizes or wire gauges, are examples of inherently ordinal parameters, as they are ordered in increasing size. Binary, categorical, and ordinal parameters can all have either qualitative or quantitative values. Continuous parameters on the other hand have values that may be any real number and are therefore quantitative by nature. Speed or mass are examples of continuous parameters.

While there exists a potentially infinite number of parameters that could characterize a design and therefore a design space, the cognitive limitations of human designers reduces this to a much smaller subset of parameters that can be attended to concurrently. This framework captures this as a designer making parameters "explicit", through their conscious consideration of a parameter at some point during the design process. Parameters can also have their explicit status discarded by the designer if they are found to be irrelevant to the design problem and its goal(s). Both processes affect the dimensionality of the design space, which is the number of explicit parameters being used to characterize the design space at any time. Designers make parameters explicit to characterize a design based on their subjective understanding of the problem, and different designers may use different parameters to describe the same problem.

An example of a parameter being made explicit is a designer considering whether the colour of a car may influence the top speed. In this scenario, the designer makes the parameter "colour" an explicit parameter of a design space with a goal operationalized along the "speed" parameter, increasing the design space dimensionality by 1. If the designer then decides or determines that the colour of the car has no relationship to its

speed, then they may decide to either discard the colour parameter from consideration or maintain it as a purely categorical parameter with no bounds or preference order.

The introduction of membership criteria can result in the addition of explicit parameters and conversely, making a parameter explicit can also drive the consideration of new membership criteria. Returning to the previous car example, an example of membership criteria introducing further explicit parameters could be the marketing department providing information on the sales figures of different coloured cars and imposing a new goal for minimum sales for the new car being designed. This sales goal may lead the designer to the explicit incorporation of colour as a parameter, with bounds and preference order being imposed on that parameter by the previous sales data. An example of the converse may be that considering the ergonomics as an explicit parameter when designing a pen may lead to the setting of ergonomics requirements.

Parameters can also be associated with other parameters, and new parameters may be introduced and made explicit by their association with other parameters, by the designer proposing a solution concept, or through the evaluation and consideration of a solution concept. For example, a qualitative parameter that characterizes the form/operating principle of a writing implement may have discrete values of pen, pencil, chalk, etc. Each of these may introduce associated parameters, for example selecting the value of pen would introduce parameters related to ink colour or viscosity, while a pencil would introduce parameters related to the graphite.

Parameters can also have hierarchical structures, where a parameter can be decomposed into several sub-parameters, or several parameters can be subsumed into a higher level, more abstract parameter. An example of decomposition could be a parameter of mass being divided into density and physical dimensions.

Covariance and causal relationships between parameters can also exist, with changes in the value of one parameter affecting the possible values of another parameter. In fact, antagonistic relationships between parameters are responsible for trade-offs in this

model. Consider an example of a design problem where the goals are to minimize the weight of a support beam while meeting the strength requirements. In this situation, the designer chooses to use steel I-beams as a solution concept and frames the problem accordingly, including the solution parameter of cross-sectional area. In this frame, the beam's strength is inversely proportional to its cross-sectional area, while the beam's weight is directly proportional to its cross-sectional area. This means that the two parameters are antagonistically related, mediated by the parameter of cross-sectional area.

Since this model contains both problem structure parameters and parameters that describe the design solution, a distinction is made between evaluative and non-evaluative parameters. This distinction is important because the designer will only determine solution preference on evaluative parameters, but non-evaluative parameters are the decisions that influence the performance on the evaluative parameters.

2.1.3.1. Evaluative Parameters

Evaluative parameters are analogous to a multi-objective function in optimization. These parameters operationalize the goals and requirements imposed upon the design problem. Values on evaluative parameters are how designs are evaluated both against each other for preference and against the goals and requirements that place bounds on these evaluative parameters. The sum of all the goals, weighted by the prioritization or relative importance assigned to a goal, is the overall preference function of the design.

For example, a design problem to design a new racing vehicle may have two goals, to increase top speed and to improve fuel efficiency, and these two goals are directly antagonistic in the current design space. Both goals contribute to the overall preference function, so design solutions that move towards either goal are more preferred and solutions that move away from a goal are less preferred. Since the two goals are antagonistically related and equally weighted, it will result in a set of solutions that have equivalent preference rankings but different combinations performance towards the two goals, the Pareto optimal set.

However, the design team may choose to either prioritize the goal for top speed, as it will help the vehicle outpace its competitors, or they may choose to improve fuel efficiency so that they need to stop less often for refuelling, avoiding time lost in the pits. If they choose to prioritize top speed, the objective function would be influenced more by design solutions that improve top speed than those that improve fuel efficiency, which is represented by a weighting factor that scales the impact of each goal to the overall preference function.

It is important to note that the evaluative parameters can represent many different forms of goals, which were outlined in Section 2.1.2.1 above, so this preference function can become quite mathematically complex and potentially computationally intractable.

For the purposes of this model, it is assumed that this preference function exists in a generalized form that is assessed by the designer, either through subjective judgements or by objectively calculating a preference function. These judgement calls on solution preference are based on a combination of the explicit information available to the designer and latent conscious or subconscious factors like fixation biases (Jansson & Smith, 1991). These judgement calls may not represent the mathematical optimal, or even the rational decision (Simon, 1956), but they provide the preference order on the evaluative parameters that is a necessary condition for trade-offs to occur.

2.1.3.2. Non-evaluative Parameters

Non-evaluative parameters are any other feature that can be used to distinguish individual designs from each other but are not used to assess the performance of a design solution (i.e., there is no preference order placed upon the values of the parameter). While non-evaluative parameters are not explicitly preference ordered, they can be tied to evaluative parameters so that the value chosen on a non-evaluative parameter directly or indirectly affects the value of an evaluative parameter, thereby indirectly affecting the preference order of designs. An example of this is the addition of a binary feature parameter describing the presence or absence of a feature that allows the design to meet a requirement that was outside of the viable design space.

Making a new non-evaluative parameter explicit and then choosing alternate values on it may also affect the interaction between other paired parameters, both evaluative and non-evaluative. For example, if two parameters in a space have an antagonistic relationship, leading to a Pareto frontier, it may be possible to alter the nature of that relationship so that it is no longer antagonistic. Returning to the train example used in Section 1.2.1.2 to explain TRIZ, a concrete example of this would be introducing magnetic levitation as a feature to trains, which completely nullifies the relationship between speed and rolling friction that limits the top speed of conventional locomotives. The magnetic levitation could be framed as a simple binary feature parameter (i.e., maglev present or not), or as an alternative value of a higher order parameter of "support type", indicating a hierarchal and compositional relationship between parameters. The top speed is still limited by other parameters such as air friction and electromagnetic parameters, but the limit on the top speed is higher, allowing the original limit to be circumvented and exceeded.

2.1.4. Pareto Frontiers

Formally, a trade-off situation can be described by the associated concepts of Pareto optimality and Pareto frontiers. An element is Pareto dominant when no parameter can be improved without an associated loss in at least one other parameter (Schulz et al., 2018). The Pareto frontier is defined as the set of elements where each element exhibits Pareto optimality, or alternatively, where there exist no elements which Pareto dominate it (ibid.). An element is Pareto dominated when there exists the potential for a Pareto improvement, which is a new element where gains can be made on a parameter(s) without any parameter(s) experiencing a loss (ibid.).

However, for a classic Pareto relationship between parameters to occur, all the parameters involved must be characterized at an ordinal level with a monotonic (i.e., continuously increasing or decreasing) preference direction at a minimum (Malak & Paredis, 2010). This is because Pareto dominance cannot occur if designs cannot be

monotonically ordered in terms of desired performance with respect to the parameters in question. Malak and Paredis (2010) proposed an expanded definition of Pareto dominance, which they called parameterized Pareto dominance, that can be applied even when one or more of the parameters in the design space is non-monotonic, and this is the definition used in this model. The new criterion for Pareto dominance is that a solution y″ is Pareto dominated by a solution y′ if the following three conditions are met:

1. The value of every non-monotonic parameter describing y′ is equal to the value of the same parameter in y″.
2. For every monotonic parameter, the value describing y′ is equal to or greater than the value of the same parameter in y″.
3. At least one monotonic parameter describing y′ has a value that is greater than the value of that same parameter in y″.

These conditions effectively apply classic Pareto dominance to the system, provided the values of all non-monotonic parameters are equal. One solution cannot dominate another if their values on a single non-monotonic parameter are not equal, and therefore both of these solutions would be a member of the Pareto optimal set. These conditions also mean that the Pareto dominance criterion reduces to classical Pareto dominance when all parameters in the design space are monotonic.

These parameterized Pareto dominance criteria are a formalization of optimality that aligns with the more colloquial concept of a trade-off. The Pareto frontier is an attribute of a design space that represents one form of boundary to the design space for a problem. Each Pareto frontier is associated directly with the current formulation of the design space that it bounds and changing either the membership criteria or the parameters of that design space can potentially alter or eliminate these Pareto frontiers. A Pareto frontier occurs due to a conflicting or antagonistic interaction between two or more parameters, either directly or through a series of indirect interactions between

other parameters. Figure 1 below provides a visual overview of a design space described by two parameters, two requirements, and a Pareto frontier between the two parameters.
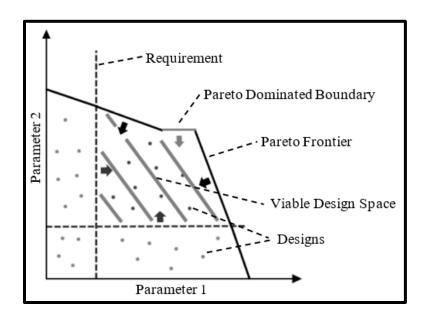
FIGURE 1. DIAGRAM OF DESIGN SPACE COMPONENTS

In design, the set formed by the mathematical intersection of a Pareto frontier and the membership criteria representing the goals along a set of parameters can drive the formation of a null design space, where no viable solutions exist, as in Figure 2a below. A typical design response to this situation is the relaxation (i.e., negotiation) of one of these boundaries or goals such as in Figure 2b, although this is generally viewed as a suboptimal approach (Gero & Kumar, 1993). Pareto frontiers can also occur in a design space with a non-zero viable region, for instance, if there are designs that meet all minimum requirements or goals of a project, but the designers are not satisfied with the performance of those solutions and want to design a better solution (ibid.).

2a   2b
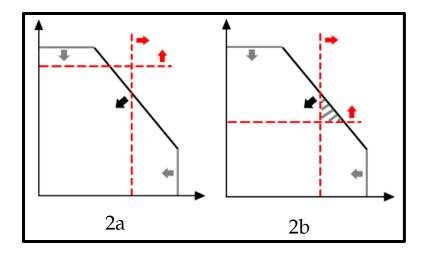
FIGURE 2A. A NULL DESIGN SPACE AND 2B. RELAXING A REQUIREMENT

2.2.   The Influence of Human Designers on Design Spaces

At this point it should be reiterated that the design space representation outlined above is a descriptive abstraction of a design situation that will be used to illustrate the potential approaches to resolving trade-off situations. The design space itself is typically too complex to characterize fully at any given instant due to the large number of theoretically viable solutions, parameters and constraints, and it evolves as the design process proceeds. The introduction of Pareto optimality and frontiers should not be taken as a recommendation that designers precisely characterize the design space to locate these frontiers, as in an optimization approach. Instead, the design space representation should drive inferences that will aid designers in their metacognitive awareness of what a trade-off entails and how it came to be.

Given the complexity and prohibitive resource cost of perfectly characterizing the design space, it is important to consider how human factors and limitations may affect how designers cognitively model and interact with their design spaces in practice. Designers' limited cognitive models of the structure and properties of their design spaces impose both conscious and subconscious limitations on the design solutions under consideration.

26

2.2.1. Cognitive Information Processing Limits

Human cognition has limited information processing capacity (Miller, 1956; Simon, 1969), which limits the capability of designers to model the entirety of the design space and the decisions they make based on those models. Even considering only explicit parameters, as detailed above, complex design situations often involve too many explicit parameters for human designers to consider simultaneously (Miller, 1956). Furthermore, if the designers cannot consider all of the relevant parameters and their interactions simultaneously, they cannot pre-emptively predict all of the potential consequences of a decision on one of those parameters (Schön & Wiggins, 1992)

Instead, this model adopts the framing perspective of Schön (1983), where designers will operate with a set of active explicit parameters that they choose to attend to, with parameters shifting in and out of active cognition as attention is paid to them. These active explicit parameters are the frame through which the designer chooses to structure a portion of the design space, and this can influence how they model conflicts between parameters.

The phenomenon of sudden mental insight, colloquially called the "aha!" moment, has been described as a problem reframing or restructuring (Akin & Akin, 1996). As the designer's perception shifts, these changes of focus drive new insight into problem structures and dramatically effect the final design solution (Chandrasekera et al., 2013; Suwa & Tversky, 1997). This phenomenon is modeled as a shift in the set of active explicit parameters the designer is using to frame the problem.

2.2.2. Fidelity of Cognitive Model

Because human designers have limited information processing capacity (Simon, 1997), they generally rely on heuristics, assumptions, previous experience, and other tools to simplify their cognitive models of the design space. Such simplifications may introduce biases and errors relative to the objective design situation, and presuppositions about the potential range of viable solutions in a given design space. For example, a designer

might have presuppositions about what solutions may be viable for a problem based on previous experience, heuristics, training, or other factors (Crilly, 2015). These presupposed limits to viability represent the boundaries that the designer believes are on the design space, and these limits may or may not represent the actual boundaries of viability.

These presupposed limits have a benefit of restricting the design space to be more manageable for the designer, but they may also artificially restrict the design space and eliminate possible solutions that outperform the designer's preconceived limits. In the context of trade-offs, this can be represented by the designer assuming a Pareto frontier exists at particular combinations of values along the intersection of the parameters in conflict, while the actual Pareto frontier exists at different values of those parameters, which potentially dominates the perceived frontier.

2.2.3. Knowledge Base and Situatedness

Incomplete or imperfect knowledge, either at the individual or at the societal level, affects the changes a designer can make consciously to the design space. If designers do not have access to the knowledge necessary to conceive of certain viable solutions, then those solutions are effectively placed outside the bounds of viability of that particular designer's design space until they attain that knowledge (Hatchuel & Weil, 2009). Designers with a broader or more relevant knowledge base may be able to conceive of these solutions, thereby including them in their design space. This notion has been called situated designing, where designers' unique experiences and environment leads to different results for a given design process (Gero & Kannengiesser, 2007). In effect, this introduces variability of design spaces for different people approaching the same problem with the same framing.

2.2.4. Design Process in Practice

Literature on design practice shows that designers do not typically perform an exhaustive search for all viable designs before deciding on the preferred solution.

Instead, the typical design process involves a seed idea that is then developed into a family of designs by iterative changes (Crilly, 2019a; Hatchuel & Weil, 2009). Furthermore, these iterative changes include series of arbitrary decisions that initially pass with their importance unnoticed, but limit the design space (Crilly, 2019b).

Within the context of this design space model, these decisions have the effect of imposing further boundaries on the design space, which reduces the size of the viable design space. Additionally, the dimensionality of the space may also be reduced through these decisions collapsing parameters onto single values by the designer "locking in" a value on that parameter, either permanently or temporarily. Indeed, the process of design could be approximated as the progressive reduction of the design space until a single solution is selected at the end. This reduction can be reversed, redirected or reset by the re-evaluation and alteration of a solution concept, problem reformulation, and the coevolution of the problem with the development of solutions (Dorst & Cross, 2001), but at the end of a design process a solution is identified within the design space or the design problem remains unsolved.

2.3.   Navigating Trade-offs by Manipulating the Design Space

The core of this thesis' argument is that there exist forms of trade-offs that are inherent only to the design space as the designer has currently formulated and framed it. By establishing this link, it can then be proposed that for these trade-offs an alternative method of resolving them exists: the manipulation or alteration of the explicit design space (i.e., the set of all explicit parameters and membership criteria) itself. This differs from the approach to trade-offs found in the design optimization and decision-making literature, which focusses on how to select the best option within a set design space (Schulz et al., 2018).

By altering the design space, the designer has the capability to alter the location of the Pareto frontier within the space, effectively manipulating the trade-off situation itself. Manipulating and altering the design space can take on one of two forms based on the

formalization of the design space as a mathematical set: either altering the set membership criteria or the parameters used to characterize the elements.

Altering the membership criteria for the set can take a variety of forms, as many things can contribute to the determination of which solutions are viable. Negotiating requirements and imposed constraints, improving technological capabilities, and adjusting the problem framing are all possible mechanisms for altering the set membership criteria.

The parameters of the design space can be influenced in multiple ways as well. For example, parameters can be added to the design space by being made explicit; they can be combined, decomposed, or substituted into alternative representations; they can be collapsed by "locking in" decisions, or expanded again by revisiting a previous decision.

With respect to navigating trade-offs, both approaches to manipulating the design space have merit but the mechanisms used to manipulate the design space vary in effectiveness and desirability. For example, while negotiating a lower requirement for an attribute like an emissions target (or even dropping that goal from consideration altogether) may make it possible to resolve a trade-off between that goal and the cost of the design, most would view this as sacrificing one of the goals of the design.

Of particular interest are mechanisms that allow designers to "bypass" the Pareto frontier in the original design space, without negotiating or sacrificing the goals of the design. Mechanisms to do this vary based on what factors are driving the Pareto frontier's existence, but examples include altering the dimensionality of the design space or changing the operationalization used for a goal. In design terms, this may include making another parameter explicit that influences the values of parameters involved in the trade-off.

For illustration of how this facilitates bypassing a trade-off see the design spaces in Figures 3 and 4 below, which show the addition of a discrete parameter and the

addition of a continuous parameter respectively. Figures 3a and 4a show a design space with two parameters, which are directly antagonistic. As the parameter values "increase" along parameter 1, they "decrease" along parameter 2. If the designer wants a solution that has a value of 3 for parameter 1 and a value of 10 for parameter 2, that is not possible in the current design space. However, if the designer makes explicit a third parameter that has a relationship with the two original parameters, as in Figures 3b and 4b, then it may become possible to create designs with alternative values on the third parameter and obtain the target values for parameters 1 and 2.
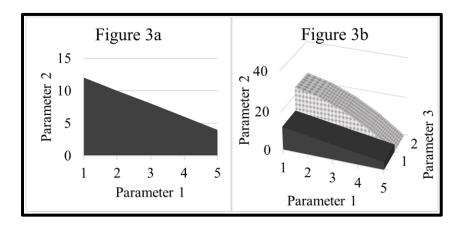
FIGURE 3. DESIGN SPACE EXPANSION THROUGH THE INTRODUCTION OF A THIRD, DISCRETE, PARAMETER
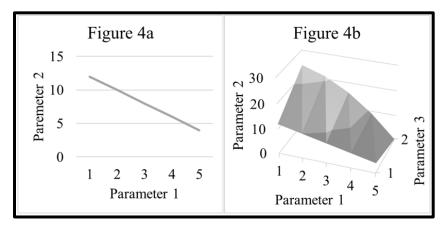
FIGURE 4. DESIGN SPACE EXPANSION THROUGH THE INTRODUCTION OF A THIRD, CONTINUOUS, PARAMETER

Consider a simplified example where a designer encounters a trade-off between the strength of a steel beam and the weight of that beam. A potential mechanism this

designer could use to bypass this trade-off as it currently exists is making explicit additional parameters that could affect the viability of the design, such as the material of the beam or the cross-sectional shape of the beam. As the designer explores different values of these new parameters, the relationship between the original evaluative parameters of interest (strength & weight) changes. The selection of a different material, or a differently shaped cross-section, may allow the designer to improve the strength of the beam relative to the original trade-off without increasing its weight. By altering the dimensionality of the design space in this example, it becomes possible to travel along the third dimension to navigate beyond a Pareto frontier that was previously restricting the design space. While the example presented above was restricted to 3 dimensions for easier graphical illustration, in principle dimensionality changes can alter the size and shape of the viable design space at any level of dimensionality.

2.4.   Summary of Theoretical Framework

The theoretical framework presented in this chapter allows design trade-off situations and the designer's framing of those situations to be modeled at discrete points across the design process. It uses a set theory foundation to formally model the concepts of problem formulation and problem framing in design. Problem formulation is defined within this framework as the evaluative parameters and membership criteria that are used to operationalize the goals of the design; while problem framing is all of the parameters and membership criteria that the designer is currently attending to (i.e., the active explicit design space).

However, this framework is a descriptive model that captures discrete instances of the frames and how they change based on the design process, and not a process model meant to explain the underlying cognitive strategies that the designers use to design.

As a descriptive model, it will be used in Chapters 4 and 5 to model the trade-off situations designers encounter, and to model if their explicit design space changes during their attempts to resolve those trade-offs, and if it does, how does it change.

Given that a designer's explicit design space is subjective and constructed, these models will reflect the designer's perceptions of the trade-off (i.e., which parameters they believe to be tied to the performance on the goals in conflict).

While the design spaces investigated later in this thesis reflect a designer's subjective understanding of the problem based on their formulation and framing, there remains a link to the real-world objective performance of a finished design. Finalized design solutions operating in their intended functional environment will have a real-world performance on the evaluative parameters formulated by the designer that reflects all the influences on those evaluative parameters, not just those explicitly considered by the designer during the design process. Furthermore, even if the designer has explicitly included a relevant parameter, they do not necessarily have a precise understanding of how decisions on that parameter influence performance on the objective parameters (Schön & Wiggins, 1992). Modeling how a designer's explicit space changes can show how designer's perceived framing of the trade-off changes as their understanding of the problem grows, demonstrating problem-solution co-evolution in the context of trade-offs.

Another layer of subjectivity in trade-off situations is that the evaluative parameters themselves are subjective, based on the designer's or other stakeholders' operationalization of the underlying design goals. If the goals of the design are operationalized differently, the problem is reformulated, and the resultant design space may be different from the original formulation. Combined, all these layers of subjectivity point to the fact that designers can manipulate their formulation and framing of a design problem in their attempts to resolve a trade-off between conflicting goals.

Going further, this model indicates that optimization within the context of design can only verifiably prove a local optimum point or Pareto set. Since the output of an optimization model is dependent on the goals, constraints, and explicit parameters that

are used in the model, all of which depend on the designer's formulation and framing of the problem, the output of that optimization is local to that specific formulation and frame. This is why it is possible to attain a design that Pareto dominates a previously optimal set through reformulation and reframing the design space.

Chapter 3 – Methodology

The literature on design trade-offs provides little insight into how designers formulate and frame the trade-offs they encountered in practice, and how they manipulate their formulations and frames to resolve those trade-offs. This study intended to explore this gap and to answer the last three research questions presented in Section 1.4. An exploratory methodology was chosen to investigate these issues, using an interview methodology to capture practicing designers' experiences and perspectives.

3.1. Participant Recruitment

Participants for this study were recruited using a combination of search and referral strategies. The primary criteria for participation were that the participants were engaged with some form of design tasks in their daily work and had recently confronted a trade-off between goals or comparable situation on a project. A secondary, preferred, criterion was that they had resolved the trade-off so that all, or most, of the goals of the design project were achieved, but this was not a mandatory criterion.

Referrals were requested from a professor in charge of a graduate engineering design program and the directors at two start-up incubators associated with a university, which resulted in six of the nine interviews. The remainder of the interviewees were recruited from the researchers' personal networks.

The primary points of contact for the referrals were asked if they could disseminate the study recruitment materials, including the study information letter, to individuals or organizations in their network that "were currently or have recently dealt with a challenging design trade-off (with a focus on those that resolved the trade-offs without significantly compromising the initial goals in conflict)".

Once the initial contact had been made with a potential participant, a second email was sent to provide them with further study details and arrange the interview time.

Following the pilot interview, this email was also expanded to request that the participants pre-emptively prepare by "recalling situations you have encountered in your design work where you have had a trade-off between two or more goals of your design". This was added to the recruitment materials to maximize the portion of the interview that could be focused on investigating the trade-off situations and the network of influences that affected the interviewee's response to those conflicts.

After the 4th interview, the language of this preparation statement was altered to "recalling situations you have encountered in your design work where you have had a conflict between two or more goals of your design". This was done because the participants were interpreting trade-off situations based on the resolution, not the problem situation. This meant that they were only providing examples of situations where they had chosen between goals in conflict, prioritizing some and sacrificing others. Since the purpose of this study was to investigate ways that designers use problem reformulation and reframing to resolve conflicts, the language was altered to be more neutral on the outcome of the conflict.

A total of nine interviews were conducted, and the demographics of the sample are summarized in Table 1 below. The interviewees came from diverse organizational contexts ranging from student design teams to large and complex organizations with several thousand employees. The industries and problem spaces were also quite diverse, although all participants engaged in engineering design, and not other forms of design like architecture or industrial design. In contrast, the sample was comprised of engineering designers who were all trained at the same university, either at an undergraduate or a graduate level. Lastly, the designer's self-reported length of experience is also included, and here there was less diversity. Designers were mostly early career, with one notable exception in I1 who had transitioned to consulting after several years as a designer.

Participant Code	Industry	Organization Type	Problem Space	Self-Reported Length of Experience (years)
I1	Robotics	Consultancy	Remote Piloted Delivery Robot	11
I2	Automotive	Student Design Team	Hybrid Vehicle Transmission	6
I3	Robotics	Student Design Team	Robotics Competition	8
I4	Building Systems	Large Firm	Refrigeration Systems	4
I5	Automotive	Start-up	Electronic Controls Hardware	3
I6	Software	Start-up	Accessibility Application for Language & Speech	3
I7	Healthcare	Consultancy	Healthcare Device User Experience	3
I8	Software	Large Firm	Accessibility Applications for Public Transit	5
I9	Automotive	Large Firm	Automated Tolerance Gauge	3

3.2. Interview Protocol

A qualitative interview study was performed to explore the experiences of designers resolving design trade-offs in practice, and to explore the extent to which the theoretical framework captures designers' experiences in practice. These interviews were semi-structured and used open-ended questions to allow participants the freedom to express their experience using the language most comfortable to them. The flexible nature of the interview approach allowed the interviewees to describe the situation in their own words with rich contextual detail and allowed the researchers to probe into emergent points of interest that presented themselves in the interviewee's descriptions of the

cases. The trade-off situations were investigated using a relatively unstructured prompt for the designer to describe the situation in their own words, followed by a series of probing questions structured using an adaptation of the echo-method (Cunningham, 2001).

The echo interview technique was originally proposed by Bavelas (1942) and is well-established as being useful and reliable approach for studying interactions associated with networks of interdependent tasks and responsibilities, from the perspective of those individuals involved (Barthol & Bridge, 1968; Duimering et al., 1998). The echo interview process is a semi-structured questioning technique aimed at uncovering an underlying network structure of influences that is implicitly presumed to exist (Bavelas, 1942; Cunningham, 2001). This network of influences is comprised of nodes, which can be other people that influenced the design process, or they could be technical and structural influences that affected the designer's design decisions. The network also contains connections between nodes which represent the influences each node has on the other. Previous studies have used similar adaptations of Bavelas' method to study how socio-technical interactions influence requirements engineering (Safayeni et al., 2008), Ashby's Law of Requisite Variety in the context of manufacturing systems (Duimering et al., 1998), and how computer gamers experience game situations within first person shooters (Clarke & Duimering, 2006).

A summary of the interview protocol is presented in this section, but for the detailed protocol the reader can reference 0. In the first portion of the interview the participants were asked to describe the trade-off situation(s) they encountered and the decisions and approaches they used to resolve it in their own words. The researchers took notes on any potential influencing nodes as the interviewees described the situation. These notes were referred to later in the echo method portion of the interview to inform probing questions.

The interviewees were asked to identify the human and technical influences that affected or influenced their decisions and approaches to resolving their trade-off. Each of these explicitly recognized nodes was recorded and combined with the list of implicit nodes the researchers identified during the participants' open-ended descriptions. Interviewees were asked to highlight key influences that were particularly impactful, so that the interviewer could prioritize them if there were too many nodes to investigate each in detail within the interview period.

The remainder of the interview period was then spent attending to each influence in detail by asking the following questions for each influence:

1. Can you provide specific examples of actions taken by (*stakeholder/influence*) that were helpful for dealing with a trade-off?
2. Can you provide specific examples of actions taken by (*stakeholder/influence*) that were not so helpful for dealing with a trade-off?

Following the 6th interview, the official language of the script was updated to:

1. Can you provide specific examples of actions taken by (*influence*) that made it easier to come to the solution that you did?
2. Can you provide specific examples of actions taken by (*influence*) that made it more difficult to come to the solution that you did?

The change from the "helpful/unhelpful" terminology was made in response to some of the interviewees' explicit reluctance to label colleague's or other people's actions as "unhelpful". In the interviews prior to officially changing the interview protocol, the semi-structured nature of the protocol allowed the questions to be clarified in-situ, and the terminology of "making it easier/more difficult" was used unofficially for this purpose.

In addition to the audio and video transcription, several participants included slides, images, props, or other demonstrations to aid the research teams understanding of the

design trade-off they were describing. The transcriptions of the interviews were initially compiled through the built-in auto-transcription feature of WebEx (Cisco, 2021)but were then manually reviewed and corrected for accuracy to the recorded video and audio.

Chapter 4 – Case Study Analysis

Over the course of the nine interviews performed, the participants discussed eleven distinct design problem situations. Each of these eleven problems discussed had instances of trade-offs between goals. Some of these problems only described a singular trade-off and its resolution, while others presented more complex narratives that included a series of linked trade-offs that they needed to attend to. In some instances, the decisions made to resolve one trade-off resulted in a subsequent trade-off elsewhere in the design. The instances where the designer described resolving or attempting to resolve multiple linked trade-offs were treated as single cases.

To answer the second research question of this thesis, these eleven distinct problems were treated as eleven separate case studies, which were analyzed using a case study approach (Yin, 2017). The goal of this analysis was to identify the way the interviewee's framing of the trade-off, and how their response to the trade-off altered that framing, if at all.

The remainder of this chapter is organized as follows: Section 4.1 presents the methodology used to summarize, model, and analyze the approaches the designers used to resolve the trade-offs they encountered; Section 4.2 presents the results of the analysis, which were a series of response types classified by how they altered the designer's explicit design space; and finally Section 4.3 discusses the findings of the analysis and presents the limitations of the analysis methodology used. A more detailed presentation of the case study narrative summaries and the analytical models is available in Appendix AAppendix B.

4.1. Analytical Procedure

The second research question of this thesis, "Do designers use reformulation and reframing to resolve trade-offs between their design goals?", required that the trade-offs

the designers perceived and communicated in their interviews be identified and modeled. To identify the patterns of responses used by the designers to resolve their trade-offs, the cases were summarized and compiled in chronological order. This facilitated the identification of the designer's initial explicit design space, the decisions they made that altered that space, and how the final explicit design space resolved the trade-off.

The analysis proceeded at the level of a designer's perceptions of the trade-off situation and their decisions within in it, as the cases were constructed from interview accounts. This was appropriate for the research question as a designer's formulation and framing of the design problem (i.e., their explicit design space) determines how they perceive to the trade-offs, and what decisions they make to resolve it.

The first step in identifying the trade-offs was to review the interview transcripts and identify the sequential order of events in the narrative presented by the interviewees. As the echo-method question structure used in the interview protocol did not proceed strictly according to event order, the problem narratives were constructed by identifying points in the transcript where the interviewee described what they perceived as causal relationships between trade-offs, decisions, and consequences (i.e., these goals were in conflict, so we did this, which led to this result.). Arranging the decisions in this way also required that the evaluative parameters involved in the trade-offs be identified, as these goals being in conflict were the reasons decisions needed to be made. These marker points were then used to arrange the cases in sequential order to facilitate the analysis of the sequences of problem, response, and results as they were perceived by the interviewees.

The explicit non-evaluative parameters that comprised the designers explicit design space were then identified in the transcripts. These parameters were identified based on the interviewees' descriptions of what was causing the trade-off on the evaluative parameters and what they changed in their solution or problem to resolve that trade-off.

42

As a result, the modeling step described in the next section only includes the parameters explicitly mentioned by the designer in the interview and represents their explicit framing of the design situation.

The unit of analysis for the study presented in this chapter was individual instances of trade-offs between evaluative parameters. These were identified from the narrative summaries with the aid of a systems modeling approach, which cast the narratives into the conceptual framework presented in Chapter 2. These trade-off narratives were then classified based on what decision the designers made, and how those decisions affect the structure of their explicit design space.

4.1.1. Modeling

The conceptual framework introduced in Chapter 2 was used to model both an initial conflict and the designer's resolution of that conflict to compare and contrast the structures of their explicit design spaces before and after their decisions.

However, the Cartesian visualization used in Chapter 2, Figure 1 to illustrate the design spaces and Pareto frontiers was ill-suited to the dataset produced from the interviews. The first reason for this was the frames used by the designers to describe their trade-off situations and explicit design spaces involved many parameters, as the smallest frame identified had five explicit parameters. It is challenging to use Cartesian representations to visualize more than three or four axes simultaneously, and the axes of the design space are the parameters.

The other primary limitation of the Cartesian representation for analyzing the dataset was that the designers described the parameters and the relationships between them in limited detail. To graph the design space using a Cartesian representative, the mathematical functions describing every relationship between parameters must be known. This presented two challenges: the level of detail provided within the interview, and the nature of the designer's understanding of the mathematical relationship. The interview approach used in this study resulted in the designers describing the

relationship between parameters in a directional manner (e.g., an increase on parameter A results in a decrease on parameter B). This was likely due to the limited time for the interview, and the challenge of explaining the detailed mathematical functions in a conversational setting. However, as discussed in Section 2.2, the designer's themselves do not always have a clear understanding of the underlying functional relationships, and instead use previous experience, heuristics, and other tools to estimate those relationships.

Combined, these limitations prompted the development of an alternative representation schema for the analysis of the designer's explicit design spaces, and how resolving trade-offs altered those spaces. Causal loop diagrams, a systems mapping approach (Sterman, 2000, pp. 137–156), were adapted for this purpose.

This approach modelled parameters as nodes in a network, with the connections between the nodes representing the relationships between those parameters. This provided several analytical benefits:

1. It could visualize design spaces with a large number of dimensions, since the dimensionality of the explicit design space is represented by the number of nodes in the network. This is contrasted with the Cartesian visualization introduced in Chapter 2, Figure 1, which can only visually represent a maximum of 4 dimensions simultaneously.
2. It can model parameters that are discussed in limited detail and the direction of their influence on other parameters without needing to understand the detailed functions that mathematically describe those interactions.
3. Interactions can be traced across multiple parameters to identify 2nd and higher order influences that affect trade-offs.

However, these systems diagrams were not without limitations themselves. The primary limitation was that individual values of parameters could not be represented clearly within the diagram. This made it challenging to represent the real underlying

Pareto frontiers between parameters, since these frontiers are the set of Pareto optimal solutions, and solutions are described by the individual values they hold on a parameter.

For the purposes of this study, this limitation was inconsequential, because the analysis occurred at the level of the designer's perception. At this level, perceived trade-off relationships, and therefore perceived Pareto frontiers, between parameters can be identified based on the designer's description of that relationship. If the designer perceives that increasing the value on one parameter will result in a lower value on another parameter, then they have identified what they perceive as the Pareto frontier between those parameters. The designer will then make decisions based on this perceived relationship, regardless if this perceived frontier is aligned with the real Pareto frontier or not, and it was these decisions that the study was focused on.

Figure 5 below provides a simplified example of how these systems diagrams modeled a design frame, but for a detailed description of the modeling approach and the models themselves please refer to Appendix AAppendix B. The explicit design space presented in Figure 5 has five explicit parameters (Scan Quality, Scan Length, Patient Movement, Patient Comfort, Bore Diameter), making it too complex to model with a Cartesian representation.

There are two evaluative parameters in this design space, "Scan Quality" and "Patient Comfort". The goals of this design project are to maximize both of these parameters. In addition to the evaluative parameters, there are three non-evaluative parameters in the explicit design space: "Patient Movement", "Scan Length" and "Bore Diameter". The "Bore Diameter" is a property of another design which the current design project attaches to, and as such its value cannot be altered, regardless of whether this would help achieve the goals or not. The remaining parameters of "Patient Movement" and "Scan Length" represent the non-evaluative parameters the designer perceives as influencing the performance on the evaluative parameters of "Scan Quality" and

"Patient Comfort". In this design space, both of the non-evaluative parameters are contributing to a trade-off between the evaluative parameters. The designer perceives that as "Scan Length" increases, the "Scan Quality" will increase while the "Patient Comfort" will decrease. On the other hand, if they allow for an increase on the "Patient Movement" parameter, the "Patient Comfort" will improve, while the "Scan Quality" will decrease. The perceived Pareto relationships can be identified by tracing the network of influences from any parameter to two or more evaluative parameters. A perceived Pareto frontier exists if decisions on the source parameter result in one evaluative parameter moving closer to its goal value and at least one other evaluative parameter moving away from its goal value.
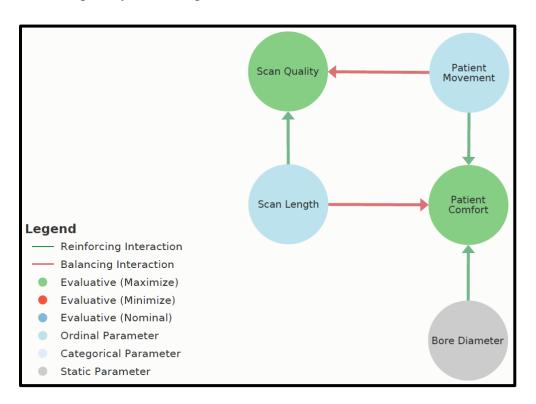
FIGURE 5: EXAMPLE OF A PARAMETER INTERACTION NETWORK FROM CASE I7

Demonstrating the other limitation of Cartesian representation, the parameters in this space were described by the designer without detailed the objective measurements from which a mathematical function describing the relationships could be derived. For example, the designer's description of the "Patient Comfort" parameter was that it was

a subjective evaluation of patient comfort, and the "Patient Movement" parameter was not given units or detailed description of how it was measured. A Cartesian representation could not model the relationship between these two parameters as they were described by the designer. Alternatively, the systems mapping approach could simply connect the two parameters based on the designer's description of the direction of the influence, which was present in the dataset.

The system diagrams outlined above, which I refer to as parameter interaction networks, were created for all eleven trade-off scenarios described by the designers, and the detailed models for each case can be found in Appendix AAppendix B. Each network modeled the designer's explicit design space and the perceived interactions between parameters within it as they described them in the interviews. These networks were used to identify both the original framing and formulation of the trade-off, and any subsequent modifications to that frame or formulation that resulted from the designer's or other's decisions in the case. By observing how the constituent parameters and interactions between them changed between the designer's descriptions of the initial design space and the resultant design space, different types of responses to trade-offs were identified and classified according to how they altered the design space, if at all.

4.2. Case Study Results

The analysis procedure outlined above identified seven distinct types of responses that the designers interviewed applied to the trade-offs they encountered. These seven responses were also classified into three categories that were defined a-priori in Section 2.3 based on how the decisions made affected the structure of the designer's explicit design space.

The first of these categories was the static space responses, where the designer did not alter the parameters or boundaries that framed their explicit design space. The second was the boundary manipulation responses. These responses altered the position of the

boundaries on the parameters that comprised their explicit design space. The last is the parameter manipulation responses, where the designer altered the set of explicit parameters that they used to define their explicit design space.

These three approaches are similar to the definitions of routine, innovative, and creative design introduced by Gero & Kumar (1993), although there are some key distinctions. Notably, the parameter manipulation responses do not necessarily increase the dimensionality of the space as in Gero & Kumar's (1993) creative design classification, as the designer can also reconstruct the space through substituting parameters without increasing the dimensionality, or potentially even remove parameters from the space.

Additionally, the differences between the designer's perceptions of their explicit design space (i.e., their predictions regarding the consequences of design decisions on a solution's performance) and the performance of a design solution in reality mean that designers can alter the perceived design space without altering the real underlying space. While this alters the boundaries of the explicit design space, it differs significantly from Gero & Kumar's (1993) concept of innovative design. Gero and Kumar's (1993) model of the solution space does not account for the differences between the designer's perceptions of a design space's form and the underlying real performance, as it only considers the real performance, so it could not account for the "Clarifying" response described in Section 4.2.2.2.

The different responses identified in the dataset are presented under the structural category they belong to, starting with static space responses.

4.2.1. Static Space Responses

Static space responses are characterized by the designer not altering the components of their design space. Instead, they attempt to create a viable solution within their original framing and formulation of the explicit design space. Three responses that fell into this classification were identified, which were labeled surrendering, prioritizing, and satisficing.

4.2.1.1. Surrendering

Failure is always a potential outcome when endeavouring into uncertainty, and design projects are no exception. When discovering a seemingly unresolvable conflict between the requirements of a design project, some of the designers expressed a desire to give up on the project, ending the project without resolving the conflict or producing a viable solution. While none of the designers interviewed ended up choosing this approach, one of the designers explicitly mentioned surrendering to the conflict as an option in case I3.

In this case, the designer was attempting to complete the design of six robots in time to meet the deadline of a robotics competition, while at the same time providing the members of their design team with sufficient experience with designing for them to learn and improve their engineering design skills. These two goals were driven by the duality of a student design team's purpose, with one aim being to compete and win, and another to provide a practical education on robotics design to undergraduate engineering students.

The interviewee was the team president of this design team and expressed that they saw two possible options for producing the parts necessary for the robot: manufacturing in house or purchasing off-the-shelf components. The conflict in this case was that the interviewee thought that they would not be able to complete the required seven robots by the competition deadline if they manufactured their components in house, but the alternative of purchasing off-the-shelf components would not provide their newer members with the opportunity to learn.

At this point, the interviewee noted that they and their team had considered quitting the competition, which would have effectively cancelled the design project. They did not end up choosing this option, because the interviewee felt that their sponsors would not accept the team not attending the competition. This was because the sponsors provided funding in return for the right to advertise on the team's robots, and if the team did not attend the competition their advertisements would not be displayed.

The eventual response in case I3 was to prioritize competition performance at the expense of the learning goals because of sponsor pressure and the internal goals of the interviewee and the team's senior members. This prioritizing approach is described in more detail in the next section.

4.2.1.2. Prioritizing

When two goals are in conflict, and the designer cannot attain both simultaneously in their current formulation and framing of the design space, they may decide to prioritize one goal over the other(s). This approach is characterized by the designer deciding to attain the required level of performance to meet one goal, regardless of the cost on the conflicting parameter(s).

In addition to the situation described in case I3 above, case I5-2 also presented an example of this prioritizing response. Case I5-2 was describing a trade-off between product price and performance, where performance was measured by the number of simultaneous video streams the device could process. The conflicting relationship between these two goals was mediated by the data transfer rate, which in turn was limited by the maximum data processing rate of the processor chip in the device. To meet the demands of this particular project, the data processing rate of the current design was insufficient to handle the four 1080p definition video streams required. One of the solutions the designers proposed was to swap the existing processor for a more powerful processor that could handle the four streams simultaneously. The conflict herein was that using a more powerful processor would result in a more costly device, which the customers also did not want. The prioritizing response to this conflict was to meet the requirement on the processor power parameter, regardless of the cost increase. This design does not technically meet all of the goals in the original framing of the design space, so would be non-viable under those membership criteria, but the designer chose to ignore one of the membership criteria to reach a viable solution on the other, conflicting parameter.

4.2.1.3. Satisficing

Satisficing is a term used in Simon's (1956) work on problem solving and is a decision-making strategy that searches for the first option that meets all the goals of project. This form of response is characterized by searching different combinations of values (different designs) on a set of parameters until the first viable solution is identified. When no viable solution exists in the current framing of the design space, a satisficing approach can also exhibit itself in combination with other parameter or boundary manipulation responses. In this case the designers stop their design exploration after the first viable solution is identified in the new design space. However, these types of responses are classified as either a parameter or boundary manipulation response, instead of as a static satisficing response, since the viable design space needed to be expanded in some way before the designer could then use satisficing logic.

One of the designers interviewed did discuss an initial, failed, attempt at using a static space satisficing response. In case I4-1, the interviewee described a refrigeration system design project for controlling the temperature of a building. The initial barrier encountered was that the designer discovered that the compressors they had chosen for the system were too small to handle the cooling load required. The designer's response to this limitation was to revisit the size of the compressor they had chosen and replace it with a larger compressor. This larger compressor did provide enough cooling capacity to meet the functional requirements of the system and had the additional benefit of increasing the energy efficiency of the system.

This is an interested facet, since while the efficiency parameter was evaluative, and the designer sought to maximize it, it was secondary to the functional goals of the system. This arrangement of priorities was a form of the prioritization response outlined above, but the overall response was classified as a satisficing response, because the designer was not attempting to maximize the primary goal on the cooling capacity. They were simply searching for the first solution they could identify that would meet all of the membership criteria and therefore be a viable solution.

51

However, the designer's attempt to satisfice all of the requirements without altering the frame encountered another trade-off that could not be solved. This was that the larger compressor increased the power necessary to drive the system. The higher power draw caused the design to violate a regulatory requirement on maximum power that applied to refrigeration systems of this type. Therefore, the satisficing response did not successfully satisfice all goals, and the designer had to look for other alternatives. The eventual successful response was to expand the design space and is covered in more detail in Section 4.2.3.1.

4.2.2. Boundary Manipulation Responses

Boundary manipulation responses are characterized by the designer altering the membership criteria at the level of their perceived explicit design space. Two responses were identified in the dataset that matched this description, which were labeled negotiating and clarifying.

4.2.2.1. Negotiating

The negotiation of requirements and constraints is a well established and well-studied response to trade-offs in design (Otto & Antonsson, 1991). The cases studied in this thesis provide further examples of this response, wherein the designer attempts to relax or remove a constraint or requirement that is involved in a conflict. This approach manipulates the boundaries of the viable design space and expands it by altering the membership criteria that define what solutions are viable.

Case I8 provided a clear example of this type of response, when they identified that a requirement they thought was immutable was actually negotiable. One of the goals in the design project described in case I8 was to reduce the data lag between accessibility service outages being logged into the transit system and that information being available to the riders of that system. There were two potential sources the current design project could use to access that data: either directly, or after it was processed by another system. The first option was to source it directly from the three systems where

the outages were initially logged, which had zero data lag, but the data was in a challenging format to integrate into the design. The second was to source it from a contractor system that was the existing solution for providing this information to the riders. The data provided by this contractor system was already processed and easy to integrate but had a data lag of 2 hours.

A key limitation in this situation was that the transit organization had some internal organizational standards that imposed requirements on design projects classified as "business critical", and one of those requirements was that there should be no data lag.

Initially the designer and their team of developers were attempting to meet this requirement by exploring the feasibility of using the direct data sources. This approach was then blocked by a development in the project caused by the COVID-19 pandemic. The pandemic caused ridership levels to plummet, causing the agency to go into financial distress. The government provided the agency with a bailout, but that bailout was conditioned on a firm deadline for completing this particular project. Due to the complex formatting of the data from the direct sources, a solution using this data would take more time to develop than there was remaining in the new project timeline. Herein was the conflict in the case, the designer could not complete the design using the direct data source within the imposed deadline but also could not use the contractor system without violating the organizational requirement on data timeliness. Therefore, the viable design space was an empty set and the designer needed to look for alternative approaches.

The approach used in this case was to negotiate the organizational constraints on data timeliness, based on an understanding of the riders' real needs. The designer estimated that 80% of riders would not be affected by a delay of 2 hours or less and presented their case to their management. The management agreed to exempt this project from the requirement that data must be presented with 0 or negligible lag that other "business critical" systems were held to. This meant that the designer could now use the

contractor's system to provide the data, which was feasible to integrate within the shortened project timeline. By relaxing the constraint on data timeliness, the conflict between data timeliness and project timeline was navigated, at the expense of the data timeliness. This sacrifice no longer affected the viability of the solution, so the viable design space itself was expanded with the addition of this one viable solution. To clarify, this response was different from discarding a membership criterion because the membership criteria was only relaxed, not fully removed.

4.2.2.2. Clarifying

The clarifying response emerges from the difference between the designer's subjective predictions of the performance of a solution concept and the real performance of that concept that accounts for all of the influences, explicit and latent. If these two are sufficiently divergent, with the perceived space being more restrictive than the real space, the designer may believe there to be a conflict or boundary where there is none in reality. This is a special case of a boundary manipulation response, since the real design space is unaltered, but instead the designer adjusts the boundaries of their perceived space to better align with the behaviour of the real space.

Case I4-2 provided an example of this response, after the designer's initial solution had been rendered non-viable by an external influence. In this case, the goal was to design a refrigeration system to cool a building, and that system contained a number of valves. Following the standards of their company and industry, the designer initially specified that a valve of size "9" should be used for this project. This size 9 valve met all of the requirements of the design, which were that it needed to allow enough cooling capacity, be under the budget of the project, and maintain a pressure loss (or drop) below an organizational "best practice" reference point. However, due to the COVID-19 pandemic's impact on global supply chains, valves of size 9 were not available for purchase during this project's timeline.

Without access to these valves, the designer did not have a viable solution to meet the design project's goals. The manufacturer who was actually assembling the system

suggested the use of size "7" valves, which they had available in their own stocks. Initially the designer was unsure if these smaller valves would work, since smaller valves increase pressure drop and decrease the cooling capacity of the system. This belief represents constraints on viability within their perceived design space, which they believe the size 7 valve to fall outside of.

Without a readily available alternative, the designer decided to simulate the performance of the system with the size 7 valves and found that it in fact met all the requirements of the project. While the pressure drop did increase relative to the size 9 valve, it still remained under the "best practice" limit imposed by their company, and the system still maintained sufficient cooling capacity to meet the functional requirements of the system. By investigating the behaviour of the parameters in reality, the designer was able to determine that their perceived limits were overly restrictive, and their perceptual design space enlarged to align with the real design space.

4.2.3. Parameter Manipulation Responses

Parameter manipulation responses are characterized by the designer actively altering the parameters that constitute their explicit design space. These alterations can be additive, subtractive, or substitutive, but the resultant design space is described by a different set of parameters than the original design space. Within the cases presented by this study's participants, both expanding (i.e., additive) and reconstructing (i.e., substitutive) responses were identified.

4.2.3.1. Expanding

The first type of parameter manipulation response identified in the case studies was when the designers attempted to expand the design space by increasing the dimensionality of the space. The designers were able to identify additional parameters to incorporate into their explicit design space that interacted with the parameters originally in conflict. When these additional parameters are added to the design space, they make a new set of parameter value combinations, or design solutions, possible. In

the exploration of this new space, the designers occasionally identified solutions that performed better on one or more of the parameters in conflict, without an associated loss of performance on the other parameters in the original conflict. This represents the identification of an element that Pareto dominates the elements in the original perceived Pareto frontier. This in turn indicates that the original Pareto frontier was only the set of locally Pareto optimal points within the original design space and the associated parameters that frame it. A representative example from case I4-1 is presented to demonstrate how a designer can add parameters to their design space to circumvent a conflict.

Case I4-1 discussed a design project with the goal of creating a refrigeration system to control the air temperature in a building. The example from case I4-1 describes a conflict that was identified when the designer's original solution did not meet one of the functional requirements of the system, the cooling capacity. The designer initially tried to revisit a previous decision on the compressor size parameter, selecting a larger compressor which would increase the capacity of the system. This approach had a side benefit of increasing the efficiency of the system, which was a secondary goal of the project. However, increasing the size of the compressor also increased the amount of power necessary to run the refrigeration system. This increase in power ended up exceeding a regulatory requirement on the maximum power draw for this class of refrigeration system. The conflict was therefore that the designer could not meet their functional goal on the capacity parameter without violating a requirement on the power parameter, resulting in an empty set for the viable design space.

 The designer's response to this conflict was to investigate additional features and components that they could add to the system, and they ended up identifying a component called a Variable Frequency Drive (VFD). The addition of this feature, which was modeled as a binary categorical parameter (present/not present), alters the design space and allows the designer to circumvent the original trade-off. The addition of the VFD allows the designer to change the rotational speed of the compressors, which also

increased their cooling capacity. This allowed the design to attain the required performance on this cooling capacity parameter. This increased compressor speed came at the cost of the efficiency gains of the larger compressors, but the efficiency of the system was still above the minimum requirements the designer had for the system. The result of adding the VFD and compressor speed parameters was an expanded design space, as it added at least one solution to the viable set. Additionally, as the compressor size and power draw of the system were now parameters with only a single value each, they could be dropped from the active design space, so this case also included aspects of a discarding approach.

4.2.3.2. Reconstructing

Beyond adding parameters to the design space to expand it, the designer also has the possibility of substituting the parameters that are currently being used to operationalize the goals of the project with other operationalizations (i.e., reformulate the problem). This substitution will not necessarily affect the dimensionality of the explicit design space (unless a goal is operationalized into multiple parameters instead of a single parameter) but has the potential to alter the interactions between the goal parameter and the other explicit parameters in the space.

One such instance was described in the first interview, I1. In this case, the designer was describing a project they were consulting on for a small start-up company. The company was looking to improve the robustness of their robots, as they were frequently breaking down on the job and forcing the company to take them out of service for repairs. The interviewee was brought on as a consultant to help improve the design's robustness. The conflict in this situation was that the project also had a goal to keep the project's timeline as short as possible. This goal, which the interviewee described as vague and ill-defined, interacted antagonistically with the goal to increase robustness in the designer's perceived explicit design space. These two goals were in conflict, and it was evident that the designer believed they were operating on the Pareto frontier of

these two variables, since they thought that they could not increase the robustness further without extending the project timeline.

The designer and the rest of the start-up team were spending a significant amount of time debating the merits of either sending portions of the design out to be manufactured earlier but in a less mature state versus waiting longer to refine the design further before starting to manufacture. This represents them comparing different members of a Pareto optimal set, which itself is an optimizing response.

However, the CEO of the company altered the design space by recognizing that a common goal underlying both of the evaluative parameters in the original formulation was to save the company money. This reformulated the goal of the design into a new evaluative parameter, "cost to company". The CEO also clarified that for every week the robots were not operating, the company lost $25,000 in potential revenue. This characterized the functional relationship between the value on the timeline parameter, which was no longer evaluative, and the performance on this new evaluative parameter.

In this new explicit design space the designer was still concerned with improving robustness while reducing the amount of time spent on the design project, but the conflict was "one-dimensionalized" to use the interviewee's terminology. Since the goal that was previously operationalized into two parameters was now being evaluated on a single parameter, the goal conflict no longer existed, as a monotonic parameter cannot conflict with itself. Instead, the goal of the design project was to minimize the cost to the company, and the two-dimensional Pareto set was collapsed to a single optimal point.

Interestingly in this case, the reconstruction did not actually bypass the original Pareto frontier, as it merely reformulated the parameters used to operationalize that conflict, while maintaining the trade-off. However, the designer did state that this new formulation of the design space made it easier to make decisions, because the decisions could be evaluated based their influence on the "cost to company" parameter.

4.3. Discussion

The different responses to trade-offs identified above provide insight into how a designer's framing of their design space can influence the performance of the final design. When goals are in conflict, as in a trade-off, operating in a static space can prevent a design project from achieving all its goals. Even though an attempt to optimize within a static space can potentially produce Pareto optimal solutions to a trade-off, which are the best possible solutions in that explicit design space, the project will not be a complete success if that level of performance is insufficient to meet the goals.

Conversely, the boundary and parameter manipulation responses allow the designer to manipulate the structure of the design space itself and in doing so alter the Pareto frontier. Through these methods, some of the designers successfully resolved trade-offs so that all goals could be attained.

As a result, parameter manipulation responses offer an interesting potential for meeting design goals that are not as highly prioritized by project stakeholders. Examples of these include goals limited to a relatively small subset of the population, such as the people with disabilities that were stakeholders in cases I6, I7 and I8; or design goals like sustainability or equity that may come into conflict with parameters that are typically prioritized highly like cost and performance. When the designer encounters these conflicts, parameter manipulation responses provide an alternative to a prioritization or optimization response. By altering the structure of the design space, the designer can discover a new design space with solutions that dominate the Pareto frontier of the original space, allowing them to attend to these other goals without the associated loss on the prioritized parameters that is characteristic of Pareto optimality.

However, not all reformulation and reframing attempts are successful at circumventing the Pareto frontier. The example provided for the reconstructing response showed this, as the final solution was still within the original Pareto frontier. The reconstructing

response in this case only made it easier for the designer to identify how their decisions impacted the solution's proximity to the Pareto frontier.

Another intriguing phenomenon that was noticed in the cases as they were described by the designers was that categorical parameters with unknown values in a static space response can mimic the results of a parameter manipulation response. Categorical parameters by their nature have unpredictable influences on the other parameters in the explicit space because the values of a categorical parameter have no inherent predictable order or directionality. This means that if the designer discovers or introduces a previously unconsidered value on that parameter, choosing that value can affect the way that parameter influences the other parameters in the space in unpredictable ways. There exists the potential that the new parameter value expands the design space and allows solutions that Pareto dominate the Pareto frontier of the space without that value.

An example of this occurred in case I2, where the designer was attempting to weld an extension onto a drive shaft to accommodate the addition of a new gear, but the welding process changed the material composition of the shaft. The combination of the longer length and the new material properties was causing the shaft to fail when subjected to the forces from the engine. The resolution to this conflict was that the designer ended up finding a new welding method that did not alter the material composition, and therefore maintained the strength of the drive shaft. The designer discussed the situation as a categorical parameter of different welding methods but choosing the alternative value of the "new" welding method decoupled this parameter from the material composition parameter.

A final interesting note within the dataset was the clarifying response. The presence of the clarifying response implies that designers perceived limits and trade-offs where there were not any, and then responded to those limits as if they were real. This suggests that designers may unknowingly and artificially limit the success or

performance of their design concepts through their perceptions of what is and is not viable.

4.3.1. Limitations of Case Study Approach

The case study analysis approach employed in this study has some limitations that affect the conclusions that can be drawn. The dataset used for this analysis was the subjective interpretation of the trade-off situations and responses to them as presented by the interviewees. This has several potential drawbacks for the analysis of responses to trade-offs.

An interview is reliant on the participant's recollection of the events, and this recollection may be inaccurate. The primary concerns for the accuracy of recollection are that human memory is fallible, as it is a reconstruction of reality filtered through people's minds and subject to several conscious and unconscious biases (Schacter, 1999). Beyond the inaccuracies of human recollection, there also is the potential for active or unintentional manipulation of the information and narratives presented by the interviewee. However, these limitations were partially mitigated by the echo methodology used the interview protocol, as the concrete and specific examples requested are harder to manipulate than the designer's more subjective and abstract opinions on the topic.

It is interesting to note that generally the designers described using a form of satisficing logic as their overall design strategy, where the design process would apparently stop once the first successful solution was found. This may indicate that the sample was biased away from optimization responses by the language in the sampling, which requested designers that had successfully resolved a trade-off.

Chapter 5 – Thematic Analysis

Designers operate in a network of influences, both human and environmental, that affect how they formulate problems, how they construct frames, and what decisions they make. This is the concept of situated cognition, which is that the one's environment affects their thinking and reasoning (Clancey, 1997), and has been identified as a feature of design reasoning and decision making (Gero, 2002; Gero & Kannengiesser, 2004; Kazakçi & Tsoukias, 2005).

The third and fourth research questions of this thesis aim at exploring and understanding the environmental and situational influences that the designers perceived as making it easier and more difficult to resolve their trade-offs, respectively. This chapter will explore these questions using a thematic analysis approach (Braun & Clarke, 2006) to identify what types of influences the designers were noting, and how those influences interacted with their formulation and framing of their design spaces. The organization of this chapter is as follows: first the methodology used to code and analyze the transcripts will be outlined; then the results will be presented, organized by theme; and finally, the findings will be discussed, and the limitations of this study will be reviewed.

5.1. Analytical Procedure

A thematic analysis following Braun and Clarke's (2006) guidelines was used to analyze the transcripts to answer RQ3 and RQ4, and an adaptation of Kurasaki's (2000) procedure was used to generate the codebook from the dataset. The thematic analysis methodology was chosen for its capacity to identify common patterns across qualitative data, and its flexibility for use in exploratory work (Daly et al., 2013). The coding scheme was primarily inductive, with codes being developed from the transcripts themselves, although the initial excerpting process utilized a deductive coding schema to organize the dataset.

The transcripts were initially coded using a pre-established deductive schema for helpful and unhelpful influences and actions. This was done to reduce the dataset to a manageable number of excerpts that were explicitly tied to the research questions, and to organize these excerpts by the designer's sentiment. These codes were applied to both the explicit responses to the echo questions in the interview (i.e., Can you provide a specific example of an action taken by *stakeholder* that made it easier/more difficult to resolve your trade-off?) and to helpful and unhelpful influences found in the interviewee's initial descriptions of their trade-off situations.

In the next round of coding the excerpts identified in the first round were reviewed, and the influences described were annotated with context-independent descriptions. These annotations were iteratively combined and revised until there was no overlap between the descriptions. An example of one of these annotations was "formal formatting of requirements discouraged questioning the rationale and the fit of the operationalized requirement to the underlying goal." A detailed list of the final consolidated annotations sorted by code is available in Appendix C. All the context independent descriptions for both the helpful and unhelpful influences were then grouped into codes based on the topic of the influence. This was accomplished using an affinity diagramming process (Haskins Lisle et al., 2020), where the annotations were clustered according to similarities, grouping them into categories to generate the codebook. The annotations were recorded on a transferrable medium (i.e., sticky notes) that allowed them to be manipulated and ordered iteratively. Clusters were developed by grouping sticky notes based on similarity, and then an overarching category name was created for the group to describe the common connecting idea between them. Returning to the example above, this annotation was combined with others like "talking with stakeholders to validate operationalization of project goals" and "reformulating a requirement based on better understanding of the goal or need that drove it" based on the common topic of operationalizing goals. This clustering process was iterated until the codes met two criteria – *internal homogeneity* and *external heterogeneity* (Patton, 2015).

The internal homogeneity criterion means that data within a code should cohere together in a meaningful way, while external heterogeneity means that distinctions between code should be clear and identifiable (Braun & Clarke, 2006). The final iteration of the affinity diagram can be found in Appendix D.

The resultant codes were then reviewed against the excerpts from the interviews to ensure that the abstraction process did not introduce meanings or concepts that did not match the underlying data. It should be noted at this point that because the developed codes were topical in nature, and an excerpt may discuss more than one topic, multiple codes can be applied to the same excerpt.

After the codes were reviewed against the excerpts broader themes were identified within the dataset. The process for this was similar to the development of codes, as an affinity mapping process of the codes themselves was performed, through the lens of the framework presented in Chapter 2. This lens was applied to see how the influences related to the designer's formulation and framing of their design space. To continue the previous example, the code of "Operationalizing Goals" was interpreted as being associated with the original formulation and framing of the design space and how it influenced the designer's decision making, along with the codes that discussed the complexity, context, and subjectivity of the initial design space. The theme of "Initial Construction of the Design Space" was identified as the common link between these codes and the design space framework.

5.2. Thematic Analysis Results

Nine codes were developed from the process outlined above, which were in turn sorted into three themes. These codes and their definitions, along with a representative example from the text of the transcripts, can be seen in Table 2 below. At least one code from this list was applied to all the helpful and unhelpful influences identified using the echo method.

Code	Theme	Code Definition	Example Quote
1. Complexity of Design Space	Initially Framing the Design Space	Excerpts that discuss how many parameters, interactions and other forms of complexity exist within the design space.	"Just designing a space with so many rules and so many limitations is more difficult than if this was a consumer product." – I7
2. Context of Design Space	Initially Framing the Design Space	Excerpts that discuss aspects of the design's functional environment that affect the design space.	"If we wanted to have a part produced it's going to be probably 5 to 8 times more expensive then producing the same exact part in China. So, obviously, if we want to make the same part, it's going to cost us more money compared to teams in China or teams in USA. " – I3
3. Operationalizing Goals	Initially Framing the Design Space	Excerpts that discuss the operationalization of the design project's goals into the requirements, constraints, limits and parameters of the design space.	"That's kind of why trying to emphasize the cost was a confounding factor. Like, it wasn't one of those two variables that mattered, but it was a rabbit hole that we were going down." – I1
4. Subjectivity of Design Space	Initially Framing the Design Space	Excerpts discussing the subjective and personal nature of understanding and constructing the design space, including the prioritization of parameters, goals and limits, as well as the differences between different people's understanding of the design space.	"They wanted us to look from the eyes of a manufacturer, how it can be done easily and using less material." – I2

5. Familiarity with Design Space	Aligning the Perceived Space with Real Outcomes	Excerpts that discuss the designer's or other's pre-established expertise and how that provided an understanding of how decisions will affect performance of a solution in its real intended environment.	"They knew what went wrong, so those inputs were valuable from time to time, and we always reviewed what we were doing with them, just to make sure that we are not making the same mistakes." – I9
6. Prototyping & Testing	Aligning the Perceived Space with Real Outcomes	Excerpts that discuss creating models, virtual or physical, of a design concept and testing them to improve their understanding of the consequences of decisions on the real performance of the solution.	"We generally have like a mentality of you prototype early and you prototype often, and that is definitely a useful mentality for us. It finds issues very quickly" – I7
7. Timeliness	Aligning the Perceived Space with Real Outcomes	Excerpts about when information became available to the designers.	"With hardware it's interesting because there's a long lead time between making engineering decisions and seeing how those pan out." – I5
8. Consequences of Design Decisions	Previous Design Decisions	Excerpts that discuss the impact that previous design decisions, by the designer or others, had on solving the conflict.	"That's another role that using an iPad or optimizing for iPad supported the aspect that we could have both core and fringe, because those are a lot of different words to show on one screen." – I6
9. Permanence of Design Decisions	Previous Design Decisions	Excerpts discussing whether previous design decisions can be revisited and revised or not.	"So, that reluctance to go back a step and start sketching again is kind of built into our environment of it and our company culture." – I7

Table 3 below shows how frequently each code was applied and provides the counts of helpful and unhelpful influences and actions assigned to each code. Excerpts that

discussed the same influence or action in different words or in different portions of the transcript were labelled as duplicates and removed from these counts.

TABLE 3: COUNTS OF UNIQUE CODE APPLICATIONS

Code	Frequency	Helpful	Unhelpful
1. Complexity of Design Space	15	6	9
2. Context of Design Space	33	7	26
3. Subjectivity of Design Space	23	16	7
4. Operationalizing Goals	21	11	10
5. Familiarity with Design Space	74	54	20
6. Prototyping & Testing	24	19	5
7. Timeliness	13	10	3
8. Consequences of Design Decisions	28	19	9
9. Permanence of Design Decisions	18	10	8

Table 3 is also presented graphically in Figure 6 below, to facilitate easy comparison of the relative helpful/unhelpful distributions within a code.
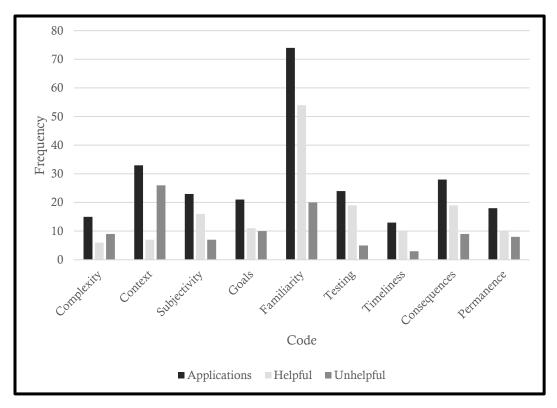
FIGURE 6: COUNTS OF UNIQUE CODE APPLICATIONS

The three broader themes identified across the codes were based on how the influence related to the designer's framing of the trade-off situation. The first theme was comprised of influences that related to the initial construction of the design space that contains the trade-off, and aspects of that design space made it easier or more difficult to resolve the trade-off. The influences under the second theme were all related to how well the designer's estimates of a design solution's performance aligned with the objective performance of the finished design, and how that alignment affected their decision making. The final theme was how the decisions made prior to the trade-off being identified affected how challenging the trade-off was to resolve, and whether those decisions could be revisited and altered.

A detailed description of the codes and themes is presented in the remainder of this section, organized by theme. Representative excerpts are provided to illustrate how the

designers phrased their discussion within each code. These excerpts are presented in a longer contextual form, containing details to facilitate the understanding of the quote in the context it was uttered. To clarify why each excerpt was coded as it was, the relevant portion of the quotes is highlighted in bold text.

5.2.1. Initial Construction of the Design Space

The first theme that was identified in the designers' responses was the importance of how the explicit design space is constructed for resolving trade-offs. As discussed in Chapter 2, the explicit design space is a constructed space, based on the parameters and membership criteria the designer is aware of and chooses to attend to. In the thematic analysis three different topics were discovered that dealt with the selection of parameters and membership criteria of the space: the context of the design project, how the goals of the project were operationalized, and the number of parameters and interactions under explicit consideration. These three topics are discussed under the codes "Complexity of the Design Space", "Context of the Design Space", and "Operationalizing Goals" respectively.

The explicit design space is also a perceived space, as a human designer is not operating in a state of perfect knowledge. These perceived spaces may have varying degrees alignment between the designer's predictions of how parameter interact and how solutions perform in their real intended functional environment, which is discussed in more detail under the theme of "Aligning the Perceived Space with Real Outcomes" in Section 5.2.2. However, within this theme, different stakeholders may have constructed different explicit spaces based on their differing goals and priorities, and the designer needed to account for this subjectivity in the construction of their own explicit design space. This subjective nature of the design space is explored in more detail in Section 5.2.1.4, under the code "Subjectivity of the Design Space".

5.2.1.1.   Complexity of Design Space

The complexity of the design space, or the number of parameters and interactions within it, was a code that primarily represents the challenges presented when working in high complexity spaces. Some of the designers interviewed noted that spaces with more goals and constraints made it far more difficult to reach a solution that met all those membership criteria simultaneously:

*"Just designing in a space with **so many rules** and **so many limitations** is more difficult than if this was a consumer product." – I7*

*"It just added a bit of time. **It added complexity, which takes a longer time to sort out**, or means (there are) **more areas that you have to go over things and do additional checks**, which takes time." – I1*

*"Same as the physical space, **it added a constraint and it added complexity**. More of a decision point." – I1*

Conversely, but on the same topic, the interviewees noted that constraining the possible values of a parameter made it easier to reach a resolution:

*"The wipe down stuff actually did make things, not specifically these problems, but the design in total, **it does actually make things easier just because you have less choice**. You pretty much have, like, 3 different finishes that are approved in that regard. In more consumer spaces you have **so many options on finishes that it can get a bit overwhelming**, whereas in the medical industry it's **1 of these 3, and they're all for different things**. So that actually did make it easier, in a weird sort of way." – I7*

*"I think (the timeline) is helpful in that it **gave us a few tangible choices to consider rather than this whole big wide-open spectrum** where we could try to land anywhere on it. It was essentially we have until today or we send it out end of yesterday." – I1*

70

Furthermore, the number of different parameters and possible parameter values also adds to the challenge of understanding the design space well enough to make decisions in it:

> *"At the moment there's a **mess of different systems that are involved and different ways that information** about lifts, information about station closures, and all this type of stuff, it's all done very separately and differently across [company name redacted]." – I8*

When the projects got more complex, or the information available was not sufficient to characterize that complexity, stakeholders sought to reduce that complexity. One of the designers noted that another team in their organization, that was focused on need identification and project ideation, would work "in a silo", ignoring the complexity of the real design situation:

> *"Their team kind of work in a silo a little bit. They come with ideas and try and go ahead and work with them. But they didn't talk with all the teams within [company name redacted]. Some teams were telling us that this is not feasible to do, and it would take a long time to do it. That's because I was talking to development teams, and to all these different stakeholders. Whereas she and her team would just go ahead and start coming up with a proof of concept. They're trying to work in a very 'we're a start-up' type of thing, but because they're working quickly but **they're not thinking about other parts of the system** and how to go forward with it." – I8*

What they meant by this was that members of this other team would focus solely on their own portion of the design, the goals, and would ignore all other influences on the problem, in an attempt to reduce complexity. This caused the designer several issues, since they were then tasked with identifying the other ignored parameters and influences in the design that restricted the design space and resolving the conflicts but had little input into the formulation of the goals and requirements that were in conflict.

As discussed in the theoretical framework, designers and other stakeholders are human, and therefore have limits on working memory and attention. As the design projects, and more specifically the trade-offs, get more complex, these limits prevent the designer from being able to simultaneously attend to all pieces of information. This in turn limits their ability to account for all the consequences of decisions they intend to make to their solution concepts or their design space, making it more challenging to predict whether a decision will help or hinder the resolution of a trade-off.

5.2.1.2. Context of Design Space

Design problems are highly contextual endeavours, with both the design process and the performance of the resulting solution being influenced by many factors outside of the designer's control. The designers in this study mentioned many of these factors that influenced the resolution of their design conflicts. As Figure 6 in Section 5.2 shows, most of the excerpts assigned to this code discussed how aspects of the context of the design made it more difficult to come to a resolution to the trade-off.

The designers found it unhelpful when project resources and limits, like budget, manpower and deadlines, prevented them from approaching a design conflict with the flexibility they felt they needed:

> *"[Company redacted] got to bail out from the government and they gave a bunch of money, **but on condition that certain things happened. One of those conditions included making sure that the app that we are developing was out by the end of the year**. Just a version of it, (it) doesn't necessarily (have) to have all the accessibility features that we were building, but the app itself had to be for Android and iOS by the end of the year." – I8*

> *"Because we can't interface with it very easily, it would be a lot of work to adjust those apps to make it so that we can interface with them. It's something that we **just couldn't do in the 1st year with the amount of time and resources we had**." – I8*

*"**Timelines are always tight, budgets are always very tight** and usually both are pretty poorly defined." – I1*

*"**He was very reluctant for us to change anything to do with the design because that would push the timelines out.** He was also very reluctant to implement the new design things we found. So, that made it difficult. We really had to examine every single aspect of keeping the design as was, before he accepted we needed to have a new design." – I7*

*"So it was one of those things we had an original work order and we had a production schedule for the 1st design. The client we were working with was a startup, so they were quite concerned about when they could get product, because they didn't have much money until they started selling product. **So they were reluctant to accept that there needs to be another design phase entirely** and that that timeline was no longer applicable." – I7*

Other than limits driven by project resources, which can possibly be negotiated with enough effort and rationale, the designers also struggled with contextual influences from the design's intended functional environment. These limits were driven because of regulations, local socio-economic factors, or other factors that were completely non-negotiable in the context of the design project:

*"If we wanted **to have a part produced it's going to be probably 5 to 8 times more expensive then producing the same exact part in China**. So, if we want to make the same part, it's going to cost us more money compared to teams in China or teams in USA. " – I3*

*"We were going to launch one test (version) of the product last year when the election was going to happen, and **so we had to pause and wait, because we couldn't do it during an election, we had to wait until after**." – I8*

*"Just designing **a space with so many rules and so many limitations** is more difficult than if this was a consumer product." – I7*

Contextual limitations were not always discussed unfavorably, a notable exception being the designers who discussed certain regulatory limitations as being helpful for certain decisions, insofar as they reduced complexity:

> "It's a bit of a stretch, but **because the medical industry is so regulated, they have very well-defined requirements for what is a pinch and what is not a pinch**. So it did save us the sort of wondering is this design okay…like, do you think people will think it's okay…it's very obvious if it's okay or not" – I7

> "So, having that **sort of strict regulation again like the wash down stuff is useful in making it easy to come to a yes or no decision**, but it is harder in getting to a design that works overall." – I7

Another influence that the designers found made it easier to resolve a trade-off was having an understanding of how the contextual interactions altered their design spaces, so that they could account for these limitations:

> "They sent us all of their, we called it **the environment CAD**, so all the CAD for the [system name redacted], the cameras and stuff, and that definitely gave us a better idea of what **we were actually working with**." – I7

The contextual influences on design are closely related to the complexity of the design space discussed earlier, as the context can either introduce new parameters and their influences on the project that the designer must consider, or it can restrict the viable space in a way that reduces the number of options for decisions. These helpful influences were quite rare however, and the designers mostly discussed the context of the design as being an unhelpful influence, limiting the flexibility and options they had available to resolve their trade-offs.

5.2.1.3. Operationalizing Goals

Requirements in a design project represent the underlying needs and goals the design project is aiming to fulfill. For the designer to develop solutions that meet these needs and goals, they must be translated into something that the designer can measure in

some way, be it rough subjective judgements of better or worse, or precise objective measurements of performance.

The designers noted that it was particularly unhelpful when a stakeholder was not able to clearly communicate their needs and goals in a clear enough manner so that the designer could operationalize them accurately:

*"Another one was they originally they told us **we couldn't have anything inside the bore to get in the way (of) the cameras and the more we pushed on that the more we came to realize, it was (only) a very slim sliver of light** that needed to reach person's eyes" – I7*

*"I'm **not sure they had a really great idea of what they needed or wanted either**, in all honesty. So we would get pretty far along, and then they would kind of remember that, 'oh, right, we have these camera bars, this design isn't going to work for us at all.'" – I7*

*"I would say **they weren't really all that well prepared in their constraints**. So we had to do a lot of that line of questioning ourselves in order to really **find out what their constraints were**. That was probably the most frustrating part of working with them." – I7*

*"(In a start-up) timelines are always tight budgets are always very tight and **usually both are pretty poorly defined.**" – I1*

Furthermore, in some of the cases, the designers were organizationally separated from the process of translating needs and goals into requirements for the project. When requirements were not being met, or in conflict with each other, the designers found this degree of separation added further challenge to resolving the trade-offs, since they were unable to determine what the real goals their designs must meet were:

*"It probably would have been more useful for us to talk with that partner instead. That would have made things faster **if we could have had a direct line to them and really understand what they needed**." – I7*

*"I'd say that process in itself was probably detrimental because there are some of these **constraints that, if it had been the engineering team gathering them from the start, probably would have been questioned earlier**." – I7*

The designers highlighted the importance of understanding these underlying needs and goals and ensuring that the parameters and requirements they used to operationalize them were a good fit. The designers said that this understanding of the real needs and goals made it easier to understand and resolve the trade-offs:

*"We modeled a lot of our design decisions off of what currently exists, but also made some slight changes there based off of **user feedback that we got on aspects that don't work for that specific demographic**." – I6*

*"We're also talking to disability advocates and just citizens. We had a public engagement as well earlier on, but I was **trying to really understand what people were needing**, and what needs we could accomplish that would benefit a lot of people, versus only a few people and be a lot to harder to do." – I8*

*"Going back and very aggressively looking at what we thought it had to do and **what it actually did have to do**." – I7*

*"They were one of the people we talked with on what **the real constraints were and worked back from what we thought they were, to what they ended up needing to be**." – I7*

*"That's why trying to emphasize **the cost was a confounding factor. It wasn't one of those two variables that mattered**, but it was a rabbit hole that we were going down." – I1*

*"Just made it very apparent that we can't provide just individual (fringe) word recommendations to these people who are nonverbal, **because they don't have the ability to add those (core) words that really provide a lot more context to what a sentence means**." – I6*

Going one step further, several designers discussed how operationalizing a goal differently allowed them to circumvent a barrier on their design space, and attain a viable solution to the conflict they were facing:

*"Going through the ISO standard and effectively trying to do that standard, yourself. So, the standard itself is a guideline for design and what we did was we tried to understand that the guideline as best we could and then **use their design standards to come up with our own criteria**, which is what would have happened if you paid somebody else to do it." – I5*

*"It helped clarify it a little bit when it was framed by the CEO as okay, for every week that we delay this design for every week that these robots are not out in the field, it's going to cost us about 25000 dollars. So, it made it a lot easier to kind of standardize things into a single variable. Which is **not necessarily the cost of this robot. It's the cost to the company**." – I1*

Lastly, one designer had an interesting observation that because their original requirements and constraints were poorly defined and operationalized, it actually drove them to explore their problem in more depth:

*"Them not knowing what their constraints were made it hard in the short run, but **because it forced us to ask some more questions, we actually probably found out more than we would have if they just had a really well written set of constraints.** Essentially their vagueness forced us to ask more questions and get the information we really wanted. So probably more unhelpful, but in a weird back handed way, it was also a little bit helpful." – I7*

The influences coded under this heading reflect the importance of understanding what the true aims of the project are when attempting to resolve trade-offs between the operationalized requirements. The designers interviewed all worked to a set of requirements that were operationalized from the underlying goals and needs, but this operationalization process is subjective and can result in requirements that do not completely align with the goals and needs. If the underlying goals and needs can be operationalized differently in these cases, either using different parameters or by structuring the membership criteria differently, then a trade-off that is preventing viability on the operationalized requirements may not actually be preventing a solution that meets all of the underlying goals and needs that drove those requirements.

5.2.1.4. Subjectivity of Design Space

Design problems are characterized by being ill-defined and ill-structured (Goel & Pirolli, 1992). As designers proceed through the design process, they are actively engaged in interpreting the problem and operationalizing the goals of the project into requirements. There is no pre-defined framework or standard for how this process of interpretation and operationalization must proceed, and as a result, different people can interpret problems differently (Dorst & Cross, 2001).

The designers talked about how challenging it can be to manage the differences in interpretations and framings of the problem, particularly when solving a trade-off. The needs and personal goals of an individual stakeholder can shape the priorities they have for the design, resulting in conflicting framings of the design space that the designers now needed to reconcile:

> *"I did talk to a speech language pathologist last week who actually cautioned against taking all the advice from speech language pathologists… and the reason why she said that is because, both the speech language pathologist and the end users, the people with disabilities, **they themselves have conflicting goals in terms of what they're looking for in a product.**"– I6*

*"He anticipated more than what we could provide. So, **his expectations were much higher than what we were able to do**." – I2*

*"They definitely **had different ideas on things like quality**. Our client was a start up, so they had no experience with quality, whereas this big corporation obviously has very stringent procedures in regards to quality. So they had different requirements there." – I7*

To successfully reconcile the different priorities and framings involved in the project, the designers spoke about the value of empathizing with another stakeholder's goals and priorities. The ability to easily alter their perspective on the problem to align with another stakeholder's perspective was described by the designers as a helpful influence:

*"They wanted us to **look from the eyes of a manufacturer**, how it can be done easily and using less material." – I2*

*"She was very good at **not only understanding her own perspective on things, but also other people she knew**. She would say, 'this would be fine for me, but if I were 2 feet taller this would be really difficult', things like that." – I7*

*"She's really familiar with what people... [recording quality cuts out] ...issues, and **just what issues people in general have when they're trying to get around**. It's hard to try and remember when you go somewhere new and it's the 1st time there, versus have you been there hundreds of times and **she's really thinking about both**." – I8*

In addition to empathizing with other people's perspectives and framings of the problem, the designers noted that effective communication was a helpful tool for harmonizing the perceived design spaces of different stakeholders, to obtain buy-in from stakeholders for decisions that rely on a specific framing of the problem:

*"So before you go down an expensive avenue, **you have to convince a lot of people and show them that it should work**, it will definitely work." – I9*

79

*"I think it's difficult when you go from an almost finished design to something made out of cardboard and very rough sketches and CAD. It's difficult to see it as better, because it looks so much worse. So his ability to come in and very quickly, do some sketches and show us this is what it'll look like when it's done, was useful for us in terms of morale, but **also critical in convincing our clients to go this route**. It ended up in pretty much everyone's opinion looking a lot better than our original design and that **was a really useful convincing tactic that we got because of them**." – I7*

The difference between the perceived design spaces of different people was not always described as being an unhelpful influence that made it more difficult to design around conflicting requirements. The designers discussed the value of brainstorming and other group ideation methods, which helped resolve trade-offs by introducing and sharing new perspectives and framings of the problem space that helped the designers understand the dynamics of the viable space:

*"She was actually present at our brainstorming session, and she vetoed a lot of ideas right away that, to us seemed very mechanically sound, but **to her, they were just not usable.**" – I7*

*"That's how most of the ideas or concepts that are used in the project came along, most of it came from the casual conversations of bouncing off ideas. I would say that whenever I suggested something, **that was all there was always a person in my team who criticized my idea**. I did the same for another person, but **positive criticism**, and **bouncing off ideas** was the best part of being a part of a team or a group." – I2*

As discussed under the "Operationalizing Goals" code, design projects can have many different goals and needs, driven by different stakeholders, that a design solution must meet. Because requirements are driven by different stakeholders with potentially divergent needs and goals, they can result in trade-offs between the priorities of different stakeholders. The designers noted that influences that made them aware of

these differing and conflicting priorities made it easier for them to account for them, and to resolve the trade-offs between them.

5.2.2. Aligning the Perceived Space with Real Outcomes

As previously discussed in Chapter 2, the explicit design space that the designer is operating and making decisions in is a perceptual design space, based on the designer's available knowledge and their understanding of the dynamics of that space. However, the parameters of this perceptual space correspond to parameters that measure the real performance of the design solution in its intended functional environment. The theme of "Aligning of the Perceived Space with Real Outcomes" deals with the designers' efforts to identify the real performance of their solution concepts, and to validate the alignment between their estimates of how certain decisions will affect the performance of a solution within their perceived space and that decision's influence on the performance of that solution in the real space. The designers frequently discussed the importance of understanding this real performance and where the real limits of their design space were for navigating a trade-off successfully.

5.2.2.1. Familiarity with Design Space

The most frequently mentioned influence was that of familiarity with the real boundaries and interactions between parameters that comprised the designer's explicit design space, and how that familiarity, or lack thereof, influenced decision making. This familiarity was presented as pre-established expertise that provided an understanding of how decisions will affect performance on the evaluative parameters in the real space, including the influences latent parameters (i.e., not explicit) may have on the real performance of a solution. From the perspectives of the designers, having this familiarity was solely a helpful influence, making it easier to resolve their conflicts. The influences that the designers noted as unhelpful stemmed from a lack of familiarity in some form. One such influence was when the interviewee either believed or knew that a limit existed, and another actor would propose a solution that fell outside of that limit:

*"Their team kind of work in a silo a little bit **so they come with ideas and try and go ahead and work with them, but they didn't talk with all the teams within** [Company name redacted]. Some teams were **telling us that is not feasible to do**, and it would take a long time to do it. That's because I was talking to development teams, and to all these different stakeholders." – I8*

*"It would have been unhelpful for instance, if they suggest the size 4. (Regardless) of the (non)availability of the (other) component I wouldn't (approve it), **because size 4 wouldn't have worked with the system**." – I4*

*"He's definitely an electronics engineer, so he participated in our brainstorming session, but a lot of **his ideas were maybe more theoretical or on the wild side of what would be possible mechanically**." – I7*

*"Maybe an unfair criticism. I think **he probably also entertained ideas that we all knew were not going to work out** longer than we should have, so we did full concept design for 3 designs, and I think fairly early on we knew that this arch design was going to be the one that we went with." – I7*

*"He anticipated more than what we could provide. So, his expectations were much higher than **what we were able to do**." – I2*

In these instances, the interviewee's believed they were more familiar with the real design space, whether this was factually true or not. On a related note, the differences in familiarity also exhibited themselves when other people thought barriers existed that the designer did not believe to be present. The designers viewed it as unhelpful when others would express sentiments of negativity or impossibility because of their own perceived limits, usually noted after a failed design:

*"The negativity that comes with a failure always impacted (us). Because **now you have someone who is telling you this is impossible to do**, but you are trying to make it work. It was an emotional setback, not financial or anything else, but it does affect you." – I9*

Both differences in familiarity tie back to the subjectivity of the design space, in that each person may have a different perceived design space, even when the parameters involved are the same. However, as touched on above, the methodology used for this study cannot determine which perspective was closer to the real design space, just that individuals perceived themselves to be more or less familiar than others.

The last unhelpful influence mentioned by the designers was a simple lack of familiarity, where another stakeholder cannot tell them the information that they need:

> *"They were **not (really) confident whether the method would work in an ideal manufacturing situation**. They were unsure, because they had, they lack professional experience, or experience in how a design can be done into an actual product." – I2*

In this instance, neither the designer nor the other person is familiar with the portion of the design space in question, but a knowledge of its real behaviour and bounds was necessary to determine the viability of a solution concept.

Other than the influences mentioned above, the designers generally favoured familiarity as a positive influence on their ability to resolve trade-offs. Having a good understanding of how choices or values on one parameter would influence the constraints or requirements on other parameters was a frequently mentioned positive influence, since it allowed the designers to predict how decisions on one parameter could restrict their choices on another:

> *"The difference between them asking someone 'is your day going well?' for a yes or no response, versus 'how is your day going?', and **knowing that for a sentence like the latter a person will require access to a lot of different words** (to respond) in a situation like that, given their varying speech needs at that point in time." – I6*

*"Yeah, we're trying to make sure that we **design it in a way where we're not blocking off** and making it so things have to be rebuilt if we wanted to add some of these other features in the future." – I8*

Beyond understanding the interactions between parameters, the designers noted that understanding the real limit on a parameter made it easier to resolve a trade-off:

*"So, let's say they chose a specific sensor, and it is costing us 2500 dollars, but we know from other operations that we are running across the plant that **there is another sensor which is available for 1600, which would also work**. So, there was always these cross questions that were happening as to why we are doing what we are doing." – I9*

*"Once you install the engine, we were able to find the distance between the edge of the test bench and the engines or the clutch assembly itself. So we were able to find the space between the clutch assembly and the end of the test bench. And what it meant was, like, **we were thinking about how it would have been in case it was installed in an automobile itself. You wouldn't have the distance that we had.**" – I2*

These real limits were the real-world performance on a parameter necessary to meet a need or goal. Understanding this was helpful to the designers, since this real limit was not always aligned with the perceived limit. Once they understood the real limits of the design space, they could choose an appropriate design response to the trade-off.

The influence of previous failed design solutions was not solely a negative influence on the designers' motivation as mentioned earlier, as the designers noted that failed designs provided them with the information necessary to identify the real boundaries of their design space and make decisions accordingly:

*"**They knew what went wrong**, so those inputs were valuable from time to time, and we always reviewed what we were doing with them, **just to make sure that we are not making the same mistakes**." – I9*

84

"If there was, it was probably more in terms of just the communication between people, 'look out for this issue I ran into, you might have something similar', not the direct solutions. And just the whole benefit of multiple heads on one design." – I7

The designers noted that pre-established familiarity was typically limited to specific portions of the design space, heretofore referred to as "domain expertise". The designers themselves may have domain expertise in some areas, but occasionally the demands of the project did not align with their own areas of expertise. To leverage domain expertise for the purposes of their specific project, the designers frequently mentioned discussions and consultations with domain experts who were not designers themselves:

*"Whenever we ask the question, **they always give us some sort of a solution or guided as to someone who can help us out**. So, when we had an issue with a say, in case of designing something, or maybe manufacturing or fabricating something, **they always guided us to someone or help us out with the design itself**." – I2*

*"(If) we were confused between 2 sensors, which one would work better, which one would last longer, which one is more financially sustainable, which one is more repetitive, which one has higher accuracy, which one is more precise. So (for) all of these things **we brought in someone -a few people- who are able to answer these questions**." – I9*

In addition to pre-established familiarity with how parameters behaved and interacted in ill-defined portions of the design space, the designers also valued the influence of having pre-established limits on parameters, as it removed any uncertainty about where the real limit on a parameter was, and made it easier to judge whether solution concepts were viable or not:

*"Maybe, it's a bit of a stretch, but because the medical industry is so regulated, they have **very well defined requirements for what is a pinch and what is not a pinch**. So it did save us the sort of wondering is this design okay…Like, do you think people will think it's okay...it's very obvious if it's okay or not."* – I7

*"So, having that **sort of strict regulation** again like, the, the wash down stuff is useful in making it easy to come to a yes or no decision."* – I7

*"(The company standards were helpful) **because we have an acceptable limit of pressure drop**. Let's say the maximum pressure drop of this particular system is 3 psi. So that is like a Bible, a guiding principle. You know that you cannot exceed 3 psi."* – I4

These pre-established limits allowed the designers to be familiar with a bound of the design space without needing to understand the real needs or goals driving that boundary. This was viewed as a helpful influence, as it reduced the number of factors that needed to be accounted for in their decision-making process.

The designers interviewed highly valued the ability to accurately predict how their design decisions would affect both the performance of the solution and the structure of the design space, and a pre-established familiarity or expertise was the easiest and least resource intensive (i.e., in terms of time and project cost) way to improve the accuracy of their predictions. This was reflected in the frequency with which this influence was discussed, being more than double the next most frequently discussed code (Context of the Design Space).

5.2.2.2. Prototyping & Testing

Prototyping, testing and other forms of simulation were some of the other common tools used by the designers to alleviate uncertainty and explore their design spaces. Prototyping allowed the designers to explore the behaviours of the real space faster and with fewer consequences than they would by observing the designs performance after

the project was completed, allowing the designer to make changes to the problem or solution based on that information:

> *"**I really see the value in learning outcomes faster, even if it means making compromises to the technical specifications** and I have no problem now trying something out much quicker, even if its kind of is a bad product. Because I know that I can make the good product."* – I5

> *"So what I **did specifically to balance the situation is the little experiments** that I talked about in the beginning that I asked (a few) members to (do) 2 or 3 parts to see **to test if this approach will work, and from that I know it will not work**."* – I3

> *"We had a giant brainstorm session with myself, another engineer, and our clients where we essentially all, uh, came together in our boardroom, and we actually, just had a bunch of crafts supplies almost. We **had like, scissors and cardboard cut-outs and we kind of just made very bad, quick prototypes of different ideas to quickly iterate through things that would and wouldn't work**."* – I7

> *"We generally have like a **mentality of you prototype early and you prototype often**, and that is definitely a useful mentality for us. **It finds issues very quickly**."* – I7

This allowed the designers to fill in gaps in their own understanding that could not be filled by consulting domain experts, and to explore novel framings of the design space to resolve the conflicts present in their initial design spaces. One of the designers also brought attention to the value of being able to predict the real performance of a solution concept and the limits on its viability from low-fidelity prototypes, which helped save them valuable time in the ideation phase:

> *"We would go to her fairly often to get feedback. So really her main contribution was **we would give her very basic prototypes** (and ask) 'how would you use*

*this? Would that be acceptable to you?'. **She was very good about giving incredibly articulate feedback**. She would never say, like, I don't like things, **she would give you exactly why she didn't like it**." – I7*

However, not all designers viewed testing and simulation as being sufficient to predict the real performance, doubting the ability of a simulation to fully capture all of the influences on the real performance, as the testing was not representative of the real operating conditions:

*"We were unable to test it in real world conditions. **We were able to simulate it on a 3D space or a computer software, but it would have been much better if it was available on an automobile itself**, so that we can test drive it and have a look at how it works, or if it doesn't work. Because once, **unless you have it as a product, it's going to be much difficult to understand how it is going to work**." – I2*

Lastly, some of the designers expressed that they had emotional barriers to using low-fidelity or imperfect prototypes to explore their design spaces:

*"Earlier in my career this fact that I had to make this Frankenstein board, **caused me a lot of anxiety because as an engineer I'm like, this is an inferior product**. This is not okay." – I5*

*"I think **it's difficult when you go from an almost finished design to something made out of cardboard and very rough sketches and CAD. It's difficult to see it as better, because it looks so much worse**." – I7*

Like the pre-established familiarity discussed earlier, the designers highly valued the processes of simulation, prototyping, and testing as aids for resolving trade-off situations. Prototypes allowed the designers to gauge more closely the real performance of a solution concept and determine whether it would be viable or not, capturing some of the influences from latent parameters they were not aware of or explicitly considering.

88

This relates to the challenge imposed by the context and complexity of the design space discussed earlier, as once the design space becomes too complex to attend to all relevant parameters simultaneously, some parameters of importance may not be considered when a design decision is made. While these decisions are made in a framing of the explicit space that does not contain these parameters or their influence on the performance of the solution, the real performance is still influenced by them. Physical prototyping allows the designer to capture the consequences of those influences from the real environment and account for them in their decision making, even if they are unaware of the parameter that causes them.

5.2.2.3. Timeliness

When making design decisions the designers can only utilize the information available to them at the time of the decision. The designers discussed how the timeliness of information availability influenced how challenging it was to resolve their trade-off situations.

Some of the designers were frustrated by requirements that were introduced late in the project, introducing trade-offs between those new requirements and the original goals:

> "*Another thing I think that made things a bit more difficult is I mentioned these 2 new constraints that they gave us, **those didn't come out right away or same time.**" – I7*

Conversely, the designers also did not appreciate discovering late into the project that requirements and imposed barriers on their design space that prevented them from reaching a solution to their trade-off were actually more flexible than they had assumed:

> "***If I knew what we were going to change our scope to, I would have ignored everything before [system name redacted] and just said, okay, let's start here*** (gestures at a node in the middle of the system diagram). Do not go into all these weeds and understand what's happening. I would focus just on if*

89

[system name redacted] has what lift is out of service, let's translate that and make sure that people can get what they need to know, even if it's a little bit delayed, let's make sure that they get it." – I8

The designers found that having a long lead time between making decisions and knowing how those decisions affected the real performance of a solution concept made it harder to resolve trade-offs, as the design project had progressed since those decisions and revisiting them would requiring revisiting other decisions as well:

*"With hardware it's interesting because there's **a long lead time between making engineering decisions and seeing how those pan out**." – I5*

On the other hand, the designers found it helpful when they knew about the limits and conflicts early in the process as it allowed them to intentionally design to avoid those limits:

*"The action that's the manufacturer actually took was to notify me early enough, before the commencement of the whole manufacturing process**. So he notified me quickly enough and I was able to make I adjustments** and issue another revised design (package)." – I4*

*"I really see the value in **learning outcomes faster**, even if it means making compromises to the technical specifications and I have no problem now trying something out much quicker, even if it kind of is a bad product. **Because I know that I can make the good product**." – I5*

*"I got a lot of pushback from technical people, because the programmers don't like seeing the word vision in a document. They're like here's the actual requirement, here's what we want. **But the future vision is important, because we want to make sure that we're not building something where we have to cut any of this off and we make sure that as possible**." – I8*

Overall, the designers highlighted how late information forced them to make decisions without that information, and the consequences of these "blind" decisions made it more challenging to resolve trade-offs. The designers preferred to make decisions with as much information as possible so that they could predict the consequences of that decision. This ties back to the choices to consult experts and prototype frequently discussed in the previous codes, as both are ways the designer can attain information about the consequences of a decision either prior to finalizing the decision, or before it is too late to revisit it.

5.2.3. Previous Design Decisions

The last theme identified among the influences discussed by the designers was how design decisions made before the trade-off was identified influenced how challenging it was to resolve their trade-offs. A design space is a representation of a snapshot in time during the design process, but the bounds and parameters that constitute the explicit design space change as the designer makes decisions. These decisions shape the subsequent design space the designer must now operate in, with some decisions restricting the number of options in the space, and others providing more flexibility to the designer. However, the end result of a successful design process is the development of a solution or multiple solutions to the problem. This finalization of a solution is represented by a final decision to restrict the explicit design space to only those chosen values on the explicit parameters that define that solution.

As the designers discussed the influences on their decision making in a trade-off situation, they mentioned two topics most frequently: how previous design decisions shaped and restricted the design space prior to them identifying the conflict, and how flexible their design process was for revisiting design decisions that made it more challenging to solve a conflict. These were coded as "Consequences of Design Decisions" and "Permanence of Design Decisions" respectively.

5.2.3.1. Consequences of Design Decisions

The designers mentioned that while exploring and improving their understanding of their design spaces in search of viable solutions, they would encounter the consequences of a design decision that had been made earlier, either in their own design process or in the design of an interfacing component or system. These previous decisions could both limit the viability of certain solutions or relax constraints on the design space. The designers found it more challenging to identify a viable solution when they discovered that a previous design decision limited the available options on a parameter they were trying to manipulate in their attempt to resolve the trade-off:

> "***I cannot compromise making less number of parts*** *than I have committed to the customer just because of this one thing. So the biggest hurdle that I have given them is the timing." – I9*

> "*It had an unhelpful influence in that **it limited the selection that we had to pick**, as building blocks, for what we were going to do. So if we had a feature that we needed, and there were 100 parts on the market that did it, **maybe 5-10% of those have this rating and so now you can only select from that**." – I5*

Conversely, the designers noted that decisions on one parameter that relaxed constraints on another made it easier to develop a viable solution to their trade-offs:

> "*So, first thing we did was **we added a taper to the gauge. So, that would help us align the two parts,** the gauge and the part." – I9*

> "*That's another role that **using an iPad** or optimizing for iPad **supported the aspect that we could have both core and fringe**, because those are a lot of different words to show on one screen." – I6*

> "*Which is why I'm saying **if that sensor wasn't included in the project, I don't think we would have come this far**." – I9*

The previous theme showed that designers wanted to predict the consequences of their decisions in trade-off situations, and the influences discussed under this code highlight some of the reasons why. Design problems are complex, and designers cannot always predict all of the consequences of their decisions on the performance of their own design. This also extends beyond the context of a single design project, since some of the limits the designers discussed were because of decisions made on other, previous, designs that the new design solution interacted with.

5.2.3.2. Permanence of Design Decisions

The conflicts and trade-offs the designers described were discovered while they were already partially through their design process. In some cases, the conflict was only presented after the designers had completed the design process and had a solution that was fully verified and validated against the original requirements.

In these situations, the designers frequently mentioned that they revisited previous decisions they had made about the design solution or the framing of the problem in their effort to circumvent a trade-off or limitation. The designers found it unhelpful when these efforts were thwarted by other stakeholders in the project, who had their own vested interests in not allowing decisions to be altered:

> *"Like in the first 3 weeks that we met with them, we met with them once a week for like a month there. Most of the conversation was them trying to sell us that their system could do what [project name redacted] was trying to do. Which is a fine idea, I'm happy to explore (it), maybe their system could do a better. But it was a lot of that, because they really trying to make sure, they have **they have a financial interest in place. So, they wanted to make sure that they're not going to get cut out**." – I8*

> *"**I cannot compromise making less parts than I have committed to the customer** just because of this one thing." – I9*

In another case, one the designers noted that they themselves were reluctant to revisit their own previous design decisions:

*"I think kind of questioning ourselves on why we were getting so angry and that kind of led down the rabbit hole. Okay, **we're just really attached to this design** and it's not that the new constraints are stupid, it's just that our design doesn't meet it anymore and that's okay. We designed something good that met what we originally thought we had to do, and now that's just changed. So now we have to design something new that meets what we have to do this time." – I7*

*"I think **the main one was definitely the emotional attachment to not only the old design, but also each of our own designs**. It made it a bit harder to come together at the end after we'd gone on our separate routes and come back towards this one. So definitely, that emotional connection to design is not generally useful, I think." – I7*

In the cases where the designers could not identify any viable solution in their current explicit design space, they discussed that two influences made it easier for them to remove the bounds that were restricting their space. The first was to consider the underlying rationale behind previous decisions regarding problem formulation and framing, and the underlying goals that drove those decisions:

*"So let's say they **chose a specific sensor right, and it is costing us 2500 dollars**, but we know from other operations that we are running across the plant that there is **another sensor which is available for 1600, which would also work**. So, there was always **these cross questions that were happening as to why we are doing what we are doing**." – I9*

The other influence that the designers found helpful was when they had the freedom to revisit and alter previous decisions, without organizational procedures and norms limiting them:

*"**With kind of cart blanche, authorization if your going to use a formal term, to keep or change any of that that I saw fit** in my judgment. So, I would consider it pretty open ended in terms of the hardware. The problem's scope in terms of the functional requirements didn't change as much we knew that it had to drive on a sidewalk and it had to fit food in it. Everything else, **any other constraints on it were very loosely defined very flexible, and I would even consider that those were pretty flexible**." – I1*

While revisiting previous design decisions did allow the designers to alter their design spaces and identify solutions that dominated the previous Pareto frontier, revisiting the decisions is typically a trade-off in itself, sacrificing project time and resources. The degree to which this sacrifice was necessary depended on the designer's and other stakeholders' subjective assessment of how much to prioritize attaining all the goals in the original trade-off versus the project timeline and cost.

5.3. Discussion

The third and fourth research questions of this study asked what influences the designers perceived as affecting their decision making in trade-off situations, and which influences made it easier versus harder.

One of the findings from the thematic analysis indicates that the designers found having a more complex design space with more parameters and interactions made it more difficult to manage trade-offs. It was also mentioned that the designers found some restrictions and constraints helped to resolve a trade-off, as it gave them fewer options to consider. Combined, this suggests that as the explicit design space increases in size and complexity, it becomes more intractable for the designer to attend to all aspects of the space simultaneously. Once a threshold is reached, the designer chooses to attend to portions of the design problem sequentially, making a decision to select a parameter value and proceeding to the next portion of the problem.

This was evident in the dataset, as some designers described how they made a decision and only later discovered that that decision resulted in another conflict. For example, in case I2 the designer chose to use a pneumatic cylinder to actuate a lever, requiring a coupling between the two components. Some time later they discovered that the lever moved in a different plane from the cylinder. This introduced a trade-off between the flexibility of the coupling and strength necessary to withstand the forces applied on the coupling.

Another finding related to the information processing limits of humans that were introduced theoretically in Chapter 2, based on an established literature of human cognitive capabilities (Miller, 1956). The design decision making process usually occurs in a state of imperfect knowledge, where the designer does not have a full and perfect understanding of every potential influence on a parameter's real performance, or of the nature of the interactions between parameters. In this state of imperfect knowledge, the designers make decisions on parameter values with only an estimate of how that decision will affect the bounds and performance of other parameters. This estimate could be quite accurate and reflect the underlying reality closely, or it may be far removed from the underlying reality, misleading the designer until the real performance is discovered. In the latter case, the designer may mistakenly believe a boundary or conflict exists preventing them from achieving the goals of the project.

In addition to the complexity causing a sequential approach, the designers' comments on the timeliness of information, consequences of previous design decisions, and the permanence of those decisions all point towards path-dependency, where the options available for a decision depend on decisions made previously, that influences trade-off resolution. Many of the conflicts described in the cases were the result of a previous design decision limiting the viable options for a subsequent decision. As these decisions continue to restrict the design space, the designers found it increasingly challenging to create solutions that met all the viability criteria of the project. Furthermore, because the designers could not attend to all the parameters and their interactions simultaneously,

they were not always aware that the decisions they were making would hinder them on future decisions.

These path-dependant sources of conflicts speak to the importance of an iterative and flexible design process, that allows previous decisions to be revisited and unlocked to improve the overall performance of the final design solution. However, the designers identified several barriers to implementing such a non-linear and iterative design process. In some cases, it was the organizational structure and norms that encouraged forward project inertia and discouraged backtracking. In others, it was the designer's own emotional reluctance to abandon the work they had already completed. In both, there appears to be a degree of sunk-cost fallacy (Parayre, 1995) from the stakeholders, wherein the project resources expended to reach the current state biases the decision making about how to expend future project resources.

The aspect that the designers returned to most frequently was understanding of the real performance of the underlying design space, and ways that understanding came about. The designers discussed the pre-existing knowledge or expertise that they or other stakeholders could bring to the project and the discovery of new knowledge through simulation, testing and prototyping to explore unknown interactions and parameters. As discussed under the "Familiarity with Design Space" code, the designers interviewed highly valued expertise and experience, and frequently consulted with domain experts to fill gaps in their own understanding. These consultations were surrogates for testing the actual performance that allowed the designers to make decisions that were more informed earlier and without expending further project resources.

However, when the designers were unable to find an expert that understood how a decision would influence performance on the rest of the design space, they resorted to simulation or prototyping. Both of these allow the designer to explore the real underlying performance implications of different decisions far quicker and at lower

cost, both financial and in reputation, than discovering these implications in the intended operating environment after finalizing the design.

However, simulations and prototypes model a design and predict its performance with varying degrees of fidelity to the properties of the real design and the influences on its performance from its functional environment. As a result, they rely on the designer to understand the potential contextual influences on the design's performance well enough to properly account for those influences in a simulation or test to produce results that align accurately with the real performance. If a designer inaccurately models an influence, or is not aware of an influence altogether, the simulation or test results may be biased away from the real performance.

5.3.1. Limitations of Thematic Analysis

The greatest limitation that this study needed to contend with was that all of the influences that were labeled as helpful and unhelpful for a case were presented from the perspective of a single interviewee from that case. Without multiple corroborative perspectives from the same project, these influences are only those that the designer felt made their portion of the design project easier or more difficult.

This potentially limits how accurately the results identified reflected which influences that affected how challenging resolving the trade-off was for other stakeholders or the project team as a whole. However, the findings above still allow for the exploration of the individual designer's formulation and framing of the trade-offs and the influences thereupon. It is equally valuable to understand what made resolving a trade-off more or less challenging from the subjective perspective of an individual designer as it is to understand the influences that made it objectively easier or more difficult for the overall design team. Since an individual's formulation and framing of the design space is personal, subjective, and constructed, the influences that they perceive are what influences that design space, and that space's influence on their design decisions.

Chapter 6 – General Discussion

This thesis contributes an improved understanding of how designers use problem reformulation in practice to navigate complex design trade-off situations. While the theoretical importance of problem formulation and framing in design has been recognized, there remains little understanding of how designers actually reformulate and reframe in practical situations like trade-offs, and how those processes alter the final design solution. The remainder of this chapter reflects on the theoretical framework used to answer RQ1 that was presented in Chapter 2 and its benefits and limitations for analysis, summarizes the key findings from the studies in Chapters 4 and 5 with respect to the latter three research questions in Chapter 1, discusses some key avenues for future work, and concludes this work.

6.1. Theoretical Framework

The theoretical framework presented in Chapter 2 was quite general in its description of design situations, and therefore could not be tested fully within the scope of the study presented in Chapters 5 and 6. Indeed, the purpose of this study was not to test the theory as a hypothesis, as it was exploratory in nature. Nevertheless, the theory provided insight and interpretive power for understanding how the designers formulated and framed the trade-offs they encountered in their design practice, and how the designers could alter their formulation or frame to achieve the design goals that were in conflict.

The framework contrasts to Gero and Kumar's (1993) original ideas about expanding solution spaces in several ways that made it better suited to modeling trade-offs. The first was that the mathematical foundations of the model were expanded through the clarification of the set theory components and their meanings in the design space and incorporation of the parameterized Pareto criterion. These expansions allowed Pareto

frontiers between parameters to be modeled and identified, which in turn allow the model to capture design trade-offs.

Secondly, the framework presented in Chapter 2 does not treat the problem and solution spaces separately. Instead, it models the designer's frame as a single set where the elements are the solutions considered, and the parameters are anything that characterize and differentiate those solutions. The design space includes the evaluative parameters that the designer formulated to represent the goals of the project, and the non-evaluative parameters that characterize the solution concepts. As a result, it models both the decisions made about solution attributes and the impacts of those decisions on the performance parameters that operationalize the goals of the project.

This merger of the problem and solution spaces was better suited to modeling the nature of trade-offs as the designers dealt with them than having them separated, since the designers interviewed manipulated both types of parameters (evaluative and non-evaluative) to arrive at a viable solution. By having the two types of parameters captured in the same space it facilitated the tracing of both the direct and indirect interactions between parameters that the interviewees were describing.

Furthermore, the designers interviewed did not attend to the entirety of their design problem at once. Rather, they would construct a frame of certain features of the problem and solution that they wished to attend to or were finding particularly problematic. This frame would include both the evaluative parameters of concern and the non-evaluative parameters that in the designer's perspective had the greatest influence on those evaluative parameters. Having both the evaluative (i.e., problem-space) and non-evaluative (i.e., solution-space) parameters in the same space better reflects the framing these designers were doing.

Another impactful expansion was that a perceptual level, representing the designer's perceptions and beliefs about the design problem and solution, was included in the framework as the designer's active explicit design space. This perceptual level allows

the framework to capture the differences between subjective expectations of performance and the real objective performance of designs. Furthermore, the designers interviewed rarely had a strong understanding of the problem requirements or goals at the moment they encountered them. This was reflected in the clarifying response identified in Chapter 4, where some of the designers discovered that either their expectations did not align well with the performance in the real world, or the requirements and constraints did not align with the underlying goals and real limits on the problem.

The perceptual level also allows the phenomenon of design framing (Schön, 1983) in trade-off contexts to be modeled as the designers actively constructing explicit design spaces. The designers would initially build their frame from the evaluative parameters that they perceived to be in conflict. They then added to the frame the non-evaluative parameters that they thought had the largest influence on the values of the evaluative parameters. The designers chose which non-evaluative parameters to add based on which parameters they believed would have the largest influence on a solution concept's performance relative to the goals.

This framing process relied heavily on the information and knowledge available to the designers. Where they were uncertain about the nature of the interactions between parameters in their frame, they would attempt to consult other stakeholders with more experience and perceived expertise to clarify, or they would prototype to gain a better understanding of the real interactions.

However, the theoretical framework as it was developed was not without limitations for the purposes of this study. A major limitation of the framework as presented in Chapter 2 was that it was not a process theory of design, and therefore could not explain the cognitive processes used to move from one explicit design space to another. Further work is needed to characterize how design spaces evolve over time, as the model presented in this work is primarily described in static "slices" at instantaneous

points in the design process. For example, studying how designers choose which parameters they make explicit and the factors that influence this process would help clarify how designers alter their design spaces over time.

The Infused Design methodology (Shai & Reich, 2004a) is a tool that may allow the expansion and exploration the design space in a more systematic manner through collaboration between different disciplines. Infused Design is a prescriptive methodology that attempts to represent design problems from different domains (e.g., electrical versus mechanical) using common mathematical representations, which Shai and Reich (2004a) call combinatorial representations. An example of such a representation is using resistance graphs to represent both electrical circuits and static mechanical truss structures, allowing electrical and mechanical engineering designers to structure the problem in the same way and communicate more effectively (Shai & Reich, 2004b). If the project goal in this example was to design a truss system, and the truss system is indeterminate (i.e., the forces cannot be calculated), the combinatorial representation allows the electrical engineer to leverage their expertise to suggest an advanced analytical method that is used on electrical circuits which allows the mechanical engineer to solve their problem (Shai & Reich, 2004b).

By using Infused Design's combinatorial representation methods to improve cross-disciplinary communication, new parameters that are common in one domain can be introduced to another domain with a reasonable prediction of how that parameter would affect the design space, rather than simply making intuitive or educated guesses at which parameters to add.

The tendency for a designer to take a single core idea and evolve it through addition or subtraction of features, as was observed in cases I2, I7, and I9, is one other major aspect of the design process that the framework presented in Chapter 2 does not capture well. This is because the framework models design frames from a parametric perspective, not a solution perspective. From the parametric perspective, the solution concept that the

designer is evolving is represented as a single element in a set of solutions, which is characterized by the values it holds on the explicit parameters. This perspective is valuable for identifying Pareto frontiers, since it allows for different solutions to be compared and ranked based on their relative performance on those explicit parameters.

However, the parametric perspective may be incorrectly interpreted as implying that an underlying set of solutions exists that a designer is simply choosing from (Hatchuel & Weil, 2009), which is not the case. This is because a designer cognitively operates within their perceived design space, which contains only the solutions which they have constructed. However, the parametric model as posits the existence of a real design space, which contains all the possible combinations of values on the explicit parameters, as an abstract theoretical construct and not a model of design cognition. This distinction between the perceived space and the real space can cause the misinterpretation that designers are merely choosing concepts from the design space.

Instead, the parametric perspective models the iterative development of a single design concept as the designer's perceived explicit design space initially containing only a single element (i.e., the initial design concept), with new elements added to that space as the solution concept is altered. Since an element in the design space (i.e., design solution) is characterized by the values it holds on the parameters of the design space, any change to any of those values will result in a new and distinct element (i.e., a new design solution). This occurs even if the value of only one parameter is altered by the smallest possible increment possible. In this manner, as the initial solution concept is evolved, the number of elements in the designer's perceived design space increases. However, not all of these new elements are members of the viable design space, as any element that violates a membership criteria is non-viable.

The alternative is the solution-oriented perspective, which is captured in modern state-space theories like C-K theory (Hatchuel & Weil, 2009, 2003). C-K Theory and other solution-oriented theories model the design process as the evolution of a single core

103

conceptual proposition that cannot be initially verified as being true or false (e.g., there exists a bicycle tire not made from rubber). These solution-oriented theories capture the designer's cognitive process and decision making better than the parametric theory proposed in Chapter 2, since they contain only the solutions that the designer has actually proposed and not the latent hypothetical alternatives. However, because these solution focused theories do not model these hypothetical alternative values of parameters, and therefore hypothetical alternative solutions, they cannot model the functional relationships between parameters. In turn, this means they cannot model phenomenon of a trade-off or Pareto frontier between parameters. This was the rationale behind the derivation and usage of a parametric theory for the studies presented in this thesis.

Case I7 illustrated this tendency to iteratively evolve a single solution, where the designers attempted to add new features to an original telescoping design until they felt they could not longer add features to arrive at a viable solution. Only at this point did they revisit their core solution concept and replace it with a rotating arch. A solution-oriented model like C-K theory captures this evolution but does not capture the conflicting evaluative parameters that prompted the redesign. Future work should be done to harmonize the features of the parametric and solution focused models to capture both trade-offs and the design process that creates and resolves those trade-offs.

6.2.   Summary of Findings

The three remaining research questions in this study all pertained to designers' perceptions of trade-off situations and their responses to those situations. The second research question, "*Do designers use reformulation and reframing to resolve trade-offs between their design goals?*", prompted an exploratory study into how designers framed their design trade-offs, and how those frames were altered by the decisions made to resolve those trade-offs.

The case study analysis in Chapter 4 provided insight into how designers used reformulation and reframing in the context of trade-offs, real and perceived, to allow them to successfully meet goals that were in conflict in the original problem formulation and framing. The static space responses of surrendering, prioritizing, and satisficing that were found in this study, in addition to explicit optimization responses within a static space all have been identified and studied within the literature (Antonsson et al., 2003; Bate, 2008; Byggeth & Hochschorner, 2006; Carnahan & Thurston, 1998; Otto & Antonsson, 1991; Wu & Pagell, 2011), and methods and guidelines exist for developing solutions using these approaches (Dubois et al., 2015; Hajela & Lin, 1992; Koziel & Bekasiewicz, 2018; Mattson et al., 2019). However, these static space responses cannot produce viable solutions when the boundaries of the design space do not allow all of the design goals to be met simultaneously. This restriction can be avoided if the designer also applies a boundary manipulation response to move those boundaries, or if they alter their space by introducing additional parameters that influence those boundaries.

The boundary and parameter manipulation responses offer some insight into how designers can restructure their design spaces, allowing them to produce creative and novel designs that meet goals that were unattainable in the original problem formulation and framing. While the negotiation response is well known and studied, and Gero and Kumar (1993) theoretically identified the expansion response, neither the clarifying, nor the reconstructing responses were previously identified within literature on trade-offs in design. Furthermore, this study identified instances of the expansion response in the context of actual design responses, providing support to the theoretical contributions of Gero and Kumar (1993).

The third and fourth research questions reflected the situated nature of design projects (Suwa et al., 2000), where the network of influences, environmental and human, will affect how designers construct and manipulate their design spaces that represent their design trade-offs and influence how they resolve them. Three overarching themes

105

emerged from the influences described by the designers: how the initial formulation and framing influenced the decision making, how well the subjective expectations of the designer aligned with the objective underlying performance, and how previous decisions affected the options available to the designer.

Among all the influences, an interplay between the concepts of uncertainty and complexity was identified. When discussing influences that made it more difficult to resolve their trade-offs, the designers frequently commented on factors that increased the complexity of their explicit design space. As the number of parameters and constraints in the explicit space increased, the number of interactions between parameters increased. This presented the designers with the challenge of having to trace the impacts of design decisions across more parameters, and as the complexity increased the designers found this process to be more challenging. Conversely, the designers appreciated influences that artificially limited the number of possible options on a decision, so long as one of those options produced a viable solution.

As the complexity of the design space increased, the designer's uncertainty about the interactions between parameters, and therefore the consequences of their decisions increased. The designers sought to reduce their uncertainty, particularly in cases where their uncertainty was so high that they felt they could no longer accurately predict the viability of their solutions. Influences such as consulting with experts, simulation, and prototyping that helped them reduce this uncertainty were perceived as making it easier to resolve the trade-off.

Another common thread between the influences on the initial framing and the subsequent reframing was that designers do not always have the agency to manipulate all aspects of their design space, despite the design space being their own constructed perspective of the problem situation.

Social and organizational influences, such as the commonly identified limits on project resources like cost and timeline, are included in the designer's explicit frame of the

problem, but they do not have the independent agency to alter them. In these instances, the designers could either accept the constraints imposed by these external influences, as in any of the static space responses; negotiate with project stakeholders who do have the influence to alter these constraints; or adjust other aspects of their design space that they do have control over.

Furthermore, the designers also indicated that their agency was restricted by institutional norms on decision making, such as the organizational "best practices" in case I4-2, or project management, such as the linear project structure in case I7.

Together, these affirm the situated nature of design trade-offs, which occur in complex, multi-stakeholder environments, with competing goals. This points to the importance of clear communication within design teams to ensure consistency in framing and to justify the rationale behind why designers can and cannot change certain aspects of those frames. This need for communication also extends to other stakeholders outside the design team, including clients and users, who must be able to clearly articulate their needs so that the design team can accurately translate those into requirements and constraints.

The findings regarding research questions three and four contribute to the literature by identifying ways in which the designer's environment affects their decision making in trade-off situations. This improves our understanding of how the situatedness of design (Gero & Kannengiesser, 2004) influences how trade-offs are resolved, and whether all goals are attained by that resolution approach.

6.3. Methodological Limitations

The qualitative methodology used in this thesis to obtain the dataset may have limited the analysis in two major ways. Firstly, using interviews as a medium to investigate how designers framed their trade-offs and the parameters involved may have caused the interviewees to present a simplified perspective of their design spaces, possibly due

to time pressure or the challenge of presenting technical information through conversation alone. It was noticed that most designers described a majority of the parameters in their frames as either simple binary feature parameters, or poorly described preference parameters.

However, despite the relatively low level of detail, a model of the designer's original framing and how their decisions altered that frame could be reconstructed. This was still possible because the reconstruction only required that the explicit parameters and the direction (reinforcing or balancing) of the relationships that the designer perceived between parameters be known.

The second limitation was that the study population was biased by the recruitment method, which resulted in participants from within the research team's personal networks. Consequently, the sample was comprised of engineering designers who were all trained at the same university (either at an undergraduate or a graduate level), and most were relatively inexperienced (<10 years professional design experience).

It is possible that the low level of experience, and therefore expertise, may have influenced how the designers resolved their trade-offs, and what influences they perceived as helpful or unhelpful. Furthermore, the approaches used by the designers in this study may also reflect their design education, so could be local only to designers trained in ways similar to the university they all studied at.

Additional recruitment was attempted with organizations and individuals outside of the researchers' networks, but this approach did not successfully yield any further interviews. This may have been due insufficient remuneration for experienced designers given the time-consuming nature of the interviews, or that the study timeline was not sufficiently long enough for the low rate of response on unsolicited contacts to yield further successful interviews. A future direction for this study would be to attempt to triangulate the findings across a broader, more representative sample of designers from different backgrounds and with varying degrees of experience.

6.4.　Future Work

As a consequence of this thesis' exploratory nature, the number of potential future research directions identified are numerous and expansive. This section will highlight some of the areas that the author believes to have the greatest potential for novel and impactful findings.

An expansion of this work could investigate the potential of using the theoretical framework or derivations thereof as interventions for improving design practice. Studying whether a designer's metacognitive awareness of their explicit design space's structure and the potential mechanisms to manipulate those spaces improves their ability to resolve trade-offs would connect this conceptual work to design practice.

Further exploration of the value of the parameter interaction networks as a tool for identifying trade-offs could prove fruitful as a prescriptive intervention. Existing tools for mapping parameter interactions such as the interaction matrix in the Quality Function Deployment (Govers, 1996) or Design Structure Matrices (Danilovic & Browning, 2007) are methods which only show 1st order connections, but do not facilitate the easy tracing of 2nd or higher order influences. Using the parameter interaction network methodology may allow designers to identify key non-evaluative parameters that do not have obvious 1st order connections to the evaluative parameters in conflict.

Another area for further exploration is the tension between familiarity and novelty in design, and how that ties into resolving challenging trade-offs. On the surface, the parameter manipulation responses identified in the case study analysis of Chapter 4 are somewhat antithetical to the importance of familiarity and expertise noted in the thematic analysis. Adding novel or unusual parameters to the space means that the interactions between these new parameters and the existing space is unlikely to be well explored and well characterized, by virtue of their novelty.

A possible explanation for why these two findings emerged from the same dataset is that parameter manipulation responses that alter the design space may be less novel and more combinatorial in nature, at least for the initial alterations. The designer may be relying on past design experiences to inform which parameters to add to the design space, relying on a set of commonly used parameters and combinations of parameters (i.e., a design frame that contains a specific combination of parameters). As the designer gets more experienced, they will have encountered more parameters and combinations of parameters, increasing the number of combinatorial options (i.e., different frames) they can apply to a new problem and improving their ability to predict which frames will contain a viable design solution. It is possible that when experienced designers introduce parameters to a design space, they initially introduce parameters that they previously used in design spaces that partially overlapped with the design space they are currently working in. This would allow them to add novelty to the current space while maintaining a familiarity with how the new parameters they are adding will influence the current space.

For example, a designer has constructed a current explicit design space D_1 with explicit parameters {A, B, C, D}, and a trade-off exists between parameters A & B. Now if the designer introduces parameter E to the explicit space to resolve the trade-off between parameters A and B, it may be because they have previously used an explicit design space D_2 with explicit parameters {B, D, E} on another project. This previous experience allowed them to develop an understanding of how parameters B, D and E affect each other. This would reduce the number of new interactions the designer needs to characterize, easing the burden of increasing the dimensionality and therefore complexity of the design space. However, these interactions between {B, D, E} would still need to be verified, since they may be altered by the additional parameters A and C.

Designers may only turn to parameters that are completely novel to them once they believe that adding any of the parameters they have previously used will not result in a

viable solution. Novice designers, like the majority of the interviewees, may encounter this situation more frequently, and therefore have to use novel parameters more frequently, adding them to their repertoire. As they gain design experience and encounter more design problems, they will continue to use more parameters and combinations of parameters (i.e., different frames) to frame those problems and create solutions for them. This would eventually allow them to rely on previous experience to inform which parameters would influence a design space in a desired way, allowing them to manipulate the design space in a more informed and intentional manner.

Future research could investigate whether the designer's previous experiences in similar projects inform the parameters they make explicit to reformulate their problem, and what their response is when this combinatorial creativity is exhausted with no satisfactory solution emerging.

Furthermore, it is possible that expertise has two aspects that affect formulation and framing: depth and breadth. The depth of expertise is the extent to which someone knows a specific subject or domain, whereas breadth of expertise would be how many different subjects or domains a person is familiar with.

Depth of expertise may help characterize specific parameter behaviours when these parameters are framed in conjunction with "typical" sets of other parameters for the domain of expertise. This characterization would allow designers to better align their expectations of performance with the real-world performance and approach the true underlying Pareto boundaries of a space much more closely without overshooting into the non-viable design space.

Breadth of expertise may not allow the same level of precision and ability to skirt close to real Pareto frontiers, but it may facilitate more novel combinatorial sets of parameters as hypothesized above, introducing new boundaries and new behaviours that are not achievable within the "typical" sets of a domain, leading to creative or unexpected outcomes.

However, it is also possible that experience and expertise has a downside that could not be identified within the current sample demographics, fixation. As designers get more experienced in a problem domain, they will become more familiar with the common parameters important in framing problems within that domain. However, this familiarity may lead them to fixate on the ways of formulating and framing problems that they are familiar with, unwilling or unable to see alternatives.

With regards to previous experiences and their impacts on the designers' formulation and framing of the design space, it was noted in the methodological limitations that the designers interviewed were predominately in their early career, with only one having more than 10 years of experience. The findings regarding the perceived importance of expertise and familiarity to better predict the consequences of framing and formulation decisions in trade-offs should be explored further with designers with greater experience. This would help determine if more experienced designers alter their formulations and frames differently from novice designers, or if they view other influences as being more salient than expertise and familiarity.

6.5. Concluding Remarks

To date, the study of trade-offs in design has been dominated by approaches focused on optimizing design solutions within a static design space (Antonsson et al., 2003; Bate, 2008; Byggeth & Hochschorner, 2006; Carnahan & Thurston, 1998; Otto & Antonsson, 1991). While optimization approaches are well-suited to identifying Pareto optimal sets of solutions to well-defined problems, relying on optimization alone in design discounts the opportunities afforded by design's ill-structured nature (Dorst & Cross, 2001; Gero & Kazakov, 2000; Stacey & Eckert, 2010).

Design optimization certainly has applications within design, as it allows solutions to be improved to the real limits of viability achievable in a particular formulation and framing of the design space. This is beneficial in routine design applications, where existing solutions are refined and improved. However, when the design project is novel

enough that the design space and important parameters are not well-understood, the optimization approaches neglect the agency of the designer in interpreting their problem and exploring novel approaches to solve it.

On the other hand, the design creativity and design cognition literature both explore how designers formulate and construct frames of their design problems, and how the formulation and frames of the problem change as the designer moves through their design process (Cardoso et al., 2016; Dorst, 2011; Dorst & Cross, 2001; Schön, 1983). Gero and Kumar (1993) initially proposed the process of adding parameters to the design space to improve the performance of solutions, but their work did not capture how designers reformulate the problem itself, or how designer's perceptions of the design space and its limits may not align with reality.

This study connects the above concepts from design creativity and design cognition to designer's response to trade-off situations. The findings presented improve our understanding of how designers manipulate their design spaces in practice, what aspects of the design situation influenced how challenging a trade-off was to resolve, and how their manipulations can result in superior solutions. The findings emphasize the importance of understanding the underlying needs and goals that drive requirements in design, designing without artificially constraining oneself through biased predictions and expectations, and the importance of iterative and flexible design processes to accommodate the information discovered through the design process.

The exploratory work presented in this study provide insight into the aspects of trade-off situations that practicing designers find salient. Future work can expand upon these findings to develop prescriptive tools and methods that help designers resolve their trade-offs so that goals are not being unnecessarily sacrificed due to optimization approaches on poorly formulated and framed design spaces, or the designers perceiving their design space as being more restrictive than it is.

As design expands in scope to tackle broader and more complex problems, problem formulation and framing becomes ever more crucial, and as designers tackle problems that affect larger and more diverse groups of stakeholders, the ability of designers to identify and resolve trade-offs between diverse and conflicting goals grows more essential. The findings of this thesis provide a foundation understanding of how designers can resolve trade-offs without unintentionally sacrificing goals through overly restrictive or poorly constructive design spaces, and how they can manipulate the structure of their design space to bypass trade-offs and constraints.

Bibliography

Akin, Ö., & Akin, C. (1996). Frames of reference in architectural design: Analysing the hyperacclamation (A-h-a-!). *Design Studies*, *17*(4), 341–361. https://doi.org/10.1016/S0142-694X(96)00024-5

Altshuller, G. S. (1984). *Creativity as an Exact Science: The Theory of the Solution of Inventive Problems*. Gordon and Breach Science Publishers.

Antonsson, E. K., Zhang, Y., & Martinoli, A. (2003). Evolving Engineering Design Trade-Offs. *Volume 3b: 15th International Conference on Design Theory and Methodology*, 819–827. https://doi.org/10.1115/DETC2003/DTM-48676

Ball, L. J., & Christensen, B. T. (2019). Advancing an understanding of design cognition and design metacognition: Progress and prospects. *Design Studies*, *65*, 35–59. https://doi.org/10.1016/j.destud.2019.10.003

Barthol, R. P., & Bridge, R. G. (1968). The ECHO Multi-Response Method for Surveying Value and Influence Patterns in Groups. *Psychological Reports*, *22*, 1345–1354. https://doi.org/10.2466/pr0.1968.22.3c.1345

Bate, I. (2008). Systematic approaches to understanding and evaluating design trade-offs. *Journal of Systems and Software*, *81*(8), 1253–1271. https://doi.org/10.1016/j.jss.2007.10.032

Bavelas, A. (1942). A Method for Investigating Individual and Group Ideology. *Sociometry*, *5*(4), 371–377. http://links.jstor.org/sici?sici=0038-0431%28194211%295%3A4%3C371%3AAMFIIA%3E2.0.CO%3B2-Z

Belecheanu, R., Riedel, J. C. K. H., & Pawar, K. S. (2005). An investigation of design trade-offs in the automotive industry. *2005 IEEE International Technology Management Conference*, 1–10. https://doi.org/10.1109/ITMC.2005.7461306

Biskjaer, M. M., Dalsgaard, P., & Halskov, K. (2014). A constraint-based understanding of design spaces. *Proceedings of the 2014 Conference on Designing Interactive Systems*, 453–462. https://doi.org/10.1145/2598510.2598533

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design Issues*, *8*(2), 5. https://doi.org/10.2307/1511637

Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in Ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*, *14*(15–16), 1420–1430. https://doi.org/10.1016/j.jclepro.2005.03.024

Cardoso, C., Badke-Schaub, P., & Eris, O. (2016). Inflection moments in design discourse: How questions drive problem framing during idea generation. *Design Studies*, *46*, 59–78. https://doi.org/10.1016/j.destud.2016.07.002

Carnahan, J. V., & Thurston, D. L. (1998). Trade-off Modeling for Product and Manufacturing Process Design for the Environment. *Journal of Industrial Ecology*, *2*(1), 79–92. https://doi.org/10.1162/jiec.1998.2.1.79

Chakrabarti, A., & Blessing, L. T. M. (Eds.). (2014). *An Anthology of Theories and Models of Design*. Springer London.

Chandrasekera, T., Vo, N., & D'Souza, N. (2013). The effect of subliminal suggestions on Sudden Moments of Inspiration (SMI) in the design process. *Design Studies*, *34*(2), 193–215. https://doi.org/10.1016/j.destud.2012.09.002

Cisco. (2021). *WebEx*. [Computer software]. https://www.webex.com/

Clancey, W. J. (1997). *Situated Cognition: On Human Knowledge and Computer Representations*. Cambridge University Press.

Clarke, D., & Duimering, P. R. (2006). How computer gamers experience the game situation. *Computers in Entertainment*, *4*(3), 6. https://doi.org/10.1145/1146816.1146827

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, *38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Crilly, N. (2019a). Creativity and fixation in the real world: A literature review of case study research. *Design Studies*, *64*, 154–168. https://doi.org/10.1016/j.destud.2019.07.002

Crilly, N. (2019b). Methodological diversity and theoretical integration: Research in design fixation as an example of fixation in research design? *Design Studies*, *65*, 78–106. https://doi.org/10.1016/j.destud.2019.10.006

Crilly, N., & Moroşanu Firth, R. (2019). Creativity and fixation in the real world: Three case studies of invention, design and innovation. *Design Studies*, *64*, 169–212. https://doi.org/10.1016/j.destud.2019.07.003

Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. In W. C. Newstetter, C. M. Eastman, & W. M. McCracken (Eds.), *Design Knowing and Learning: Cognition in Design Education* (pp. 79–103). Elsevier Science.

Cross, N. (2006). *Designerly Ways of Knowing*. Springer-Verlag.

Cross, N. (2011). *Design Thinking: Understanding How Designers Think and Work*. Berg.

Cross, N., & Clayburn Cross, A. (1998). Expertise in Engineering Design. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, *10*(3), 141–149. https://doi.org/10.1007/BF01607156

Cunningham, J. B. (2001). *Researching Organizational Values and Beliefs: The Echo Approach*. Praeger.

Daly, S., McGowan, A., & Papalambros, P. (2013). Using qualitative research methods in engineering design research. *Proceedings of the 19th International Conference on Engineering Design (ICED13)*, 203–212.

Danilovic, M., & Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Project Management*, *25*(3), 300–314. https://doi.org/10.1016/j.ijproman.2006.11.003

de Koeijer, B., de Lange, J., & Wever, R. (2017). Desired, perceived, and achieved sustainability: Trade-offs in strategic and operational packaging development. *Sustainability (Switzerland)*, *9*(10), 1923. https://doi.org/10.3390/su9101923

Dorst, K. (2011). The core of 'design thinking' and its application. *Design Studies*, *32*(6), 521–532. https://doi.org/10.1016/j.destud.2011.07.006

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem-solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Dubois, S., Lin, L., De Guio, R., & Rasovska, I. (2015). From simulation to invention, beyond the pareto-frontier. *Proceedings of the 20th International Conference on Engineering Design (ICED 15)*, 6.

Duimering, P. R., Purdy, L., Safayeni, F., & Road, D. M. (1998). Applications of Ashby's Law of Requisite Variety to the Practice of Manufacturing. *Proceedings of the World Multiconference on Systemics, Cybernetics, and Informatics*, *3*, 749–756.

Ekelund, R. B., & Hebert, R. F. (2007). *A History of Economic Theory and Method* (5th ed.). Waveland.

Fischer, G. (2018). Identifying and exploring design trade-offs in human-centered design. *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*, 1–9. https://doi.org/10.1145/3206505.3206514

Gero, J. S. (1990). Design prototypes : A knowledge-based schema for design. *The AI Magazine*, *11*(4), 26–36. https://doi.org/10.1609/aimag.v11i4.854

Gero, J. S. (2002). Computational models of creative designing based on situated cognition. *Proceedings of the Fourth Conference on Creativity & Cognition - C&C '02*, 3–10. https://doi.org/10.1145/581710.581712

Gero, J. S., & Kannengiesser, U. (2004). The situated function–behaviour–structure framework. *Design Studies*, *25*(4), 373–391. https://doi.org/10.1016/j.destud.2003.10.010

Gero, J. S., & Kannengiesser, U. (2007). An ontology of situated design teams. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *21*(3), 295–308. https://doi.org/10.1017/S0890060407000297

Gero, J. S., & Kazakov, V. (1999). An Interpolation/Extrapolation Process For Creative Designing. *Computers in Building*, 263–274. https://doi.org/10.1007/978-1-4615-5047-1_17

Gero, J. S., & Kazakov, V. (2000). Adaptive enlargement of state spaces in evolutionary designing. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *14*(1), 31–38. https://doi.org/10.1017/S0890060400141034

Gero, J. S., & Kumar, B. (1993). Expanding design spaces through new design variables. *Design Studies*, *14*(2), 210–221. https://doi.org/10.1016/0142-694X(93)80048-H

Gibson, R. B. (2013). Avoiding sustainability trade-offs in environmental assessment. *Impact Assessment and Project Appraisal*, *31*(1), 2–12. https://doi.org/10.1080/14615517.2013.764633

Goel, V., & Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science*, *16*(3), 395–429. https://doi.org/10.1016/0364-0213(92)90038-V

Govers, C. P. M. (1996). What and how about quality function deployment (QFD). *International Journal of Production Economics*, *46–47*, 575–585. https://doi.org/10.1016/0925-5273(95)00113-1

Hahn, T., Figge, F., Pinkse, J., & Preuss, L. (2010). Trade-offs in corporate sustainability: you can't have your cake and eat it. *Business Strategy and the Environment*, *19*(4), 217–229. https://doi.org/10.1002/bse.674

Hajela, P., & Lin, C.-Y. (1992). Genetic search strategies in multicriterion optimal design. *Structural Optimization*, *4*(2), 99–107. https://doi.org/10.1007/BF01759923

Hall, A., Mayer, T., Wuggetzer, I., & Childs, P. R. N. (2013). Future aircraft cabins and design thinking: optimisation vs. win-win scenarios. *Propulsion and Power Research*, *2*(2), 85–95. https://doi.org/10.1016/j.jppr.2013.04.001

Halmos, P. R. (1974). *Naive Set Theory* (S. Axler, F. W. Gehring, & K. A. Ribet (Eds.)). Springer. https://doi.org/10.1007/978-1-4757-1645-0

Haskins Lisle, A., Merenda, C., & Gabbard, J. (2020). Using affinity diagramming to generate a codebook: a case study on young military veterans and community reintegration. *Qualitative Research*, *20*(4), 396–413. https://doi.org/10.1177/1468794119851324

Hatchuel, A., & Weil, B. (2009). C-K design theory: an advanced formulation. *Research in Engineering Design*, *19*(4), 181–192. https://doi.org/10.1007/s00163-008-0043-4

Hatchuel, A., & Weil, B. (2003). A new approach of innovative Design: an introduction to CK theory. *Proceedings of the 14th International Conference on Engineering Design (ICED03)*, 109–110.

Ilevbare, I. M., Probert, D., & Phaal, R. (2013). A review of TRIZ, and its benefits and challenges in practice. *Technovation*, *33*(2–3), 30–37. https://doi.org/10.1016/j.technovation.2012.11.003

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11. https://doi.org/10.1016/0142-694X(91)90003-F

Johansson-Sköldberg, U., Woodilla, J., & Çetinkaya, M. (2013). Design thinking: Past, present and possible futures. *Creativity and Innovation Management*, *22*(2), 121–146. https://doi.org/10.1111/caim.12023

Jonassen, D., Strobel, J., & Lee, C. B. (2006). Everyday Problem Solving in Engineering: Lessons for Engineering Educators. *Journal of Engineering Education*, *95*(2), 139–151. https://doi.org/10.1002/j.2168-9830.2006.tb00885.x

Kaliszewski, I., Kiczkowiak, T., & Miroforidis, J. (2016). Mechanical design, multiple criteria decision making and Pareto optimality gap. *Engineering Computations*, *33*(3), 876–895. https://doi.org/10.1108/EC-03-2014-0065

Katz, J. I. (2014). Quantifying "cliffs" in design space. *Journal of Engineering, Design and Technology*, *12*(3), 374–388. https://doi.org/10.1108/JEDT-11-2012-0048

Kazakçi, A. O., & Tsoukias, A. (2005). Extending the C-K design theory: A theoretical background for personal design assistants. *Journal of Engineering Design*, *16*(4), 399–411. https://doi.org/10.1080/09544820500131300

Koziel, S., & Bekasiewicz, A. (2018). Point-by-point Pareto front exploration and adjoint sensitivities for rapid multi-objective optimization of compact impedance matching transformers. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, *31*(5), 1–7. https://doi.org/10.1002/jnm.2350

Krippendorff, K. (2006). *The Semantic Turn: A New Foundation for Design*. Taylor & Francis.

Kumar, B., & Gero, J. S. (1993). Designing for conflicting constraints. *Computing Systems in Engineering*, *4*(1), 75–86. https://doi.org/10.1016/0956-0521(93)90031-Q

Kurasaki, K. S. (2000). Intercoder Reliability for Validating Conclusions Drawn from Open-Ended Interview Data. *Field Methods*, *12*(3), 179–194. https://doi.org/10.1177/1525822X0001200301

Lawson, B. (2005). *How designers think* (4th ed.). Architectural Press.

Maher, M. Lou, & Poon, J. (1996). Modeling Design Exploration as Co-Evolution. *Computer-Aided Civil and Infrastructure Engineering*, *11*(3), 195–209. https://doi.org/10.1111/j.1467-8667.1996.tb00323.x

Malak, R. J., & Paredis, C. J. J. (2010). Using Parameterized Pareto Sets to Model Design Concepts. *Journal of Mechanical Design*, *132*(4). https://doi.org/10.1115/1.4001345

Mastroddi, F., & Gemma, S. (2013). Analysis of Pareto frontiers for multidisciplinary design optimization of aircraft. *Aerospace Science and Technology*, *28*(1), 40–55. https://doi.org/10.1016/j.ast.2012.10.003

Mattson, C. A., Pack, A. T., Lofthouse, V., & Bhamra, T. (2019). Using a Product's Sustainability Space as a Design Exploration Tool. *Design Science*, *5*(e1), 1–34. https://doi.org/10.1017/dsj.2018.6

McDonnell, J. (2018). Design roulette: A close examination of collaborative decision-making in design from the perspective of framing. *Design Studies*, *57*, 75–92. https://doi.org/10.1016/j.destud.2018.03.001

Miller, G. A. (1956). The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. *The Psychological Review*, *63*(2), 81–97. https://doi.org/10.1037/h0043158

Otto, K. N., & Antonsson, E. K. (1991). Trade-off strategies in engineering design. *Research in Engineering Design*, *3*(2), 87–103. https://doi.org/10.1007/BF01581342

Parayre, R. (1995). The strategic implications of sunk costs: A behavioral perspective. *Journal of Economic Behavior & Organization*, *28*(3), 417–442. https://doi.org/10.1016/0167-2681(95)00045-3

Patton, M. Q. (2015). *Qualitative research and evaluation methods* (4th ed.). Sage Publications, Inc.

Poon, J., & Maher, M. Lou. (1997). Co-evolution and emergence in design. *Artificial Intelligence in Engineering*, *11*(3), 319–327. https://doi.org/10.1016/S0954-1810(96)00047-7

Rafiq, M. Y. (2000). Importance of Pareto optimum solutions in making informed decisions in engineering design. *Computing in Civil and Building Engineering*, 1325–1333. https://doi.org/10.1061/40513(279)173

Reich, Y. (1995). A critical review of General Design Theory. *Research in Engineering Design*, *7*(1), 1–18. https://doi.org/10.1007/BF01681909

Safayeni, F., Duimering, P. R., Zheng, K., Derbentseva, N., Poile, C., & Ran, B. (2008). Requirements Engineering in New Product Development. *Communications of the ACM*, *51*(3), 77–82. https://doi.org/10.1145/1325555.1325570

Schacter, D. L. (1999). The seven sins of memory: Insights from psychology and cognitive neuroscience. *American Psychologist*, *54*(3), 182–203. https://doi.org/10.1037/0003-066X.54.3.182

Schön, D. A. (1983). *The Reflective Practitioner*. Basic Books.

Schön, D. A. (1988). Designing: Rules, types and words. *Design Studies*, *9*(3), 181–190. https://doi.org/10.1016/0142-694X(88)90047-6

Schön, D. A., & Wiggins, G. (1992). Kinds of Seeing in Designing. *Creativity and Innovation Management*, *1*(2), 68–74. https://doi.org/10.1111/j.1467-8691.1992.tb00031.x

Schulz, A., Wang, H., Grinspun, E., Solomon, J., & Matusik, W. (2018). Interactive exploration of design trade-offs. *ACM Transactions on Graphics*, *37*(4). https://doi.org/10.1145/3197517.3201385

Shai, O., & Reich, Y. (2004a). Infused design. I. Theory. *Research in Engineering Design*, *15*(2), 93–107. https://doi.org/10.1007/s00163-004-0047-7

Shai, O., & Reich, Y. (2004b). Infused design. II. Practice. *Research in Engineering Design*, *15*(2), 108–121. https://doi.org/10.1007/s00163-004-0048-6

Simon, H. A. (1956). Rational choice and the structure of the environment. *Psychological Review*, *63*(2), 129–138. https://doi.org/10.1037/h0042769

Simon, H. A. (1969). *The Sciences of the Artificial* (1st ed.). The MIT Press Ltd.

Simon, H. A., & Newell, A. (1971). Human problem solving: The state of the theory in 1970. *American Psychologist*, *26*(2), 145–159. https://doi.org/10.1037/h0030806

Stacey, M., & Eckert, C. (2010). Reshaping the box: creative designing as constraint management. *International Journal of Product Development*, *11*(3/4), 241. https://doi.org/10.1504/IJPD.2010.033960

Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill Higher Education.

Stevens, S. S. (1946). On the Theory of Scales of Measurement. *Science*, *103*(2684), 677–680. https://doi.org/10.1126/science.103.2684.677

Suwa, M., Gero, J., & Purcell, T. (2000). Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies*, *21*(6), 539–567. https://doi.org/10.1016/S0142-694X(99)00034-4

Suwa, M., & Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies*, *18*(4), 385–403. https://doi.org/10.1016/s0142-694x(97)00008-2

Thomas, J. C., & Carroll, J. M. (1979). The psychological study of design. *Design Studies*, *1*(1), 5–11. https://doi.org/10.1016/0142-694X(79)90020-6

Ullman, D. G., Dietterich, T. G., & Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *2*(1), 33–52. https://doi.org/10.1017/S0890060400000536

Wu, Z., & Pagell, M. (2011). Balancing priorities: Decision-making in sustainable supply chain management. *Journal of Operations Management*, *29*(6), 577–590. https://doi.org/10.1016/j.jom.2010.10.001

Yin, R. K. (2017). *Case Study Research and Applications: Design and Methods* (6th ed.). Sage Publications.

Appendices

Appendix A - Interview Protocol

Interview Questionnaire: Trade-offs[1]

Demographic and Background Information

1. What is your current title/role?
2. How long have you been a designer/design engineer?
3. What other design roles have you had in your career?
4. What different types of design have you been involved with over your career (e.g., industrial design, architectural, mechanical, graphic, software…)?
5. Have you received any training in design, either formally or informally?

Exploration of Trade-off Situations

Provide the participant with a definition of design trade-offs and a simple example or two.

Requirement Conflict: *A situation wherein two design requirements cannot be met simultaneously using the current approach.*

Design Trade-off: *A situation where any gains in one area or aspect of the design are associated with sacrifices in other area(s) or aspect(s).*

Examples:

- Ease of assembly vs strength of connection
- Recycled material content vs strength and durability of material
- Pleasantness of an alarm vs effectiveness of the alarm

6. Can you provide us with an example of a difficult situation while designing where you were faced with a conflict between design requirements?
    i. How was this situation resolved? Was the result satisfactory to the design team?

---

[1] Other questions may arise during the interview as it is semi-structured and will take the form of a guided conversation. The echo interview technique will be used to gain insight into the designers perceived network of influences on trade-off situations and to determine the designers perceptions of positive and negative influences elements of this network can have on their design process in trade-off situations.

    b. Alternatively, can you provide us with an example of a situation while designing where you were faced with a trade-off that you found challenging to deal with?
        i. What elements/goals of the design were in conflict?
        ii. What was the eventual solution
    c. Alternatively, can you provide us with an example of when you came to a creative solution in your design process to a problem that was posing severe difficulty?
    d. Alternatively, can you provide us with an example of an instance where your design process experienced a significant change in design direction?
    e. Alternatively, can you provide us with an example of when your design was not able to meet all the requirements associated with it?

7. Can you provide some examples of things you did (decisions you made, things that happened, etc.) that made it easier reach your solution?
8. Can you give some examples of things that made it more difficult to reach your solution?

Follow up on the stakeholders and influences identified above.

9. Can you identify the stakeholders and human influences that affected that trade-off situation?
10. Can you identify any non-human or technical influences on that trade-off situation?

For each of the identified influences:

11. Can you provide specific examples of actions taken by (*stakeholder/influence*) that made it easier to come to the solution that you did?
12. Can you provide specific examples of actions taken by (*stakeholder/influence*) that made it more difficult to come to the solution that you did?

Conclusion/Debrief Questions

13. Can the research team contact you again after this interview to arrange a follow-up interview should the findings warrant it?

Appendix B – Detailed Modelling of Case Studies

Systems Modeling Process

All the networks presented in this appendix model the explicit design space and its components as they were framed by the subjects during their interviews. Figure 7 below provides a common legend that will be used by all the parameter influence networks in this thesis. The nodes in the network are colour-coded according to the level of measurement of a parameter (Stevens, 1946), as it was framed by the subject. The lowest level of measurement present in the networks were static parameters. Static parameters represent explicit influences and parameters that the designer had no agency to change. Examples of these include properties of a design's intended functional environment and parameters that characterize other, already completed, designs that interfaced with the new design.

Legend
- —— Reinforcing Interaction
- —— Balancing Interaction
- —— Changes
- —— Makes Explicit
- ---- Imposes Limits
- —— Parameter Value
- ● Evaluative (Maximize)
- ● Evaluative (Minimize)
- ● Evaluative (Nominal)
- ● Ordinal Parameter
- ● Categorical Parameter
- ● Static Parameter
- ● Parameter Value
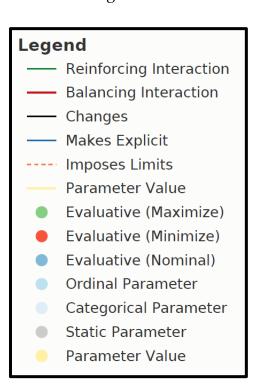
FIGURE 7: LEGEND FOR PARAMETER INTERACTION NETWORKS

The next level of measurement was the categorical parameters, which may also be called nominal parameters. These parameters represented categories of options that

have no inherent order or ranking. This category also includes a sub-classification of parameter the theoretical model refers to as "feature" parameters. These feature parameters are binary parameters that represent the presence or absence of a feature in the design. Typically, these feature parameters are not part of the explicit design space when they hold the value of absent, being made explicit when the designer decides to add the feature to the design.

Because categorical parameters have no inherent order, the influence networks presented in this thesis will occasionally separate out the different values of the parameter, which are represented by a colour-coded link and node. This allows the visualization to show the different influences the different values of the categorical parameter have on the other parameters in the explicit design space.

The remaining two parameters, ordinal and evaluative, represent parameters that have some form of rank or order, either inherently or imposed. Ordinal parameters in this usage are the parameters that have an inherent ranking between values, and can be discrete or continuous, not just rank ordered.

The evaluative parameters are a special case of ordinal parameters in the context of the design space. These evaluative parameters are ordered based on a preference assigned to them by the designer or another stakeholder. Typically, this preference ordering implies a goal of the design was operationalized into this parameter. The evaluative parameters are colour coded based on the direction of that goal, split into three categories: minimizing, maximizing, and nominal. Minimizing and maximizing goals imply that the designer preferred either the lowest or highest possible performance they could on those parameter respectively, while still meeting all of the other constraints and goals.

Nominal goals were harder to model in these networks, since they represent the designer seeking to hit a target, with the preference of a solution decreasing as the value moves away from that target in either direction. Since the parameter interaction

networks as it is currently formulated does not represent individual parameter values, the value of this nominal goal, and therefore the proximity to it, is not modelled. Instead, the connections between other parameters and a nominal goal are classified as moving closer to the goal or further away based on the designer's description of both the influence and the starting point on that parameter. Usually this starting point represented an initial solution concept's placement on that parameter, and so connections were classified based on whether increasing that parameter would get closer or further from the nominal target, relative to the initial solution's value.

The legend for the connections between nodes in the network is also defined in Figure 7 above. The two primary types of connection are reinforcing and balancing interactions. Both influences are modeled as directional, based on the designers' descriptions of which parameter affected the other. Reinforcing interactions mean that a move in one direction on the source parameter (i.e., either an increase or a decrease) results in a move in the same direction on the destination parameter. Balancing interactions on the other hand move in opposite directions. They are colour-coded as in Figure 7.

Reinforcing and balancing influences are multiplicative, which means that the resultant influence on an evaluative parameter from an indirectly connected parameter can be calculated by translating reinforcing to "positive" and balancing to "negative" and multiplying all of the positive and negatives, including the sign of the goal (i.e., maximizing = positive, minimizing = negative),together with the resulting sign indicating the directionality of the indirect influence.

There are three other types of influences that are modeled in the parameter influence networks, which are tagged "Imposes Limits", "Makes Explicit", and "Changes" in Figure 7 above. The last connection type "Parameter Values" was already discussed above and is used to connect parameter values to the categorical parameter that contains those values. Connections coded as "Imposes Limits" represent an interaction between parameters that imposes a boundary on the destination parameter. These are

125

not classified as complementary or antagonistic influences because changing the value of the source parameter does not change the value of destination parameter.

A connection labeled as "Makes Explicit" represents the concept of associated parameters from the theoretical model. This code is applied when the analysis of an existing parameter or the addition of a new parameter cause the designer to explicitly consider another parameter.

Lastly, the "Changes" category has two functions in the parameter influence networks. The first is to label influences that the designers mentioned as explicitly existing between two parameters, but without providing enough details to determine directionality.

The second is to denote influences between two categorical parameters. Directional influences cannot lead into a categorical parameter because they have no inherent order. If the source of the influence is also categorical then an interaction between the two can only be classified as "Changes", where changing the value of the source will result in a different value on the destination with no predictable or consistent pattern.

Case I1

The interviewee was a consultant who had been brought in by a start up firm to solve a problem they were having with low robustness and reliability on their robotics product, which was operationalized using the metric of mean-time-between-failures.

Initially the interviewee and the rest of the design team spent time and effort attempting to optimize several parameters like the cost and weight of the robot. However, by spending this time designing and refining they were inadvertently costing the company more money in opportunity costs lost from having the robots out of service than they were saving by optimizing the costs of individual components. This trade-off was made explicit by the CEO of the start-up, who noted that having the robots out of service costed the company $25,000 per week. By introducing this framing,

the interviewee described the situation as being "one-dimensionalized", with the cost to the company becoming a "weighting function" of how much relative gain each design decision would have. This weighting function allowed the interviewee and design team to prioritize which design features to focus on by their expected savings, if a feature does not have the potential to save more than $25,000 times the number of weeks it would take to design, then it is not a viable feature.

Modeling Case I1

The initial goals of the project were to increase the robustness of the robots, operationalized into the parameter of "mean-time-between-failures" (MTBF), and to reduce the cost of the robot. Additionally, there were some flexible requirements on evaluative parameters of component cost and weight, storage volume, and aesthetics; although the operationalization of these requirements was not discussed in detail by the interviewee.

The conflict in this case was initially framed as a project timeline versus robustness of design, as shown in Figure 8 below. The timeline was a context specific factor that influenced which solutions are viable, given the project resources, and therefore influenced the boundaries on the design space.

This was modeled as the parameter representing the timeline goal interacting with the robustness parameter in a reinforcing relationship, so that when the MTBF for robustness was improved (moved to a more preferred value along the parameter) then the timeline was extended (moved to a less preferred value along the parameter).
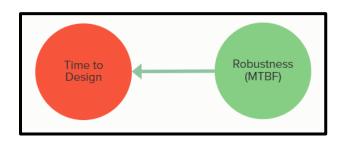
FIGURE 8: INITIAL TRADE-OFF IN CASE I1

It should be noted that the interviewee did not have validated evidence that spending longer on the design would improve MTBF. This indicates that the interviewee was making judgements in a perceptual level of the design space, based on their beliefs about how the two parameters interacted. Whether the real interaction between these parameters followed the interviewee's intuition cannot be determined from the data presented in the transcript.

Additionally, the team spent time investigating and developing to improve performance along several other evaluative parameters, with the interviewee primarily discussing the cost and weight of different components. The interviewee then retroactively characterized this exploration as a confounding factor, that distracted the team from the real underlying goal of the design, which was made evident by a reformulation driven by the CEO. The resolution of this conflict, when the CEO of the start-up reformulated the goal of the project being to reduce costs at the company level. This was modeled as them revisiting the underlying goals of the design project and choosing different, more representative operationalizations for these goals.

The underlying need behind the goal for increased robot robustness was revisited and a separate evaluative parameter, cost to the company, is made explicit in the design space, as shown in Figure 9 below. The new project goal was to minimize the cost to the company, and the "time to design" and "robustness" parameters were no longer evaluative. Development time is no longer used as an evaluative parameter but is directly correlated to the new cost to the company parameter at a rate of $25,000 per week that the robots are not operating. The robustness parameter, MTBF, also reduces cost to the company through the mediating parameters of reduced repair cost and lost operational time due to failure, but the interviewee did not quantify the relationship as explicitly as they did the development time to cost relationship, so the mediating parameters are not included in the frame.
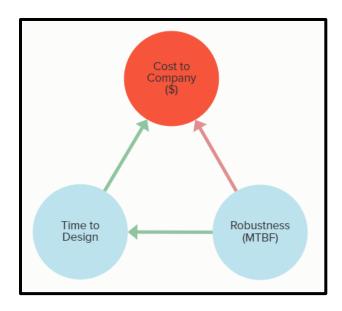
Since both parameters originally in conflict, development time and robustness, could be evaluated using the new cost to company parameter, the trade-off in the design project was simplified, but not avoided, and could be evaluated by minimizing the net cost to the company.

Case I2

The second case was an engineering student final year design project with the aim to design aftermarket system that could convert a consumer vehicle powered by an internal combustion (IC) engine into a hybrid vehicle with a secondary electric motor. The design team was sponsored two engines by the original equipment manufacturer (OEM) of the consumer vehicle for the purposes of this project. These engines were provided separate from the vehicle and without any auxiliary systems such as exhaust or cooling.

The addition of hybrid functionality to the engine drive system was accomplished by adding an additional electric motor that connected to the power output shaft before the mechanical clutch that connected the IC engine to the transmission and allowed the power delivery to be temporarily interrupted during shifting between transmission

gears. This interruption allowed the shifting to be smooth and "jerk-free", which was a requirement imposed on the design by the desires of potential future customers. The designer chose to use a chain drive to connect the electric motor to the power output shaft. To transfer power from the chain to the output shaft, the shaft needed to accommodate a new sprocket (a toothed wheel which meshes with the chain and transfers power to a shaft).

However, the distance between the mechanical clutch and the IC engine was too short to accommodate the width of the sprocket selected. The designer's response to this limitation was redesign a longer power output shaft. Additionally, the transmission housing had to be extended to accommodate the longer gap between the engine and the clutch for the new sprocket. The designers initial attempt to extend the power output shaft failed because their manufacturing method altered the material composition of the shaft, and it no longer had the mechanical strength to resist the load placed upon it and it failed in operation. To solve this issue the designers sought out an alternative welding approach, which did not alter the material composition, for extending the shaft.

There was also a desire to incorporate wireless remote shifting capabilities into the system, as the designers believed that this was a direction the automotive industry was trending towards. A pneumatically actuator was selected as the solution to remotely engage and disengage the mechanical clutch lever, which also introduced the requirement to include an air compressor. However, the actuator could not be attached directly to either the engine or transmission cases, since doing so required specialized welding equipment and expertise, and was quite risky as it could weaken the integrity of the engine case.

In response, the interviewee and his teammates designed a mounting bracket that could attach to an existing mounting point on the transmission case. This mounting bracket as designed caused the linear actuator to be unaligned with the clutch lever operating plane, necessitating a solution that converted the linear motion of the actuator into an

arc motion to operate the clutch lever. The design team attempted to use a section of cable normally used to operate brake systems because it was flexible enough to convert the motion but had enough mechanical strength to withstand the clutch load but were unsure if they could attach the brake cable to the actuator and lever. A search of different welding methods again proved fruitful, and the team was able to identify a method that would allow them to weld the cable to both other components.

While the team was successful in designing the systems to most of the requirements they set out for themselves and were working on securing a patent for the design, one requirement was unmet at the conclusion of the project. By using a pneumatic actuator, they introduced a requirement for an air compressor of sufficient capacity to operate the actuator under the clutch loads. The only compressors they could identify and procure that met this requirement were quite large, approximately 2 feet cubed in volume. The result was that these compressors would not fit into the intended vehicles for the system, and this issue was unresolved at the time of the interview.

Modeling Case I2

The goal of making the vehicle a hybrid required that a connection to transfer the electrical power to the power output shaft of the IC engine and a way to switch between power sources that was smooth and "jerk-free" be incorporated in the design.

As shown in Figure 10 below, the connection to the power shaft was modeled as a binary feature parameter (i.e., was the connection present in the design or not) with a requirement that the connection be present, as this is how it was described in the interview. Using this modelling, any design solution that did not connect the electric motor to the power output shaft violated a membership criterion and was therefore not viable. As the operationalization of the smooth shifting goal was not discussed in detail by the interviewee, other than the allusion that this goal prompted the placement of the chain drive sprocket prior to the mechanical clutch, it was not included in the model in Figure 10.
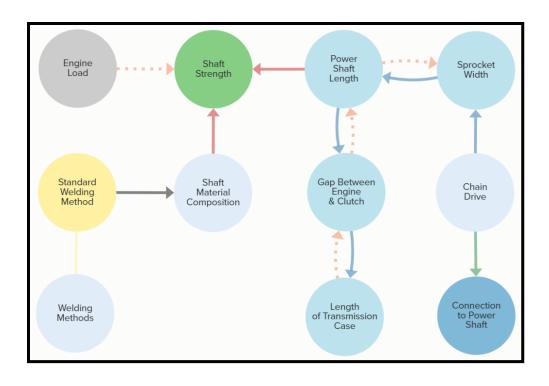
FIGURE 10: INITIAL CONFLICT FOR CONNECTING THE ELECTRIC MOTOR IN CASE I2

The decision to use a chain drive to connect the electric motor to the main driveshaft introduced the need for a sprocket on the power output shaft to connect the chain. At the level of detail provided by the designer in the interview, both the chain drive mechanism and the sprocket were also binary feature parameters. However, the selection of a chain drive mechanism, an associated set of parameters on sprocket size were made explicit, due to the thickness of the sprocket selected being too wide for the space available on the original power output shaft of the vehicle. This can be modeled as an interaction between the parameters of power output shaft length and sprocket thickness, with the value for the power output shaft length being locked to a value selected by the OEM, which imposes bounds upon the sprocket thickness parameter. In turn, the length of the power output shaft was constrained by the length of the external casing that encapsulated the transmission.

The dimensional conflict was resolved by revising decisions made on the values of the parameters that were imposing the limits. This required that the designers redesign a

longer transmission case and power output shaft, which relaxed the boundary on the thickness of the sprocket parameter.

The length of the shaft was also constrained minimum by strength requirements driven by the power output of the IC engine and the electric motor. Initially the strength of design solution described above with the new, longer, shaft was below the functional requirement driven by the mechanical load applied to the shaft. This meant the shaft was not meeting a membership criterion on an evaluative parameter and therefore was non-viable. This non-viability was physically evident for this instance because the shaft failed when tested at the operating conditions.

As the interviewee had not expected the shaft to fail, this indicated that their expectations of the strength parameter's performance was not aligned with the real-world performance. Prior to this failure the designer had not explicitly considered the composition of the shaft material, which were non-evaluative parameters that partially determined the strength of the shaft. Once the designer investigated the source of the failure these parameters were made explicit. However, the method they used to lengthen the new shaft, welding an extension onto the original shaft, interacted with both the material composition parameter, which in turn negatively influenced the strength of the design.

The solution the designer described, a novel welding method that did not affect the material composition, can be modelled in one of two ways. The first is to treat the new welding method as a separate binary feature parameter that is mutually exclusive (see Table 4 below for clarification) with the feature parameter for the original welding method.

TABLE 4: POSSIBLE PERMUTATIONS OF MUTUALLY EXCLUSIVE FEATURE PARAMETERS IN CASE I2

Original Welding Method	New Welding Method	Viable Combination?

Absent	Absent	Yes
Present	Absent	Yes
Absent	Present	Yes
Present	Present	No

The second is to model both welding methods as different values along a higher-order, nominal "welding method" parameter. This higher-order parameter is categorical because it is not internally preference ordered (i.e., no welding method is preferred when removed from the context of the other parameters like material strength). However, choosing different values for this welding method parameter does indirectly influence an evaluative parameter, shaft strength, by proxy of its direct influence on the material composition parameter. This second representation better reflects how the designer discussed the resolution in the interview and is presented in Figure 11 below. The new welding method no longer influences the shaft strength, so there is no link between that parameter value and the shaft strength evaluative parameter.
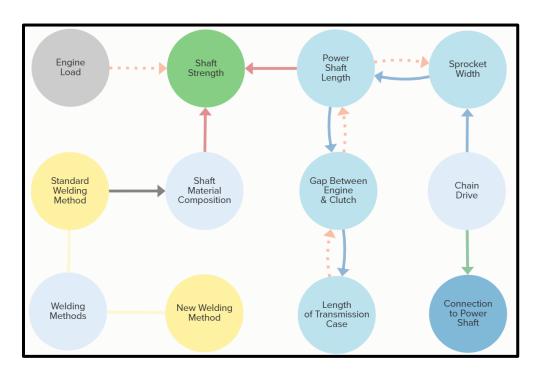
FIGURE 11: RESOLUTION FOR CONNECTING THE ELECTRIC MOTOR IN CASE I2

The second conflict was driven by the need to remotely actuate the original mechanical clutch that connected the IC engine to the transmission gears for shifting. This need was driven by several factors, the first of which was the goal for the system to be remotely operable, which was operationalized as an ordinal (preference ordered) binary feature parameter for remote operation capability, as shown in Figure 12 below. This goal meant that design solutions relying on manual operation of a pedal mechanically attached to the clutch to actuate it were preferred less than solutions that could be actuated from an operator at a distance. Therefore, the designer decided to use a pneumatic actuator that could be controlled by a wireless signal.
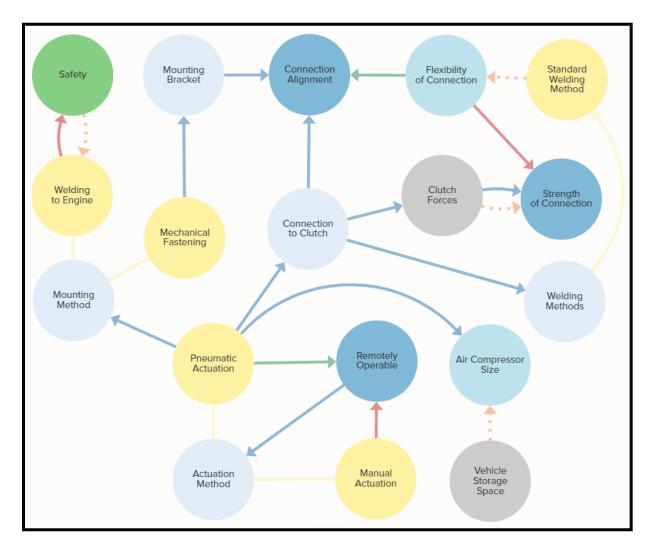
FIGURE 12: INITIAL CONFLICT FOR REMOTE CLUTCH ACTUATION IN CASE I2

However, the designer encountered several conflicts and barriers when they attempted to mount the pneumatic actuator so that it would align with the clutch lever it was supposed to actuate. The first of these barriers was the restriction on welding it directly onto the transmission case. In the interview, the designer stated that they were limited by the equipment they had available to them and their level of expertise for using that equipment even if it were available. The designer did not have access to welding equipment appropriate for use on an engine or transmission case and using inappropriate equipment to weld on these components would weaken them and increase the risk of material failure. This equipment can be represented as a value on a categorical parameter describing welding methods, or at a higher level of abstraction, a categorical mounting methods parameter as it is represented in Figure 12.

Regardless of which level is used to represent it, the designer is explicitly aware of a value on that parameter that they believe will allow them to attain the goal of attaching the actuator, with attachment being an evaluative binary parameter (attached/not attached). However, the welding option they did have available to them was not viable, because it had a detrimental influence on the safety of the system, which was another evaluative parameter.

The designer's response to this limitation was to use a different value on the joining method parameter, "mechanical fastening" using a bolt. This value was viable because of an available mounting point on the transmission case, which was represented as a binary feature parameter that hold the value of "present".

After the attachment bracket used to mount the pneumatic cylinder to the transmission case was manufactured, the designer discovered that the motion of the actuator did not align with the motion of the clutch lever. This boundary on the viable design space exists on a parameter or set of parameters representing the alignment between the actuating pneumatic piston and the clutch lever. This alignment parameter(s) has membership criteria representing the amount of misalignment the clutch lever can

136

tolerate and still function. The conflict here was that the current bracket caused the pneumatic piston's operating path to fall outside these bounds on misalignment, making it a non-viable solution.

The designer characterized the goals for this conflict as being a combination of flexibility and strength. They predicted that the flexibility of the connection between the piston and the clutch lever would relax the constraints on the alignment parameter, but the connection still needed to maintain a minimum physical strength to handle the forces imposed by the pneumatic piston and the clutch.

The trade-off between the parameters of strength and flexibility was resolved by proposing the use of brake cable material as the connection between the pneumatic actuator and the clutch lever, as shown in Figure 13 below. This brake cable had sufficient strength and flexibility to meet both of the conflicting requirements.
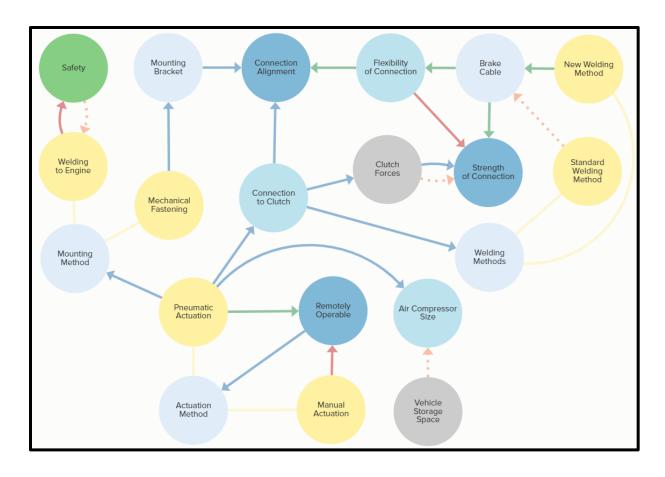
However, the solution using the brake cable material was initially non-viable in the explicit design space, because the designer was not aware of any way to attach the different materials of the cable, actuator, and lever together. The welding methods they were aware of, represented as the "standard welding method" value of the "welding methods" categorical parameter in Figure 13, limited the use of brake cable material.

This sub-conflict was resolved when the designer explored the possible welding methods further and identified a new option on that categorical parameter that could be used to join all three dissimilar materials. This at last provided the designer with a viable design solution to have a remotely operable clutch lever.

However, the overall project ran into one last barrier that the designer was not able to resolve. The use of a pneumatic actuator to manipulate the clutch lever required that an air compressor be included in the system somewhere. The compressor required to

operate the cylinder was quite large, approximately 2 feet on all sides. This conflicted with one of the primary goals of the project, to design a hybrid conversion system that could be installed on an existing consumer vehicle, because there was insufficient cargo space to include the compressor in that existing vehicle.

Case I3

Case I3 was another student design team who were confronted by a project resource constraint that caused a conflict between two goals stemming from two different interpretations of the team's purpose. This conflict occurred during the team's inaugural year, wherein they came to the end of a semester realizing that they had significantly undershot their design targets, only having completed 1 out of the 7 robots necessary for the competition. The interviewee, the team president, noted that they did not think it would be possible to design and manufacture the remaining 6 robots in-house within the remaining time in the schedule. To test this, the president arranged an experiment to measure their pace of manufacturing on a few components, which validated the assumption that they could not meet their goals using the in-house design approach. An alternative path that was allowed by the rules of this competition was to purchase consumer robotics components off-the-shelf and integrate them into their designs, to bypass some of the work necessary to design these components.

Herein lay the conflict at the heart of this case, which was between the goals of the design team to place highly in the competition and the goal for a student design team to help its members learn and develop hands-on engineering and manufacturing skills to complement their classroom learning. The interviewee, senior members of the team, and the external sponsors prioritized success in the competition, because of personal goals for success and pressure from the sponsors to place better, which would increase the exposure of their advertisement decals on the robot bodies. Whereas the university and the younger members prioritized the student learning goals, as well as a

complementary goal for the team to grow in a sustainable manner and retain expertise in the environment where members leave after graduation.

In this case, the interviewee called for a team meeting where the team discussed the options the president presented: giving up and withdrawing from the competition or buying off the shelf components and allowing the more experienced members to complete the design, while the less experienced members performed the "labour tasks". They chose to go with the purchasing and integrating option, and placed 2nd in the competition, achieving the goals of success in competition. However, members of the team expressed dissatisfaction with this result and process because they felt that the learning goals were sacrificed too much.

Modeling Case I3

This case had a network of parameter conflicts driven by two broad organizational goals, student learning and competition performance. These goals were driven by different stakeholders both within the student team and outside, demonstrating how the subjective nature of design goals and evaluation can result in different design spaces across different stakeholders.

As described in the summary above, the interviewee had encountered a barrier in the form of the competition deadline. Having exhausted a significant amount of time designing and manufacturing the first of seven robots, the designer predicted that they did not have sufficient time to design and build the remaining six robots before the deadline. The interview validated this assumed behaviour of the time spent designing parameter with a quasi-experimental trial. This is modeled as the designer aligning their perceived design space to the real underlying behaviour to improve the validity of their predictions.

Figure 14 below shows a model of this network of parameters and interactions as the interviewee characterized them. At the top lay the two goals, learning and competing. The interviewee did not discuss the operationalization of the learning goal(s) in detail,

just that they desired to maximize it, so it was modeled simply maximizing goal labeled "learning goals". The operationalization of the competition goals was discussed by the interviewee, as they were translated into completing the project by the deadline, and some form of parameter representing performance at the competition.
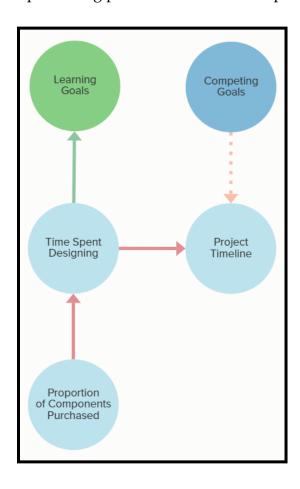
FIGURE 14: TRADE-OFF SITUATION IN CASE I3

However, the competing goals and the learning goals were in conflict by proxy of the project timeline parameter and the parameter representing time spent designing respectively. The project timeline and the time spent designing are quite clearly directly related, as more time spent designing would result in a longer project timeline. Herein lies the primary conflict in this case, as the interviewee believed that spending more time designing would increase learning, particularly for the newer members of the team. However, there was a boundary on the project timeline parameter that is imposed by the competition organizers and cannot be negotiated.

141

The interviewee had identified two approaches to designing the remaining six robots. The first was that they could design the remaining six in-house, as they had done with the first robot. This approach increased the time spent designing, and thereby the performance along whatever parameter(s) operationalized the learning goals. However, the interviewee believed that this approach would result in a project timeline exceeding the deadline, which makes this approach non-viable with respect to the goals of the project.

The second approach of purchasing the necessary components and simply assembling the robots had opposite effects on the evaluative parameters. This approach reduced the amount of time spent designing, and thereby decreased the project timeline under the deadline boundary. However, because less time was spent designing and therefore the performance on the learning goals was lower than the first approach. Performance on the learning goal was not completely removed though, since the assembly and manufacturing stages permitted the newer members to familiarize themselves with some aspects of the robots.

Both approaches as the interviewee described them can be modeled as two of the possible values for continuous parameter representing the proportion of the components that are purchased versus handmade. This description frames the decision as being between two ends of a spectrum, but the interviewee did mention a third option, giving up on the project altogether.

Modelling this third option is challenging within the theoretical framework, because the model assumes that the design project has goals that it is working towards, whereas giving up implies that the design project itself is halted, and therefore cannot be modeled as a set of viable solutions, so it was not included in Figure 14.

Returning to the model presented in Figure 14 earlier, the different choices along the proportion of purchased components parameter influenced the parameter of time spent designing, which in turn influenced project timeline. In this framing, the project

timeline and the time spent designing exist in a form of local Pareto optimality, where any gain on one must be associated with a loss on the other. The designers' response to this conflict was to prioritize the competition goal, based on the priorities of themselves, the more experienced team members, and the sponsors; but sacrificing the goals of the university and the newer team members.

Case I4 - 1

The 4th interviewee discussed several examples of conflicts and trade-offs they encountered in their role as a refrigeration system designer at a large infrastructure firm.

The first situation they described was during the design of a compressor rack that had to meet a cooling load of 300,000 British thermal units per hour, which they represented as 300 MBH. The designer had completed their preliminary design and had chosen a set of four compressors to meet that load, but when analyzing further found that the system could only handle 290 MBH. Initially, they attempted to replace one of the compressors with a larger compressor, which also happened to be more energy efficient. However, the horsepower required to run the larger compressor they specified was too high and violated a regulatory requirement for HVAC (Heating, Ventilation, and Air Conditioning) systems of this nature. The designer then investigated adding a supplementary component called a variable-frequency drive (VFD), which allowed the smaller compressors to be run at higher speeds (70 vs 60 Hertz). By running the compressors at a higher frequency, the system capacity was increased to 320 MBH, and therefore met the functional requirements, while sacrificing the potential efficiency gains of the larger compressor and adding the cost of the VFDs to the project.

Modeling Case I4-1

Case I4-1 exhibited two evaluative parameters in conflict: system capacity, operationalized as MBH; and system efficiency, operationalized as % energy efficiency. The goal on the system capacity parameter was operationalized as a nominal

143

requirement based on the system's intended heating and cooling load ("Functional Requirements of the System"), which was measured in MBH, plus whatever "safety factor" the designer included, as shown in Figure 15 below. This safety factor is represented as excess performance along the capacity parameter beyond the requirement. The structure of this goal was to meet this requirement, but not exceed it, since exceeding the goal by a significant margin would negatively influence performance on a fourth evaluative parameter, system cost.
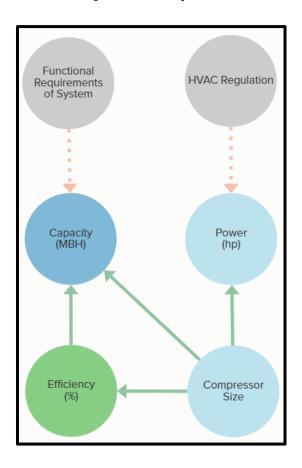
FIGURE 15: INITIAL TRADE-OFF SITUATION IN CASE I4-1

The system efficiency was a continuous evaluative parameter with a goal to maximize, where solutions with a higher % efficiency was preferred to lower, but the designer did not discuss any specific lower bounds on the efficiency during the interview. The parameter representing the power necessary to run the system was a continuous

144

ordinal parameter, and had a maximum bound placed upon it by external requirements ("HVAC Regulation") imposed by a regulation agency.

Figure 15 presents the initial conflict that limited the performance on the evaluative parameters and precluded a viable solution in this case. The initial solution designed by the interviewee failed to meet the minimum requirement on the capacity parameter, meaning that this solution fell outside of the viable set. In response to this, the designer initially looked at sourcing larger compressors, which was represented by the parameter of compressor size, which was already explicit in the problem frame. This size parameter was discrete, as the designer was sourcing compressors from external companies and not designing their own, but ordinal ranked on size.

The designer selected a larger value on the compressor size parameter and simulated the system performance to check if the real performance on all the evaluative parameters would meet all requirements. This simulation step represents a form of testing that aligns the designer's perceptual design space with the underlying real space. The designer discovered was that the larger compressor did meet the capacity requirement to be viable and proved to be more energy efficient than the smaller compressor. However, the new solution violated the regulatory requirement on the maximum system power parameter, which had not been explicit in the design space until now.

The final solution proposed by the designer, adding a VFD to the system, can be modeled as adding a feature parameter (presence of VFD) to the frame, as shown in Figure 16 below. This unlocks a previously unalterable parameter of compressor speed, operationalized in rpms. By allowing the designer to increase the original, smaller, compressors' speeds, the addition of the VFD improves the performance on the system capacity parameter. This improved performance is sufficient for the design solution to meet the requirements on the system capacity parameter.
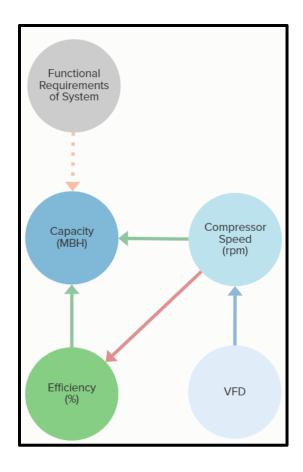
The interviewee noted that this VFD solution did have worse performance on the efficiency parameter than the larger compressor solution, but since there was no lower bound on this parameter the solution was still viable.

Case I4 - 2

The second situation that this interviewee described occurred after the design of a system had been completed and was being issued for construction, but an unexpected shortage of a specific valve size caused the designer to re-evaluate their design. The designer had original specified valves of size 9 for this system to meet the required system capacity while maintaining a maximum pressure-drop across the system that was under their company's best practice limits. However, due to unforeseen supply shortage caused by the COVID-19 pandemic in 2020, the manufacturer working on the project was not able to obtain any valves of size 9 and were unsure of when supply

would become available. The manufacturer did have access to size 7 valves, and they suggested using them as an alternative. When the designer ran their simulations to check whether a size 7 valve would work, they found that the size 7 valve met the functional requirements on system capacity and was still under the best practice pressure drop threshold, although it had higher pressure drop than a size 9 valve, reducing the capacity. In switching to a size 7 valve, the designer also saved on capital investment in the system, since size 7 valves were cheaper than size 9 even in situations with normal amounts of supply. However, this change did reduce the factor of safety on the system, and the designer noted that if the client ever wanted to increase the load on the system, they would have to upgrade all of the size 7 valves to size 9. This did not concern the designer much though, as they stated that requirements for this project were met, and if the client wanted to change those requirements by adding load, then that would be a new project with a new scope.

Modeling Case I4-2

Case I4-2 describes the addition of a limit onto a solution after the design had been completed that made it non-viable. The COVID-19 pandemic is an external factor, which could be modeled as a feature parameter (i.e., is the pandemic present or not). The onset of the COVID-19 pandemic caused a previously latent parameter, availability of the valves, to be made explicit. The manufacturer was the first to make this parameter explicit, as they were aware of the real availability in their stocks. This parameter representing the availability of components was framed by the interview as binary (available/not available), and the bounds on this parameter were that only a solution with that had a value of available was a member of the viable design space. After communicating this to the designer, the manufacturer suggests an alternative size for the valve. Valve size was already an explicit parameter, as it directly influenced the performance on three of the evaluative parameters of the project: the capital cost of the project; the system capacity, operationalized as MBH; and the system pressure drop, operationalized as pounds per square inch (psi). Figure 17 below models this situation,

with a slight alteration from the format presented at the beginning of this appendix. The difference is that the discrete ordinal parameter of "valve size" is broken into the two parameter values of "size 7" and "size 9" that the designer discussed, instead of presenting it as a single parameter. The reason for this will become apparent with the description of the case presented below, but the key benefit is that it allows the limit on size 9 to be clearly displayed.
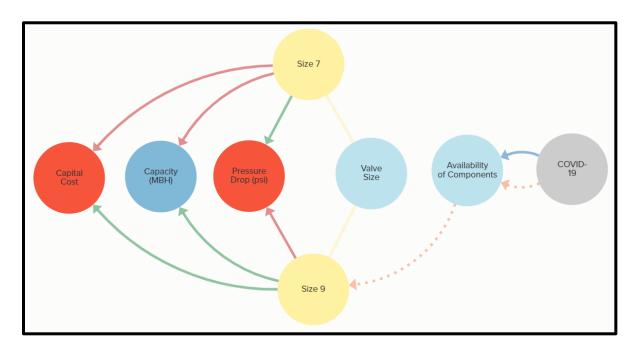

FIGURE 17: TRADE-OFF SITUATION IN CASE I4-2

The original solution with the larger valve was designed to stay under a company "best practice" maximum limit on the pressure drop parameter. It was also designed to meet the expected cooling load of the system, which was the minimum bound on the capacity parameter. The original solution met the capacity requirement, plus included a "safety factor", or a margin of performance in excess of the requirement.

The designer was not aware whether a solution using a smaller valve would perform on the evaluative parameter. The main potential conflict they were concerned about was that smaller valves would lower the system capacity, and increase the pressure drop, both of which were undesirable changes.

To check the viability of the smaller valve, they computationally simulated the system performance using computer software to check whether the smaller valve would work. At this point the designer was made aware that the smaller valve met all the requirements on the system and was therefore a member of the viable design space. The designer's uncertainty about this result is represented by an uncertain mapping of their perceived design space to the real space.

Case I5 - 1

The fifth case was a product-centered start-up company, which was built around a piece of electronic control technology the CEO/co-founder, who was interviewed, and his team designed. The interviewee described two separate challenges they encountered as they designed, developed, tested, and implemented their product.

The first conflict they encountered was during the functional design and testing phase, where they needed to test components to ensure that their product functioned according to their functional requirements. To do so, they needed to prototype their design. The challenge here was that as a start-up they had limited financial resources and having an external manufacturer custom-design and produce a PCB for testing purposes would cost far more than they could afford, particularly if they needed to produce multiple iterations in response to findings during the testing stage.

In response to this barrier, the team began searching for off-the-shelf consumer PCB boards made for early phase development, which the interviewee referred to as "dev-kits", with portions of the functionality they needed. This was facilitated by the wide availability of these modular components within the electronics industry, which allowed them to find a set of dev-kits that combined met all of their functional requirements.

However, the prototype assembled from the various dev kits was not without its own issues and sacrifices. Each of the dev-kits selected had been designed to its own specifications that differed from the interviewee's goals, and both restricted features

that components in the kit were capable of and added unnecessary functionality that the interviewee's product did not need. An example of this was that some of the dev-kit boards required electrical power to be supplied through a barrel jack, with esoteric current properties, whereas the designer said they would have preferred to simply solder power supply onto the electrical leads of the chips themselves.

The interviewee described the prototype as a "Frankenstein board", alluding to the fact that it was far larger than a purpose-built PCB and had less robust connections and components. The interviewee and his team found that they needed to replace the boards quite frequently because of the less robust connections as the iterative testing process damaged them to the point where they would not function as intended. This high failure rate introduced another challenge, which was the availability of specific dev-kits, or ones with equivalent features. Some of the dev-kits that were failing most frequently had limited and unpredictable availability, and equivalent replacements could not be found.

Prior to the identification of these failing boards, the team designed the prototype system to use standardized interfaces to connect between the different dev-kit components. While this did not help in the case discussed above where equivalent replacements could not be found, it did have a benefit when a different component did not perform as expected and caused the prototype to not meet certain technical requirements. In this case, the team was able to search for an alternative, more capable component, that would connect to the same interface and successfully meet the targets. This more capable component ended up being around 4x the cost of the component that failed to meet the criteria, but this was not a concern for the team as it was still within the budget considering the limited number of prototype boards being manufactured.

A further drawback of this prototyping method using modular, pre-built components was that the product was designed to operate within an automotive engine compartment, where packaging space is quite restrictive, and the final assembled

prototype was very close to, but within, the space limitations. An additional influence of the automotive operating environment of the device was that the design team wanted every component in the device to be certified for automotive applications, even though this was not a client or regulatory requirement. By adding this internal requirement, the design team artificially limited their selection of dev-kits and the associated functionalities, as only a small fraction of kits on the market had this automotive designation.

Despite all of these limitations and sacrifices that the interviewee described, they were able to complete their testing and validated their functional requirements sufficiently to confidently spend the capital to custom prototype their PCBs for the next phase of design. However, the production design did carry forward some of the sacrifices and limitations that the team had to accept from these dev-kits used in testing. The interviewee noted that as they attempted to avoid picking dev-kits with risky supply availability, they ended up choosing the most "vanilla" dev-kits, or those with the most standard functionality and feature sets. This was viewed as a loss by the interviewee, who noted that they would have liked to have some of the functionality not present in the "vanilla" dev-kits. Additionally, the team lost some testing data because of the cellular modems they had available to them off-the-shelf, which were of inferior quality to those the custom prototyper and manufacturer had access to.

Modeling Case I5-1

The goal in this case was to test the functionality of the device, which was operationalized as the "number of tests" parameter in Figure 18 below. The first challenge discussed by interviewee I5 was that their budget as a small, early phase start-up limited the amount that they could spend on prototyping. Figure 18 below represents this as the company budget imposing a membership criterion on the prototyping cost parameter. This parameter is evaluative, and the preference order is for cheaper prototyping cost. The designer mentioned that the "typical" solution to prototyping systems like theirs was to get a custom PCB designed and manufactured

for testing performance. However, the designer and his team did not have the expertise or tools necessary to design and build a custom PCB in-house. The expertise and availability of tools can be represented as imposing further membership criteria on the prototyping method parameter, that exclude custom prototyping from the viable design space.
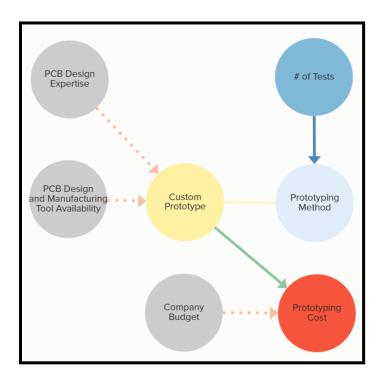

FIGURE 18: INITIAL CONFLICT IN CASE I5-1

In response, the interviewee stated that they explored alternative options for prototyping, represented by alternate values on the categorical prototyping method parameter. The domain they were designing in, electronics, facilitated an alternative method, modular prototyping, as shown in Figure 19 below. The availability of these components was modeled by a parameter representing the availability of components with functionality that matched the functional requirements of the system. In the electronics industry, components called "dev-kits" exist, which provide a breadth of different functionalities so that designers can prototype easily. The availability of dev-kits that could perform the functions that the interviewee wanted in their device allowed them to prototype using the modular approach. The modular prototyping

value of the prototyping method had a complementary influence on the prototyping cost parameter, reducing the cost below the boundaries imposed by the company budget. This meant that the solution using a modular prototyping approach was a member of the viable design space for the goal of testing the device's functionality.
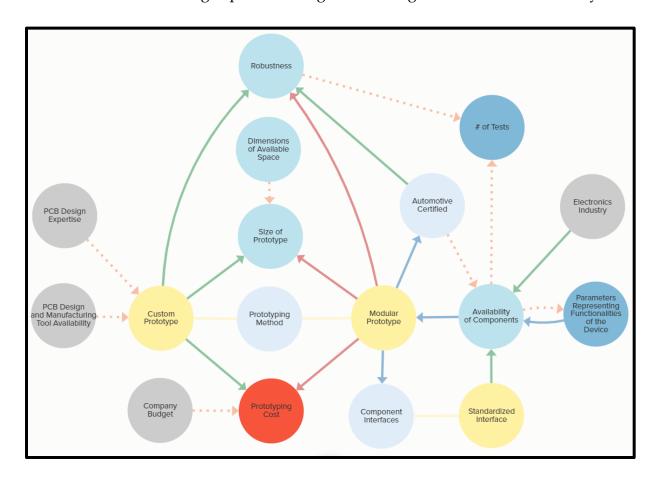

FIGURE 19: RESOLUTION OF CONFLICT IN CASE I5-1

However, the modular prototyping method was not without its drawbacks. The designer mentioned several parameters that were sacrificed by going down this route. One was that the modular prototypes were significantly larger than the custom designed PCBs. This was a potential conflict, as the device was intended to operate in a vehicle's engine compartment, where space is at a premium. This was modeled as a set of dimension parameters describing the available packaging space, which in turn impose maximum limits on the parameters representing the size of the prototype. Despite the concern that the larger modular prototype may not fit in the space available,

and therefore not be a viable solution, it was successfully installed. This meant that the designer may have slightly underestimated where the limits on available space were in the real design space, which is represented by a minor misalignment between their perceptual space and the real space.

In Figure 19 above, both the dimensions of the available space and the size of the prototype are represented as single nodes, despite each being comprised of several different dimension parameters (e.g., length, width, height, orientation). They are represented as single nodes because the interviewee did not decompose them beyond the discussion around the "size of the device" and "space available".

Another parameter that had its performance sacrificed when selecting the modular prototype option was the robustness of the prototype. The interviewee described the modular components and their connections as being less robust than a custom PCB would be. This lower performance on the robustness parameter was involved in a potential conflict with the parameter representing availability of modular components. Since some of the components with low availability were also less robust, replacements were sometime unavailable when the testing process ended up damaging these less robust components. One particular component did not have replacement options with equivalent functionality, represented as a further bound on viability on the availability parameter. The potential conflict here was that if the robustness of this part, combined with the number tests necessary, would result in more failed components than there were available. This did not end up being the case, as the team was able to procure sufficient stock of components to complete the required number of tests to meet the goal of testing the device's functionality.

The team also pre-emptively designed the modular prototype to use a standardized interface to connect the different dev-kits. This is represented by a categorical parameter of component interfaces, with the parameter value of the standardized interface in Figure 19 above. The intent of this standardized interface was to relax the limits on the

component availability parameter, which it accomplished by accommodating all dev-kits and components that used the standardized interface. The implication from the interviewee was that by being standardized, the number of alternative components that could connect to that interface outnumbered the number of alternatives that could connect to any other interface.

While this standardized interface did not sufficiently relax the constraints on the availability for the component with low robustness discussed above, it did aid the designer in a different instance. During one of the tests, it was discovered that another component that was used in the modular prototype did not provide the functionality the design team had predicted it would. This discovery of the behaviour of the real design space threatened to exclude the modular prototype from the viable design space. However, because the teams selected the standardized interface option on the component interface parameter they were able to find an alternative component within the constraints of available components. This alternative component ended up performing the functionality required. A drawback of this alternative was that it performed 4x worse on the cost parameter, but this was acceptable to the designer since there were no other options in the viable set that could perform the function needed.

The last parameter in the interaction network presented in Figure 19 is the automotive certification of components. The interviewee mentioned that they imposed a requirement that automotive certified components would be used wherever available. This goal was operationalized into a categorical feature parameter, with the values being the different levels of certification, and a requirement on that parameter that made the non-certified options not viable. This goal imposed a limit on the availability of components, since the designer mentioned that only about 5-10% of components were automotive certified for any given functionality.

Despite all of these restrictions on the viable design space, the interviewee and their team were able to find components that met all of the membership criteria of the design

space. This meant that their resulting prototype was successful in meeting all of the goals imposed upon it.

Case I5 -2

The other situation this interviewee discussed was a conflict between user-derived goals and requirements for the product, namely the desire for better performance coupled with the aversion to higher costs. The specific case was a teleoperated vehicle application which required multiple camera feeds so the driver would be aware of the vehicle's surroundings in all directions. The product as designed, with lower cost hardware, could only run one or two 1080p definition cameras at the most.

The CEO described three solutions they were considering for this application: using higher performance hardware, which could handle five to six 1080p streams at the cost of a 30% to 40% cost increase; using lower quality camera streams such as a 720p front camera supplemented by 480p streams for the sides and rear to maximize the number of streams on the current hardware while sacrificing the visual fidelity; and introducing a supplementary processor to the system called an accelerator chip, which would boost performance by 15% while only being 2% more expensive, allowing the current hardware to handle the minimum number of 1080p streams required for the application.

Modeling Case I5-2

The initial trade-off could be modelled quite simply, using only five parameters, as shown in Figure 20 below. The goal for this design is to allow remote piloting of a vehicle, which requires visual information from all four directions (front, both sides, and rear) to make the pilot aware of their surroundings, and to minimize the cost of the device. The number of streams, represented by a discrete parameter with a nominal goal, operationalizes the remote piloting goal in this conflict. However, increasing the number of streams directly increases the data transfer rate, which in turn requires a

156

higher data processing rate, which was limited by the processor power available in the current device design.
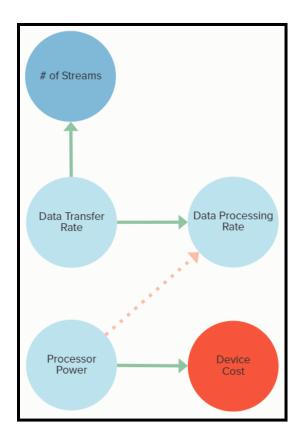
The first solution discussed by the interviewee simply uses a more powerful process, which sacrifices the performance on the cost parameter in favor of improved performance on the device processing power parameter, to allow for enough video streams to meet the project goals.

The second solution revisited the stream quality parameter and determined whether the stream needed to be 1080p resolution to meet the underlying goals of visual awareness, introducing the evaluative parameter of "stream resolution" as in Figure 21 below. This parameter was continuous, and had a preference towards maximizing, as better resolution would allow better accuracy in the system's image recognition. The designer determined that the real requirement on this parameter for every stream was not 1080p as originally defined, and that the front stream could be reduced to 720p and the rear

and side streams to 480p. By doing this, the necessary data transfer rate was reduced, falling under the limits imposed by the processing power of the device. This solution achieved the underlying goal of providing sufficient visual information on the vehicle's surroundings, without increasing the device cost parameter.
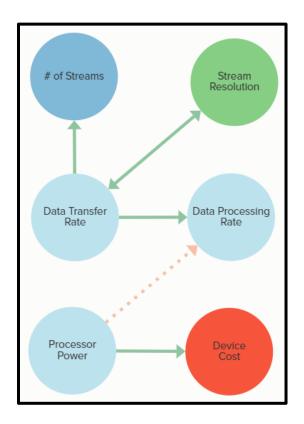

FIGURE 21: FRAMING OF THE SECOND SOLUTION ALTERNATIVE IN CASE I5-2

The third and last solution in this case was the addition of a supplementary "accelerator chip" component to the device, as shown in Figure 22 below. This accelerator chip was modeled as a binary feature parameter (present or not) that was made explicit after the antagonistic relationship between the device cost and processor power was identified. The effect of adding this parameter to the design space was to increase the data processing rate sufficiently to handle the required number of streams while increasing the cost less than upgrading the processor power would.
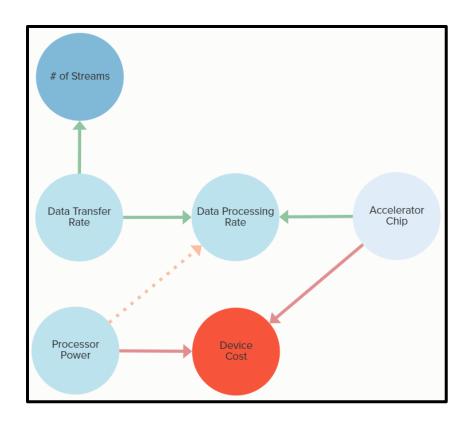
FIGURE 22: FRAMING OF THE THIRD SOLUTION ALTERNATIVE IN CASE I5-2

Effectively, the different values of the accelerator chip altered the function describing the Pareto frontier. When the chip was not present, the device was on a perceived Pareto frontier; as far as the designer is aware, the processing rate cannot be increased without an associated increase in cost. When the chip is included, the function representing the Pareto frontier was altered so that the increase in processing rate is associated with a smaller increase in cost. The design solution was still moving between two different Pareto optimal points, but the sacrifice necessary to meet the requirement on the data processing rate is reduced. By adding the chip, the designer created a solution that could handle four 1080p streams, but at a lower cost than the first solution. This third solution can therefore be modeled as Pareto dominating the first solution, but the third solution was not possible within the original frame.

Case I6

Another start-up co-founder was interviewed for the 6th case, with the company's product being a communication-support application for tablets and potentially mobile devices in the future. This project had evolved from the co-founders' final design project they undertook as a part of their engineering undergraduate education, but the design had shifted its target users during the commercialization transition into a start-up.

Early in the project, the interviewee and her team conducted a set of stakeholder interviews of users and other people in the user's "care circle" to identify the needs and requirements for their design. The care circle encompassed the specialists who diagnose these disabilities and help the users manage their disabilities, which include speech language pathologists (SLP), communicative disorder assistants (CDAs), and occupational therapists; the user's caretakers, either professional or members of the user's family or social circle; and the user's communication partners, or those they will converse with. Within this group of stakeholders, the designers identified conflicting goals, particularly between the SLPs and the user, and the communication partners and the users.

The user goals were for more personalized vocabulary and the ability to express themselves in a complete yet individualistic manner. The two primary user needs this design set out to solve were that existing communication aids had a nested folder structure for vocabulary, which makes it very time consuming to access to niche words that are usually used in specific contexts such as the user's hobbies; and adding new words to the database to personalize the user's vocabulary to their own unique interested was also difficult and time consuming. The designers translated this into two goals: improving the rate of communication and improving the personalization of communication.

160

On the other side of the conflict, the SLPs were very busy professionals who handled many clients simultaneously, and as such wanted a solution that took the least amount of time to set up for a user, since they were usually the party responsible for training the user with a system. They also preferred to recommend as few different solutions as they could, as that would allow them to familiarize themselves enough to train users. Lastly, the SLPs were typically responsible for adding new words into the database to personalize the vocabulary to the user, and in the interest of saving time preferred solutions that had as large a vocabulary as possible. However, having a larger vocabulary was limited by device data storage capacity and was negatively correlated with the speed of navigating the folders.

Existing solutions using nested folder structures struggled with both rate of communication and personalization but were particularly bad at allowing the user to discuss personal interests and niche topics. To do so, the user or a support personal would first need to check if the niche words were in the database and add them if they are not present. Then the user would need to navigate through a series of folders and sub-folders that arranged words in categories to reach the niche words they are seeking, repeating for each word in the sentence, which was incredibly time-consuming.

The designers improved rate of communication and the personalization of the topics discussed by leveraging sensor data such as GPS location from the mobile device the application is running on and interpreted it with an artificial intelligence algorithm to provide contextually appropriate word recommendations to the user.

Another challenge the interviewee encountered in this case was the difficulty accommodating the highly varying needs that the users of this application may have and deciding on which set of user needs to focus on for the initial product release. The users of this application vary significantly in both their physical capabilities and cognitive needs, with conflicting needs for users on either end of each spectrum, as well as interactions between the physical and cognitive needs. For example, a user with

physical speech impairment needs the ability construct and vocalize complete sentences, whereas a user with minor aphasia may only need reminders of very specific words. This division in needs was referred to by the interviewee as a division between core words, which are generic and used to construct most sentences, and fringe words, which are specific to topics, environments, or individuals.

Designing to accommodate those with the most extensive and extreme needs, or those who need both core and fringe words as well as physical accessibility support, would take more time and resources to design for, and since this combination of needs is rarer it would be harder to recruit participants for design testing and validation. Whereas designing for those who just need to context specific recommendations would be much easier and faster, but in so doing the designers were worried they may develop the application in such a way that they cannot add the additional features in the future.

In this situation, the designers decided to design and develop for the most extreme cases and then add customizability to the application later so that users could customize the application to their own unique needs. This decision came with a sacrifice in the interim, as users who do not need the complete feature set are currently expected to simply ignore those features, resulting in a more cluttered user interface (UI) and thereby a worse user experience (UX).

Modeling Case I6

This case was characterized by the designer attempted to meet a series of conflicting goals driven by different stakeholders of the project. The network of parameter interactions in Figure 23 below shows the key goals as they were described by the interviewee and the initial trade-off they identified in the existing solutions. The primary stakeholders were the potential users of the application, the SLPs and care team, and the communication partners.

The interviewee and their team identified that their potential users wanted a communication aid that would allow them to talk about their own unique and personal

interests, that they wanted the software to be easy to use, and that they wanted to be able to communicate independently. The personalization goal was operationalized into the discrete continuous parameter of number of personalized fringe words, measured in number of appropriate fringe words that are available with a preference towards maximizing this number. The ease-of-use goal was operationalized by the designer into two parameters: ease of accessing appropriate fringe words and consistency of the UI. The goal of independent communication was operationalized as the "rate of communication" and "ease of accessing fringe words" parameters. This was because the interviewee had conducted user research that indicated that the existing solutions on the market were not allowing the user to communicate quickly enough for their communication partners. This resulted in their communication partners either moving on in the conversation or structuring their questions to the user in simplified forms (e.g., yes or no questions) that restricted the user's agency to participate in conversation.
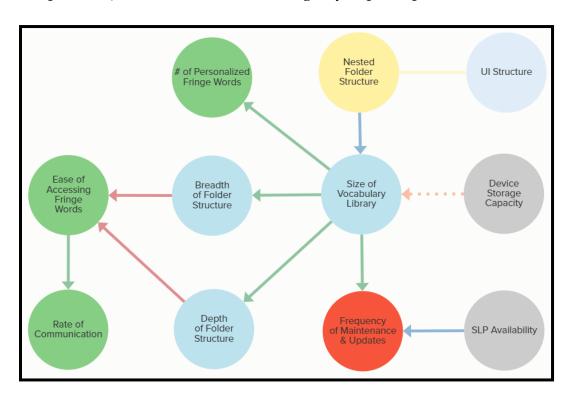

FIGURE 23: PARAMETER INFLUENCE NETWORK FOR CASE I6

The goals of the SLPs in this case were not completely aligned with those of their patients, the users. Due to the demanding and time-consuming nature of their profession, and the number of patients they would work with at a time, SLPs wanted solutions to be easy to train users on; easy for them to learn; and would require the least amount of time spent updating, customizing, and maintaining the system for user. These goals to reduce the amount of time spent learning, updating, and customizing the vocabulary were operationalized as the "frequency of maintenance & updates" parameter, with the SLP's goal being to minimize this parameter.

Lastly, the goal of the communication partners as the interviewee understood them was to be able to communicate with the user at a rate equivalent to talking with someone without a speech and language disability. The interviewee mentioned that they had not put too much effort into understanding the perspective of the communication partners, since their primary stakeholder was the users, but the communication partners remain important to this case because of how they influence the users own goals. This was operationalized as a membership criterion on the rate of communication parameter. The placement of this requirement was uncertain to the interviewee, and likely varied between different communication partners.

A conflict becomes apparent when the model is extended to capture how the existing, nested folder solutions interact with the parameters of rate of communication and availability of appropriate fringe words. In order for a nested folder solution to improve the availability of appropriate fringe words either the solution's library of words must be expanded to include all of the necessary fringe words, or the library must be customized to each individual. Since customizing the database for each user was not a viable solution due to the SLPs' goal to minimize the amount of time required to set-up, the only viable way to increase the personalization of a nested folder solution was to increase the size of its word library, which was a discrete ordinal parameter.

The organization of a nested folder library is characterized by two parameters, the breadth and depth of the folder system. The breadth of a folder represents how general of a category is used to classify the words that the folder contains. Using broader categories allows more words to be nested under a category. The depth of the folder represents how many layers of sub-folders the system organizes its words into, or how many layers of sub-categories a category gets divided into.

Both breadth and depth of the folder system negatively influences the rate of communication, since it takes longer to search through a larger folder or to navigate into deeper sub-folders. This means that the larger vocabulary library necessary to increase the personalization of a nested folder structure would result in a slower rate of communication and increasing the rate of communication would require fewer words in the library, or more time spent customizing that library. This indicated that design solutions using a nested folder structure eventually encountered a Pareto frontier. Furthermore, the device library size was also constrained by the amount of storage space available on the users' devices.

In response to the designer's perceptions that current solutions were not performing well enough on both the rate of communication and the availability of appropriate fringe word parameters, and the perceived Pareto frontier; they proposed an alternative solution. This solution was to provide context-aware recommendations of fringe words, which they framed as an alternative UI to the existing solutions of nested folders that sorted words into categories. This can be modeled as being an alternative value on a categorical parameter representing the UI structure, as shown in Figure 24 below.
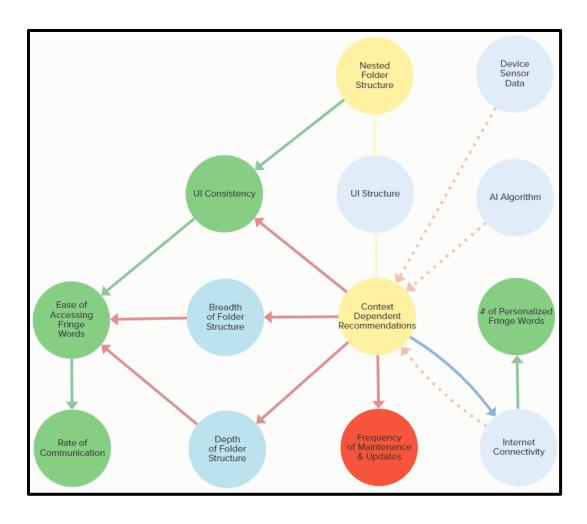
However, this alternative value was constrained and non-viable until that constraint is relaxed through of the use of an AI algorithm and sensor data from the user's device. Based on how much detail the designer provided about both these factors meant that they could only be modeled as feature parameters (present in design/not present), which when absent constrained the context dependent recommendation value of the UI structure parameter.

The selection of context independent recommendations as the UI structure value altered the structure of the explicit design space quite drastically. The number of personalized fringe words was no longer directly tied to the vocabulary library size on the user's device, but instead the personalized fringe words were drawn from the internet based on contextual factors that informed the AI algorithm. This was represented by the

feature parameter of internet connectivity increasing the number of personalized fringe words available to the users.

Further changes were in the relationship between the UI structure and the breadth and depth of folder structure parameters. Since the UI adapted to the user's context and changed the words presented on the screen to reflect that context, the breadth and depth of the folder structure was minimized to a single screen. However, if the initial set of words presented does not contain the word the user is looking for, the new UI still contained a folder structure. This structure still performed better on the folder depth and breadth parameter because it presented the folders that were contextually appropriate for the situation, reducing the amount of searching necessary for the user.

However, the new UI was not without drawbacks. As a result of how it functioned, the contextually aware recommendations resulted in the UI being very dynamic, and words were not presented in consistent locations. User feedback indicated that another evaluative parameter was important to them, the UI consistency, which was a subjective parameter that the users wanted maximized. On this parameter the new contextually aware recommendation UI performed worse than the nested folder structure UI, presenting a subsequent trade-off in the design that at the time of the interview had not been resolved.

Case I7

This case was presented by a consulting designer describing a project they had recently been contracted to. Their client, a small start-up firm, was designing an entertainment system for inside of a medical device and contracted the consultant's firm to complete the mechanical engineering and industrial design of the device, while internally handling the electrical engineering design. The goal of this project was to improve the patient experience within a medical scanning device. During a scan, the patient must remain completely still otherwise the data from the scan is rendered useless to the

physician interpreting it. As scans could take upwards of an hour and a half and the space where the patient lays is very restricted, the experience is quite unpleasant.

The solution the start-up proposed to improve this experience was to engage and distract the patient with an audiovisual entertainment system. However, due to the restricted space within the medical device, the audiovisual entertainment system could not be placed directly in the user's line of sight. The designer solved this issue by using a mirror to allow the patient to see the visuals being projected from outside of the medical device.

As the design is intended to operate within a medical device, the design needed to be useable by patients with varying degrees of physical impairments. The addition of the mirror restricted the ability of the patients to lie onto the bed from above and made it so patients would have to "shimmy" their way up under the mirror to be properly positioned for both the scan and to view the entertainment. This motion was not easy or even possible for some elderly patients, unconscious patients, or other patients with mobility impairments.

To meet the requirement of functioning for all patients regardless of physical capability, the designers introduced a telescoping mechanism to slide the mirror into and out of position. This allowed the mirror to be retracted and stowed as the patient got into position and then extend into the optimal viewing angle after they were positioned and ready for the scan.

One of the key features of this case is that the design was completed and had met all original requirements when a pair of new requirements were imposed that effectively invalidated the completed design. These requirements were introduced when the start-up firm was acquired by a much larger, established medical company that produced the larger medical devices the start-up firm's product would attach to and operate within. The first constraint was introduced by one of the larger firm's other products, which tracked eye movements during a scan to allow corrections to be applied when scanning

168

the brain in certain situations. This product needed a clear path to the patient's eyes to track them, and the telescoping mirror system blocked this line of sight. The designer's response to this was to make the entire telescoping mirror assembly detachable, so that it could be removed during the scans that required eye movement tracking.

The other major constraint introduced through the acquisition after the original completion of the project was a safety constraint. The larger firm that acquired the start-up also designed and manufactured the beds for the scanning machines. They designed these beds to be mobile so that immobile patients could be picked up in other rooms of the hospital, or so that in medical emergencies the bed could be removed from the scanning room so defibrillation equipment could be used. The designer's entertainment device attached to the bed, and so would move with it in these situations. This introduced a major safety concern, since in high pressure urgent medical situations there was a risk of the bed running into walls or other barriers. In such a collision, the entertainment device as designed would crumple forward and had a risk of lacerating or crushing the patient, which was entirely unacceptable.

This new requirement of crashworthiness caused the team significant frustration and they were unable to meet this goal using the current telescoping approach while still achieving the other requirements listed above. The team held a brainstorming session with the start-up and a nurse representing one of the users, where they iterated through several design concepts using rough paper prototypes in what the interviewee described as a "arts and crafts approach". From this emerged three potential concepts which three engineers from the consultancy developed independently, and the results were then compared and contrasted to select the best solution.

The solution that ended up meeting all of the requirements, including the crash worthiness and the eye tracking line-of-sight, was a mirror that pivoted around an attachment on the bed, instead of telescopically sliding in and out. The eye tracking system was able to function alongside this new pivoting solution, since the supports

that held the mirror in place were primarily vertical, whereas the telescopic supports were horizontal and cut through the line-of-sight. In a collision situation, the pivot mechanism had a mechanical stop that would allow the whole device to pivot out of the way of the collision, but prevent it from contacting the patient.

The pivoting solution solved nearly all of the issues the previous design was having, but it also introduced some new concerns to the problem. The primary concern with the new pivoting design was that rotational components introduce pinch-point risks. Medical device regulators in Canada have well-defined pinch-point risk categories and appropriate responses, and the risk level of the pivoting device was classified as a moderate risk. This allowed the designers to bring the design within regulatory compliance by simply adding safety warning labels to the pinch-point risk area, saving them from having to compensate through structural design changes again.

Modeling Case I7

This project, like Case I6, had the designer attempting to balance the divergent goals of two different stakeholders. In Case I7, the stakeholder goals that were initially in conflict were the patients' desire to be physically and mentally comfortable, and the physicians' requirement on scan quality, driven by the need to interpret the scan results. As shown in Figure 25 below, the interviewee operationalized the goals of the patients into a single parameter, patient comfort. The interviewee did not describe units of measurement for this parameter, so it was modeled as a subjective discrete ordinal parameter with a goal to maximize. The physicians' goal for scan quality was also operationalized into maximizing target on a subjective ordinal parameter, based on the level of detail in the interviewee's description.
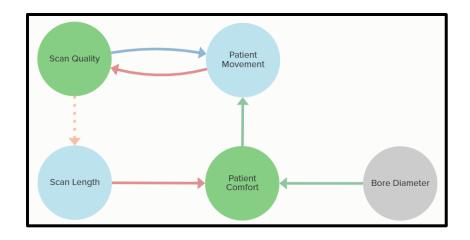
The conflict emerged from two lower-level parameters that influenced both scan quality and patient comfort: scan length and the amount of patient movement. To obtain a sufficient scan quality, the scan will take a specified amount of time, depending on what the scan is looking for. This scan length parameter is a continuous parameter, which is bounded by the required scan quality. In the interviewee's framing, increasing the length of a scan would decrease patient comfort.

The parameter representing the amount of patient movement was operationalized as an ordinal parameter, since the interviewee did not go into detail on what measurement scheme they used. The performance on the patient comfort was tied to the patient movement parameter, where more uncomfortable patients were more likely to move more. This in turn affected the performance on the scan quality parameter, since the increased patient movement decreased the quality of a scan, with excessive movement rendering a scan useless. The summation of these parameter interactions results scan quality being inversely correlated to patient comfort, which indicates a Pareto frontier on the design space.

Since the design project set out with the explicit goal to improve the patient experience, and the requirements on scan quality were non-negotiable, the designers needed to identify a way to bypass or alter this Pareto frontier. The solution they proposed was to

171

distract the patient with audiovisual entertainment, which they predicted would reduce the patient's perceived discomfort.

This solution encountered several further barriers and conflicts as it was developed throughout the case. The first of these was that the bore diameter of the medical device was too small to incorporate an audiovisual system. This bore diameter also had a major influence on the patient comfort level parameter, with the small bore size inducing discomfort. However, the bore size was pre-established during the design of the medical device, and for the purposes of this project was non-negotiable. As it was, the bore diameter placed a constraint upon using an audiovisual system to distract the patient, rendering the solution non-viable in the current frame.

The designers introduced another feature parameter to the design space that relaxed this constraint, which was the inclusion of a mirror to redirect the visual entertainment from a projector outside of the bore. This mirror was initially designed as a static mirror, but during the evaluation of this design it was identified that this had a negative influence on a newly explicit parameter representing the accessibility of the device. Both the audiovisual system and the mirror were modeled as feature parameters in Figure 26 below. Figure 26 represents the accessibility requirements as a new evaluative parameter that the designer needs to maximize, and the presence of the mirror decreases performance on that parameter.
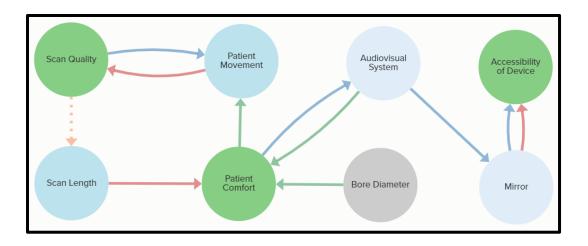
In response, the designers introduced another categorical feature parameter to the explicit design space, which was the inclusion of a positioning mechanism for the mirror. Making this parameter explicit and selecting a value on it severs the relationship between the mirror feature parameter and the accessibility parameter, since the presence of the mirror no longer influences the accessibility of the system.

The initial value selected by the designer on the positioning mechanism parameter was to use a telescoping mechanism. When the telescoping feature was present, the solution met all the current membership criteria of the design space, making it a member of the viable design space. Figure 27 below shows the explicit design space at the point where the designer had produced a viable solution to the known requirements, prior to the new requirements being introduced.
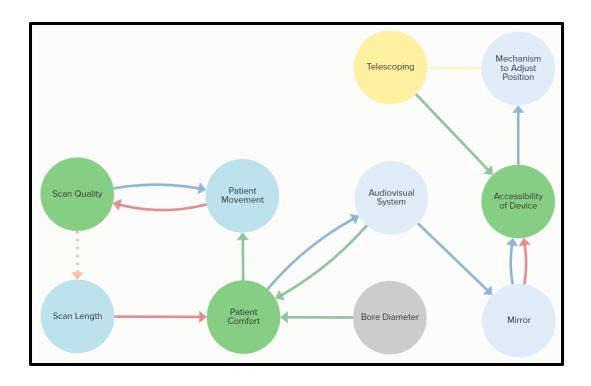
FIGURE 27: SOLUTION PRIOR TO ADDITIONAL REQUIREMENTS IN CASE I7

However, this case was also characterized by the imposition of new goals and constraints upon the project quite late into the design process, after a concept had been selected and validated. These alterations to the design space came as the result of the start-up's acquisition by the larger firm, which manufactured the medical device that the start-up's design interfaced with. The interviewee noted that two requirements imposed by this larger firm were particularly challenging to deal with using their existing solution. A further challenge was that the large firm provided these two new requirements at different times, reshaping the design space twice.

The first of the new constraints added to the design space was the larger firm had a separate technology to improve the scan quality of certain specialized types of scans using eye-gaze tracking cameras. This technology made explicit a parameter representing the line of sight of the cameras. This was modeled as a binary ordinal parameter because the interviewee only characterized the line of sight as being clear or blocked. The requirements imposed meant that only solutions that had a parameter value of clear line of sight were members of the viable design space.

174

The telescoping mirror solution did not meet this requirement as it was initially designed, and the designer did not believe that it was possible to change the dimensions of the mechanism to make it viable. In the designer's current perceptual framing of the design space, no viable solutions existed. This was remedied by introducing the feature parameter of detachability to system, which represented whether the entire device could be detached and re-attached freely from the larger medical device. This allowed the mirror to be detached for the specialized scans. When this parameter was true, the telescoping solution again met all the membership criteria and was made a member of the viable space once more, although it did not achieve the goal of improving patient comfort for the specialized scan use case. The frame at this point in the design process was modeled in Figure 28 below.
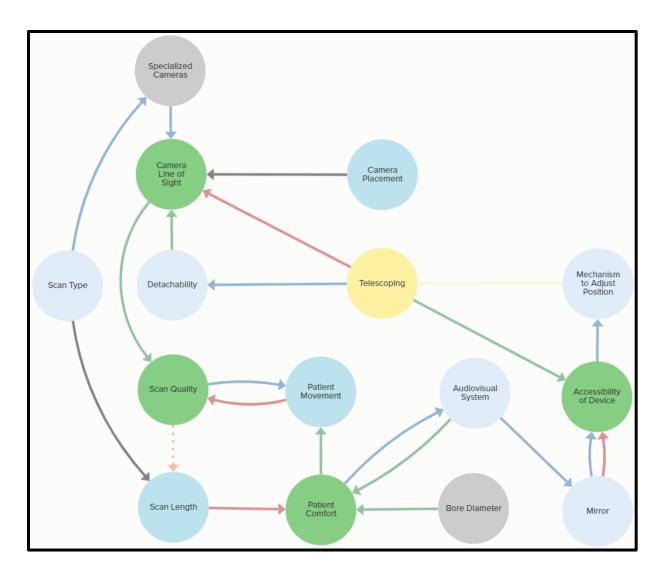
The second requirement introduced by the merger proved to be a greater challenge to the design team, and eventually resulted in them revisiting and replacing previous design decisions to create a non-empty design space. The managers at the larger firm remembered that they had mobile patient beds as a feature in their medical device, to allow for rapid transport in medical emergencies. Patient safety drove a further requirement that the start-up's design must be "crashworthy" in case the bed hit an obstacle during emergency transport. This crashworthiness parameter was discussed by the interviewee as an ordinal parameter, where a solution was either more or less

crashworthy than another solution, with a minimum requirement existing at some reference point determined by patient safety.

The telescoping design performed poorly on the crashworthiness parameter, as during a collision the mirror would come down onto the patient's head, neck, or body, posing a very severe safety risk. The interviewee and their team did not believe that this requirement could be met with a telescoping solution by altering any existing explicit parameter values, or by making explicit any other parameters they were aware of. This indicated that their perceptual design space was again a null space, with no members in the viable set. The design space at this instance shown in Figure 29 below.
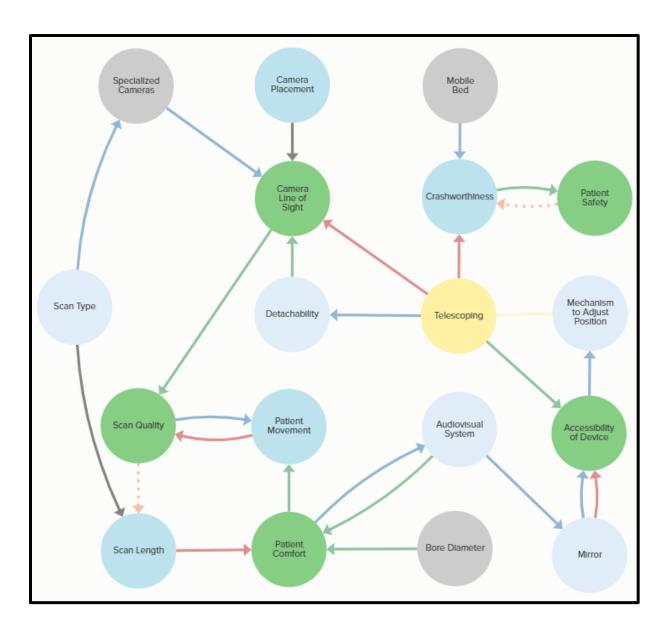
Revisiting the positioning mechanism parameter in their brainstorming session, the designer made alternate values of this parameter explicit. One of the alternative values that the designers explored in depth was using a pivoting mechanism to position the mirror instead of telescoping. Figure 30 below shows how this new pivoting mechanism rearranges the interactions in the explicit design space.
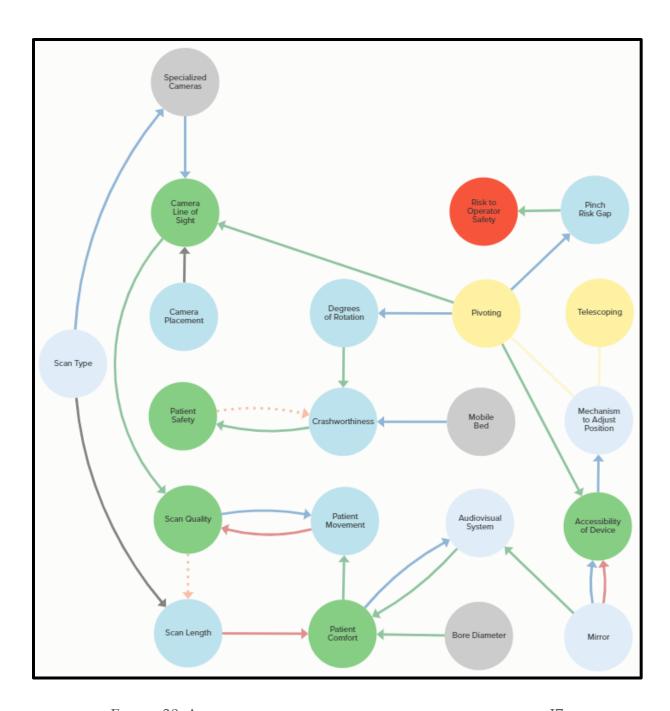
A solution using the pivoting mechanism was designed that did not interfere with the camera line-of-sight, without requiring that the design be detachable. This represented the detachable parameter being discarded from explicit consideration, returning to a latent status. However, while a design using the pivoting mechanism did perform better on the crashworthiness parameter because it rotated out of the way during a

collision, it still did not meet the minimum requirement on this parameter. This was because the design could over-rotate and crush the patient. This made the parameter of degrees of rotation explicit for the pivoting mechanism. To solve the over-rotation issue, the designer added a physical stop to the design. This was represented by a binary feature parameter in Figure 31 below because the dimensions and properties of this stop were not made explicit during the interview. Regardless, when the stop was present in the design space it imposed a limit on the degrees of rotation parameter. This in turn improved the performance on the crashworthiness parameter sufficiently to meet the requirement driven by patient safety.
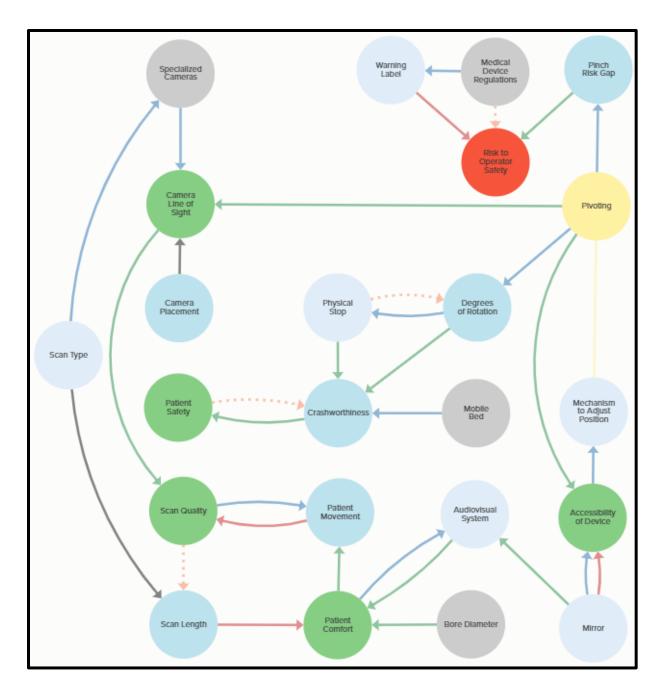
FIGURE 31: FINAL RESOLUTION IN CASE I7

This design now met all the pre-existing membership criteria for the design, but the pivoting mechanism made one further criterion explicit, a minimum level of operator safety or "risk to operator safety". This was because the pivoting mechanism introduced a pinch risk to the design, wherein a part rotating about an axis comes into close proximity another component. The width of the smallest possible gap determined

the risk to operator safety, with larger gaps posing less risk. Medical device regulators have established limits on how much risk there can be to the operator's safety. Risk to operator safety was operationalized as a discrete ordinal parameter that the designers wanted to minimize, which was because the regulators laid out a defined set of discrete risk levels. However, the medical regulations also made explicit the option to reduce the effective risk level by one step by adding a warning label to the device. The warning label was a feature parameter that when added to the design made it meet the requirement on the risk to operator safety parameter. This was the final design decision the interviewee described as being necessary to create a viable solution. This was modeled as the addition of the warning label parameter increasing the explicit design space's dimensionality, and with the inclusion of this new dimension the explicit design space now contained a viable solution.

Case I8

The 8th interviewee worked as a "Senior Solution Architect" for a transport management organization in a large global city. The project they described in their interview was the design of a backend system to provide station and transportation system accessibility information to an in-house transport system navigation app, as well as third party applications such as Google Maps.

The project dealt with two large challenges: the goal to add as many accessibility features as possible to the design conflicted with an externally imposed schedule deadline that was also tied to project funding; and a related conflict between the goal to improve the timeliness of data being presented to users and a lack of knowledge about the data formats and availability from systems earlier in the data stream. One feature that was initially prioritized by the interviewee and their team was to reduce the "data lag" between elevators being marked out-of-service and that information being available to users. This was prioritized because the organization applied a data

timeliness requirement on all services of a particular classification, which the system being discussed was a member of.

However, the design project had to change goals due to two unpredicted limitations on the project. The first was the onset of the COVID-19 pandemic, which greatly reduced ridership on the transport system and thereby operating revenues and the project budget. The other was that other than vague allusions from colleagues that "it is more complicated than you think", the overall system map was very poorly understood and documented, and the knowledge necessary to plan and prioritize features was not available to the designer and their team at the project outset.

In response to the COVID-19 pandemic's affect on the financial solvency of the organization they received a financial bailout from a higher tier of government. This bailout came with many conditions, one of which was particularly influential on the case discussed by the interviewee. This was the requirement that a minimum viable product (MVP) version of the accessible navigation application be released before the end of the calendar year, or the financial support may be reduced or removed. This MVP did not need to have all the functionality planned for the original system, but it did need to provide some functionality that benefited users. The backend system the interviewee and his team were designing were also tasked with this deadline since it supported the frontend application that was explicitly bound to the deadline.

At a similar point in time, the interviewee noted that they pivoted the primary project goal to providing users with information on how elevator outages would affect accessibility routes moving throughout the station and between stations and the rest of the transport system. This change was instigated by a feasibility assessment of what could be accomplished by the new deadline, using a decision matrix to weight which functions were achievable and would have the greatest impact on the largest number of users.

The feasibility of each potential feature was in turn informed by the interviewee's exploration of the other systems that provided the necessary data for their design to function. During this exploration, the designer found that the systems that provided the most up to date information output their data in a format that was incompatible with the new system they were designing. An existing interim system, provided by an external contractor, translated this data into a useable format, but had an average data lag of 2 hours, conflicting with the organization-imposed requirement on data timeliness. However, without using this data from the contractor's system the interviewee and their team would be unable to complete the design and development of a functional system before the government-imposed deadline.

In response, the interviewee and their management petitioned the organization to grant them an exemption of the data timeliness requirement that other systems of the same category were required to meet. The organization granted the exemption and the interviewee and their team were able to complete the design and development of their system in time to support the launch of the customer facing MVP.

Modeling Case I8

The primary goal of the project as the interviewee described it was to make it easier for people with accessibility needs to navigate a large, complex transit system. This goal was operationalized into many different functional parameters representing different information that these people may need, such as lift operation status, accessible washroom availability, or in-station routing. Together, all these different functional parameters can be represented by a more abstract parameter of "number of accessibility features", as shown in the top left of Figure 32 below, which was at an ordinal level of measurement. The designer wanted to maximize this parameter, to in turn maximize the number of help with accessibility needs helped.
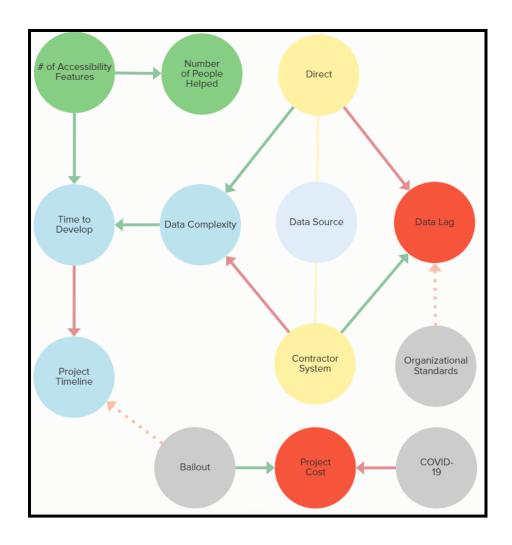
The other goal of this design project was to reduce the data lag on information about service outages, specifically for outages to accessibility services like elevators. This goal was operationalized by the designer in the interview as the desire to improve the "data timeliness" parameter. Based on this goal, the designer had been investigating the sources of these outage data streams, which was poorly understood by the designer and the organization at the time. This made the parameter of which data source the design would use explicit, as a categorical parameter. The interviewee's exploration of the data streams' network structure can be represented as them aligning their perceptual space with the real space. In particular, they identified what the real options were for sourcing the data, and the properties of the data coming out of each source. Two primary options

on the data source parameter were found: directly from the originating system and from a contractor's system that reformatted the data. This exploration also made the different data formats apparent to the designer, which they introduced as "data complexity". This data complexity parameter operationalizes how easy it is to integrating data in different formats into the new design so that it can manipulate and use that data.

The contractor system was used by other existing solutions and provided the data in a format that reduced the data complexity. However, it did so at the cost of worse performance on the data timeliness parameter, being 2-hours delayed. This was above the requirement imposed on the data timeliness parameter by the organization, and so a design using the contractor system was not a member of the feasible set.

The alternative, directly sourcing the data from 3 systems where outages were first entered into the system, provided data with zero lag, and therefore performed far better on the data timeliness parameter. However, the data it provided was formatted in a manner that made it far more complex to handle, reducing its performance on the data complexity parameter. This indicates that the two different values of the data source parameter were both members of a Pareto Frontier between the data complexity and data timeliness parameters. Despite this, the solution that directly sourced the data was the only one that met the requirements on data timeliness, making it the only member of the viable design space.

However, in this case, like in case I4-2, the COVID-19 pandemic introduced unexpected changes to the design project. In this case, the rapid contraction in ridership on the transit system due to lockdown orders and other pandemic prevention measures cut heavily into the transit agency's budget. This threatened to put the entire organization into financial distress and therefore threatened cancel this design project. A higher tier of government provided a financial bailout, reducing the constraints on the project budget, but they also mandated a new requirement on the project timeline.

Due to the more complex data formatting, the solution the designer chose ended up being limited by this project timeline requirement. This was because the more complex the data was, the longer it would take the developers to code it. This was modeled as a newly explicit continuous parameter, time to develop. The interviewee also noted that this parameter was influenced by the number of different accessibility features they wanted to incorporate into their design. Their current solution would take far too long to develop, causing the project timeline to exceed the imposed requirements, rendering this solution no longer viable. As a result, the current explicit design space had no elements, making it a null space.

The interviewee responded to this development in two ways. The first was that they used a decision matrix to decide which features to include in the MVP version of the system, and which to put off until later. This decision matrix ranked possible accessibility features by the time to develop parameter and a parameter that the interviewee explicitly introduced at this point, the number of people helped by a feature. The use of a decision matrix can be modeled as the designer exploring design options in their perceived design space and determining where they lay on these two evaluative parameters.

The second response from the designer was to petition the organization to exempt this project from the standard data timeliness requirement. They were successful in this request, and the requirement was relaxed enough on the data timeliness parameter to make using the contractor system as a data source viable. This in turn decreased the data complexity, and thereby reduce the time to develop further. These two responses in tandem reduced the time to develop parameter enough that the designer could identify a viable solution that achieved some of their accessibility goals while meeting the new constraint on the project timeline. This final design space is shown in Figure 33 below.
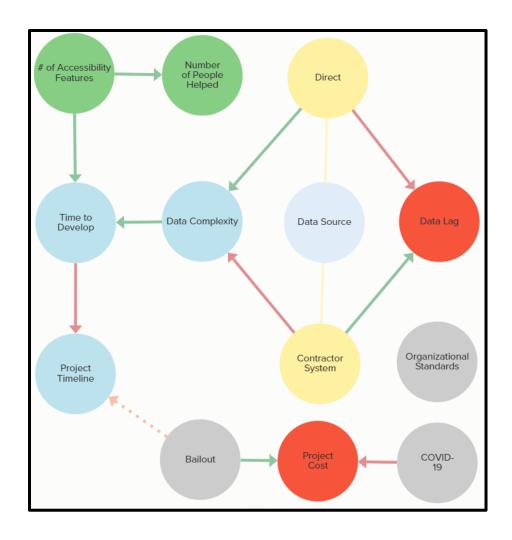
FIGURE 33: FINAL RESOLUTION OF TRADE-OFF IN CASE I7

Case I9

The 9th and final case presented in this thesis was the design of an automated tolerance checking gauge for a gear component. The goals of the designer and the firm that underpinned this drive to automate this task were to save on operation costs and to eliminate operator errors stemming from fatigue and routine. However, this project had been attempted several times by other teams within the company, without any success due to the challenge of aligning the component and the automated gauge while meeting line throughput requirements and operating within floorspace constraints.

The alignment of the parts was particularly challenging because the gauge measured many tolerances simultaneously, including the major, minor, and pitch diameters, and

the chamfer of the gear splines. The tolerances themselves were also extremely small, with some of the tolerances approaching 10 microns. When attempting to automate this challenge, the previous teams and the interviewee's team found that the variation in the parts combined with the fact that the automated gauge could only move linearly led to high rates of failure in detecting good parts, with only 0-5% of parts passing, and only those parts that were extremely close to the nominal dimensions.

Despite all these challenges, the potential savings of the project were deemed sufficient to make another attempt, and this is where the interviewee and his team were at. They partially resolved the conflict between aligning the part axes and using linear actuators in the automated station was resolved by adding by two features to the gauge fixture: one that introduced 3 new degrees of freedom around the 3 rotational axes, and a taper to all mating surfaces to guide the gauge into the part. By giving the part the flexibility to rotate around these axes, the part would adjust its angle as the tapered gauge slowly engaged it, allowing the central axes of the part and the gauge to align.

All of these factors increased the success rate of the gauge to 40%, and the interviewee expressed confidence that the initial conflict had been resolved. However, this solution introduced some new conflicts and trade-offs including increased maintenance and time to measure the part.

Modeling Case I9

The primary goals that prompted the company to start the project in this case were to reduce the operating costs and the number of bad parts they were sending to their customers. These two goals were operationalized into two evaluative parameters, operating costs and false negatives, as shown in the top right of Figure 34 below. Operating costs was framed as a continuous parameter by the interviewee, with a preference order for lower operating costs. The false negative parameter was measured in parts per million (PPM), a ratio representing how many "bad" components were not found by the gauge and made it out to the customer, and possibly even to consumer

189

vehicles on the road. The target for this false negative parameter was to minimize, with any value above 0 resulting in a financial penalty applied by the customer.
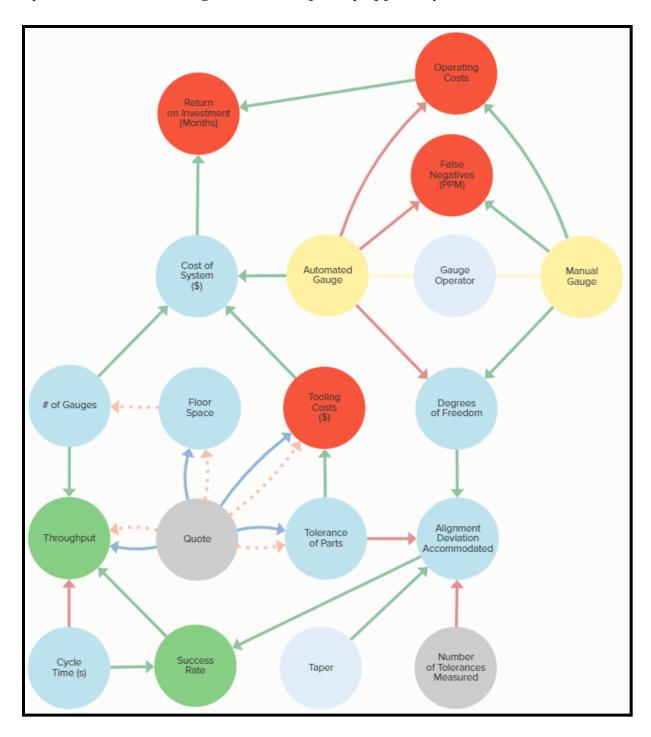

FIGURE 34: INITIAL TRADE-OFF SITUATION IN CASE I9

The designer had to meet one other primary goal, regardless of their solution. This was the throughput requirements, or number of parts made by the plant, which was constrained by the quote. The quote was the contractual agreement where the interviewee's company agreed to make a certain number of parts, at a certain tolerance, within a specified amount time and for a specified price. This made the throughput and tolerance of parts parameters explicit. The throughput was a discrete evaluative parameter with a maximization aim, while the tolerance of parts parameter represented how tight the tolerance on the part dimensions were.

With the current solution, which used a human operator to check the parts with a manual gauge, both of these two parameters were performing worse than desired. Operating costs were high because of the operator's salary and other financial benefits, while the false negatives were high because of the human error inherent in using a person. This design project's attempt to improve the performance on these parameters was to automate the gauging process, using robots to move the parts, measure their tolerances using a gauge, and then sort them appropriately into good and bad parts.

This was not the first time this project had been attempted, but the previous attempts had resulted in a null design space, because the rate of false positives were too high. False positives was an evaluative parameter that represented how many good parts were incorrectly labeled as bad. The interviewee framed this parameter as the "success rate" of the design, which was the percent of good parts that were correctly recorded as such, as shown in the bottom left of Figure 34.

The previous attempts at solving this issue provided the designer with awareness of where some of the limits on the real design space were, and what parameters were limited. In particular, the number of tolerances being measured and how tight the tolerances were negatively influenced the amount of deviation that could be accommodated on the alignment between the part and the gauge. This relationship held true for both the automated and the manual gauge, and both parameters had

191

requirements imposed upon them by the customer. The number of tolerances was a static parameter in the context of this design project, since it was pre-established by the customer during the design of their part and could not be altered at this stage. How tight the tolerances were could be changed by altering the tooling of the parts, but the customer imposed a maximum limit on this parameter, based on how this part needed to interface with other parts in the larger vehicle system.

The primary difference in performance on the false positive parameter during the previous attempts was that the automated gauge restricted the degrees of freedom on the movement of the part. The degrees of freedom were modeled as a single discrete parameter because the designer discussed it as increasing or decreasing the degrees of freedom in the interview. When the performance on this parameter was reduced (i.e., fewer degrees of freedom), the amount of alignment deviation that could be accommodated was also reduced. This in turn meant that the performance on the false positive parameter was reduced, and that reduces the throughput of the plant, since more parts are thrown away.

The interviewee noted that the solutions needed to improve on two parameters to be viable. Firstly, the design needed to improve its performance on the success rate parameter, with the target on this parameter being to maximize as close to 100% as possible, to meet the throughput requirement. Second, the system design needed to maintain an appropriate rate of return on the investment (ROI), which was driven by the interviewee's manager and the financial goals of the company. The ROI parameter was measured in the months it took for the savings generated by a decision to cover the initial capital cost of that decision. In this case, these two factors were represented by the parameters of cost of the system (continuous parameter measured in dollars) and the operating costs, which were defined previously.

To meet this goal the interviewee and their team introduced two new parameters to the design space: the binary feature parameters of the floating fixture and the taper, which

altered the design space into the structure shown in Figure 35 below. The floating fixture was a feature that added three new degrees of freedom to the automated system, raising the performance on the degrees of freedom parameter to match the manual gauge approach. This increased the amount of alignment deviation that could be accommodated. The addition of a taper to all of the edges of the gauge also improved the amount of alignment deviation that could be accommodated. With the addition of both of these features, the success rate was improved from a maximum of 5% to around 40%.
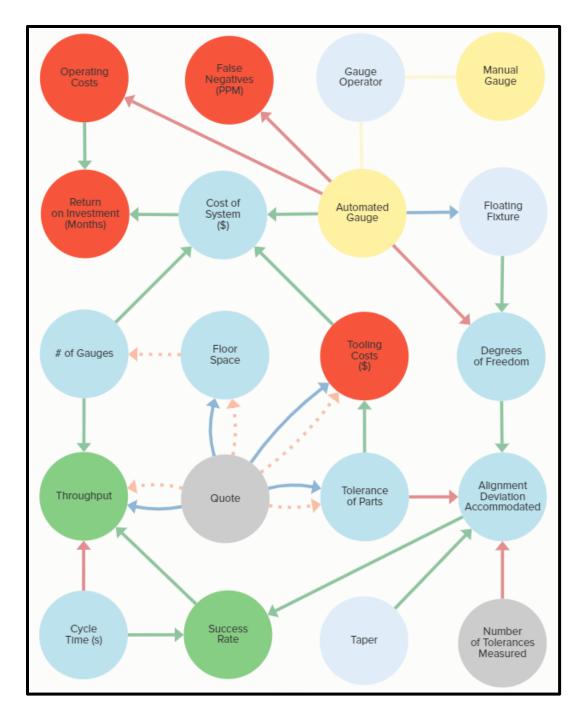
FIGURE 35: FINAL TRADE-OFF RESOLUTION IN CASE I9

40% was not sufficient to meet the goals of the project though, so these two changes alone were not enough to find a solution that was a member of the viable design space. At this point the different stakeholders had different suggestions for increasing the

success rate further, but none of these suggestions were viable because they violated one or more membership criteria on the design space.

The interviewee themself made the decision to tighten the tolerance on the parts beyond the requirement imposed by the customer. By decreasing the variation in the part dimensions, this decision allowed the system to accommodate more variation on the alignment and improved the success rate to 90%. However, this also increased the tooling cost, making this parameter explicit in the design space. The interviewee said that they had access to a tooling budget that was 10% of their sales, which was represented by the quote node in Figure 35. Under this 10% limit, the interviewee could distribute the tooling budget how they wanted, and the solution of tightening the tolerance fell within this limit, appearing viable. Further elaboration from the interviewee uncovered that the tooling costs also influenced the cost of the system, and through that the ROI. When the designer tightened the tolerances on the parts, they increased the ROI far beyond the requirement imposed upon that parameter by their manager and organization, making this solution non-viable.

The design and automation engineers working under the interviewee proposed increasing the cycle time for the automated gauge as a solution. The existing cycle time was 15 seconds, determined by the throughput of the line. The interviewee and his team believed that if they could increase the cycle time the success rate would be higher, since the automated gauge could make multiple attempts at measuring the part. However, this solution was not viable because the designer could not relax the throughput requirements imposed by the constraint.

Alternatively, the interviewee's team proposed installing two automated gauges onto the line, parallelizing the task. This would allow each individual gauge to double their cycle time without affecting the overall throughput of the line. This would double the cost of the system, but this still resulted in an acceptable ROI. The constraint that prevented this solution from being viable was that during the bidding process that

defined the quote, the amount of floor space assigned to the line is determined and priced out. To increase the amount of space used by the line to accommodate a second gauge would require the quote to be revisited and altered, which the interviewee, their manager and the customer all would not allow.

As a result, all of the options discussed with the interviewee during the interview fell outside of the viable design space. However, this project was not yet completed, and the interviewee believed that they could continue adjusting dimensions and other parameters on the system to eventually get the automated gauge solution working. This is modelled as the designer believing that the design space is not a null space. As the project proceeds, the success of the project will determine whether this perceived non-null design space aligns with the real design space or not.

Appendix C – Coding Schema

Complexity of the Design Space

- Difficult to focus on multiple complex projects simultaneously.
- Having limited number of choices aids analysis and decision making.
- Modular design limits options and permutations of feature/capability sets.
- Not able to keep current up-to-date requirements and limits in mind while designing.
- System complexity and number of interacting parameters.

Consequences of Design Decisions

- Adding a goal or requirement that causes other related parameters to be limited.
- Adding complementary parameters/features that relax constraints on other parameters.
- Confronting the repercussions of sacrificing or deprioritizing a goal or parameter.
- Discovering complementary parameter relationships from previous design decisions.
- Implementing a feature that facilitates the discovery of limits on other parameters.
- Other entwined antagonistic parameter relationships (Knock on trade-offs).
- Previous design decisions "locking out" options in future design decisions.

- Stakeholder and organizationally driven rigidity on requirement causing limit on other requirement.

Context of the Design Space

- Environmental context of the design imposing a limit or barrier not present in other contexts.
- Environmental context of the design negatively influencing parameter behaviour.
- Regulations preventing access to specific levels of performance in components.
- Exploring alternative solutions "too long".
- Organizationally imposed limits on project resources.
- Overanalyzing the conflict wastes time.
- Reluctance to relax project deadline.
- Removing organizationally imposed limits on project resources.
- Restricting project resources (time, money, manpower, etc...).
- Time and effort required to prototype using a particular method.

Familiarity with the Design Space

- "Push back" against imposed constraints that are seen as unachievable.
- Awareness of available options in modular design.
- Consistent pre-established limits that are common across a problem class or domain.
- Designing in a "silo", without information on the behaviours and relationships with interfacing systems.
- Discovery of unexpected or unknown options in modular design.
- Familiarity with aspects of the design solution makes it easier to design related aspects.
- Generalized solution properties within a domain.
- Good understanding of where the limits are make it easier to "design around" them
- Lack of experience and understanding.
- Negativity from others predicting challenges, barriers, or failure.
- Networking designer to experts with a better understanding of parameter behaviour.
- Poorly articulated information about other elements or components of the design/system.

197

- Preference for known, "typical" solutions.

- Stakeholder with better knowledge of parameter behaviour.

- Suggesting solutions the interviewee knows or strongly believes to be not viable.

- Understanding how parameters in the design/system interact with each other.

- Unreasonably high goals or targets from the designer's perspective.

- Well articulated rationale for predicted behaviour/failure.

Operationalizing Goals

- Formal formatting of requirements discouraging questioning the rationale and operationalization fit of those requirements.

- Operationalizing a goal differently on one parameter to improve performance on another.

- Organizational structure impeding speed and clarity of information transfer about goals and viability assessments.

- Poorly articulated rationale for why goal isn't being attained.

- Reformulating a requirement based on better understanding of the goal or need that drove it.

- Requirement gathering and formulation organizationally separated from design.

- Requirements do not align well with the goals and the underlying behaviour necessary to meet those goals.

- Talking with stakeholders to validate operationalization of project goals.

- Vague requirements.

- Vague requirements initially led to deeper exploration of what the real goals and needs were.

Permanence of Design Decisions

- Accommodating changes to other parts of the design that they have "ownership" of.

- Attachment to features of solution attempts.

- Attempting to maximize salvaged content from previous, failed, solution attempts.

- Fixation on own or others ideas.

- Imposing new requirements after design decisions have been made.

- Influencer bias towards their own, already attained, goals preventing changes that may improve overall design performance.
- Organizational structure that allows backtracking and iteration.
- Organizational tendency to forward project inertia.
- Questioning rationale behind design decisions.
- Releasing emotional attachment to previous failed solutions.
- Willingness to revisit previous design decisions.

Prototyping & Testing

- Ability to quickly predict likely real behaviour and failures from low fidelity prototypes.
- Anxiety from using unoptimized designs or prototypes to explore the behaviour of the design space.
- Comparing concepts at different levels of aesthetic refinement introduces bias.
- Failed designs provide better understanding of parameter behaviour and where the real limits are.
- Negative feelings of impossibility after a failed design.
- Prototypes help convince stakeholders and decision makers.
- Prototypes help understand underlying real performance.
- Prototyping allows low cost, low commitment exploration of "atypical" solutions.
- Prototyping helps designer conceptualize complicated solutions more easily.
- Testing and simulation to quickly identify uncertain/unknown barriers.
- Testing for actual performance.
- Unable to test for real performance in accurate environmental contexts.
- Using benchmark solutions to understand performance and parameter behaviour.

Subjectivity of the Design Space

- Communicating strategically to prevent bias driven barriers to information transfer.
- Conflicting goal priorities between different stakeholders and influences.
- Coordinating decisions across all or most of the stakeholders.
- Differing expectation of performance targets between stakeholders.
- Empathy for other stakeholder's priorities.

- Ideation with multiple designers.

- Making stakeholder biases and priorities explicit.

- New perspective on a solution prompting discovery of a boundary through critique and criticism of concepts.

- Poorly framing communication of changes to other stakeholders and decision makers.

- The challenge of convincing stakeholders and decision makers to increase project resources.

- Value of stepping back/out of the immediate design situation to see the problem differently.

Timeliness

- Aversion to thinking beyond the scope of the current project.
- Considering limits earlier in the design process prevents unexpected failure.
- Delay between decisions and consequences.
- Early awareness of barriers and limitations.
- Early awareness of parameter behaviour.
- Emotionally frustrated reaction to new constraints.
- Predicting future goals or requirements of designs that may interact with the current concept.

Appendix D – Affinity Diagram

Legend

Complexity of Design Space
Consequences of Design Decisions
Familiarity with Design Space
Permanence of Design Decisions
Contextuality of Design Space
Prototyping & Testing
Subjectivity of Design Space
Operationalizing Goals
Timeliness