Identifying & Modelling Design Effort Influencing Factors in Product Design Company Projects

By

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

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Abstract

Product design is an uncertain, complex activity that is difficult to predict, being influenced by many factors. Understanding how these factors behave can provide great insight and value to practicing designers when planning their projects. A review of the approaches that identify these factors, specifically those influencing project resources show found that these methods tend to either have a specific use case or require the sophisticated analysis of large data sets. Valuable in their own context and emphasising the need to understand these factors, but are of little use to product design companies, who rely on expert judgement to estimate project resources. The capture of that expert judgement may offer a means of understanding these factors for product design companies.

This research presents the methods, analysis and findings of an evolutionary multiple round case-based approach, working with three UK-based product design companies (PDCs) to answer the following research questions:

RQ1: What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in the literature?

RQ2: How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?

RQ3: How might PDC teams enhance their understanding of the project planning process and of their own teams through the collaborative capture and modelling of their own understanding?

Answering these research questions resulted in four contributions.

1. The identification and modelling of which factors have the greatest influence on design effort demands of PDC projects, based on the PDC team's tacit knowledge and experience.

Five factors with the greatest influence on design effort needs of PDC projects were identified: "Brief Clarity", "Designer's Experience", "Designer's Intuition of the Client", "Delivery Output Complexity" and "Product Complexity". Sets of graphical models were produced depicting the behaviour of each factor.

2. The identification and synthesis of various dimensions of product complexity

As "Product Complexity" was the most significant factor identified in the cases, the accompanying collected data has been used to synthesise a range of dimensions and units of measure for the factor. These dimensions are: the number of parts a product is anticipated to have and whether they need to be custom designed; the intended functionality of the product,

including its degrees of freedom, and the technologies required to enable those freedoms and functionalities; and the creativity required of the design team to design the project.

3. The identification of "budget" as a novel category for design effort influencing factors and the synthesis of a novel set of categories to apply to design effort influencing factors in design projects derived from literature

Through the analysis of design effort influencing factors found in literature, several categories were synthesised. Through the findings of the cross-case analysis, an additional, novel category of "budget" was identified, resulting in the following nine categories: Team Management, Product, Business Management, Information, Tools & Technology, Client, Project, External Influences and Budget

4. The development of the CoFIDE method, a novel, tacit knowledge capturing, influential factor identification and modelling method for design effort level influencing factors in PDC projects.

To address RQ3, a method was developed to identify and model the behaviour of the most influential factors of design effort demands of design projects. Based on the case-based research approach, CoFIDE is a method which models the behaviour of the most influential factors per phase of a design project, utilising two graphical methods to produce the models. The Mean Effect Plots (MEP) of each design team member for a given factor overlaid in a simple line graph provide a clean means of identifying the behaviour of a factor, and how its average influence changes from being at its perceived lowest state to its perceived highest. The Percentage Influence Graphs (PIG) provide a direct means of identifying which factors exert the greatest influence over design effort requirements. By representing percentage influence in linear bars, direct comparisons between designers and their perceptions of factors can be made quickly. In combination, these models enable design teams to identify which factors have the greatest influence and how that influence behaves based on the magnitude of their presence. This provides design teams with potential opportunities to take action to reduce negative impacts, and increase positive impacts, on projects.

The novel research presented in this thesis and its outputs has the potential to save the SME-intensive design industry time and resources by offering insight into their design space and the factors that influence it.

Published Work

"Being a writer is a very peculiar sort of a job: it's always you versus a blank sheet of paper (or a blank screen) and quite often the blank piece of paper wins" -- Neil Gaiman

Journal Papers

Holliman, A., Thomson, A.; Hird, A. (2020) *"What's taking so long? A collaborative method of collecting designers' insight into what factors increase design effort levels in projects"* Artificial Intelligence for Engineering Design, Analysis and Manufacturing.

Conference Proceedings

Holliman, A., Thomson, A.; Hird, A. (2017) "*Engineering design resource planning: A case study in identifying resource forecasting opportunities in research project planning"* 21st International Conference on Engineering Design (ICED 17), Vancouver, 21st – 25th August 2017.

Holliman, A., Thomson, A.; Hird, A. (2018) "*Planning Product Design & Development: Resource-Influencing Factors Based on Experience"* 25th Annual European Operations Management Association (EurOMA) Conference 2018, Budapest, 24th – 26th June 2018.

Holliman, A., Thomson, A.; Hird, A. (2019) "*A Mater of Factor: A Method for Identifying Factors That Influence Design Effort Levels in Product Design"* 22nd International Conference on Engineering Design (ICED 19), Delft, 5th – 8th August 2019.

Holliman, A., Thomson, A.; Hird, A., Wilson, N. (2020) "*Collaborative project brief scorecard (CPBS) method: Evaluating product design projects to aid design effort estimation*" 16th International Design Conference, Cavtat, 18th – 21st May 2020.

Holliman, A., Thomson, A.; Hird, A. (2021) "*Estimating the Design Effort needs of Product Design Agency Projects using Captured Expert Knowledge – A Proposed Method*" 23rd International Conference on Engineering Design (ICED 21), Gothenburg, Sweden, 16th – 20th August 2021

Holliman, A (2023) "*Dimensions of Product Complexity from Designers' Perspectives*" 24th International Conference on Engineering Design (ICED 23), Bordeaux, France, 24th – 29th July 2023

Contents

Glossary

Design Effort: A resource of design activities. Typically measured in person-hours or person-days, it is the duration of a design activity, activities or design project.

Design Activity: Any process or action undertaken by a designer that contributes to the design and development of a design project.

Design Project: A set of design activities that, when combined, are used to design and develop a new product or service. These can be undertaken by anyone, but are typically done by design teams.

Design Space: The holistic environment within which designers operate. This includes the physical space, internal factors such as the dynamic and structure of the business they work in and the socio-political environment.

Design Team: A group of persons, typically designers, working collaboratively towards completing design projects. These teams may also include other professionals, such as engineers, researchers, model makers, and other skilled individuals. Design teams may also include members of the target user group/market for a particular product.

Product: In the context of this study, a product is typically an artefact that is the output of a design project that has been developed with particular intentions and functions in mind. Any product that is the output of a design project may be accompanied by documentation and diagrams, manufacturing instructions, prototypes and other physical models; and CAD drawings and renders.

Product Design Company (PDC): A business that is appointed by a third party (both individuals and other organisations) to develop physical products to fulfil said parties' functional requirements. Sometimes referred to as a *product design agency* or a *product design consultancy*.

Project Brief: A document describing the product to be designed by a design team. This document may specify particular technologies to be used or incorporated into the product, patients and other information to inform the design of the product, descriptions of the end-users and other persons or parties that may use the product, timescales and other deliverables of the design project. The brief should be agreed by all stakeholder parties prior to the start of a project.

Contribution Statement

The content of this thesis provides evidence for the advancement of knowledge in three areas:

Contribution 1

The identification and modelling of which factors have the greatest influence design effort demands of PDC projects based on PDC team's tacit knowledge and experience.

Contribution 2

The identification and synthesis of various dimensions of product complexity

Contribution 3

The identification of "budget" as a novel category for design effort influencing factors and the synthesis of a novel set of categories to apply to design effort influencing factors in design projects derived from literature.

Contribution 4

The development of the CoFIDE method, a novel, tacit knowledge capturing, influential factor identification and modelling method for design effort level influencing factors in PDC projects.

PART 1

1.1. Introduction

"Everything is design. Everything!" *-- Paul Rand*

1.1 Motivation & Background

A 2022 Design Council report found that the UK design economy (which includes product design, graphic design, digital design, etc.) contributed £97.4 billion in gross value add (GVA) in 2019 and employing 1.97 million people in design roles (Hay et al., 2022). This economy is growing and is characterised as having a "long tail"; one with many small firms referred to as small to medium-sized enterprises (or SMEs) and only a few large ones. According to the Office of National Statistics (2018), only 60% of these SMEs survive for more than three years, which although greater than the average (44%), still represents a 40% failure rate. One subsector within the design economy is product design.

Product design companies (PDCs), organisations and businesses appointed by third parties to design and develop products to a specific set of needs and criteria, are typically SMESs. PDCs face a significant challenge when conducting their business; they do not know what the outcome of any project will look like from the outset. They cannot rely on iterative evolutions of past projects, they start each project with a "blank slate". Undoubtedly many designers are be able to get an inkling of what the result of a project might look like, but beyond a general notion, more specific ideas are just not conceivable in the main. They use creative processes to conceive novel artefacts and objects to fulfil the requirements detailed in a brief provided by their client, a brief that is diverse as the products available on the market today. One project may be to develop simple kitchenware and the next a multi-million-pound product for the Oil and Gas industry. With such diversity, project plans and resource estimates cannot be duplicated and re-applied from one project to the next.

With an industry of small businesses that only survive 60% of the time, there is a great need for efficient working and effective project planning. Like in many businesses, experts are used in project planning (Andersen, 1996), and in the case of PDCs, much of the project planning is completed by members of the design team (Bashir and Thomson, 1999; Bischof et al., 2007). These planning activities are lengthy and time-consuming, which reduces the volume of design work done by these same designers. Since it is design work that leads to the generation of revenue for these businesses, the more time spent planning projects, rather than working on projects, impacts the potential income available for such businesses. In larger organisations, project planning may be conducted by project managers whose core competency is that of project planning and execution, which in turn keeps designers working productively. Fundamentally, every hour spent by designers planning projects is an hour that cannot contribute to the survivability of the business.

Additionally, errors in project planning can equally have devastating consequences for an SME PDC. An underestimate of design effort (and therefore cost, based on a designer-time pricing structure typical in the industry) can have a significant impact on business reputation, finance and ultimately survivability. Therefore, any means of offering insight into what influences PDC project design effort needs and can provide an essential lifeline and improve the chances of survivability through improved project planning accuracy.

In contrast, although their design processes and organisation are similar, new product development (NPD) teams are notably different. NPD teams benefit from several advantages, which are summarised in Table 1. As they are part of larger organisations, NPD teams have the financial backing of their larger organisations, reducing the financial pressure on them and enabling mistakes or project failures to be absorbed more easily. Additionally, NPD teams can take advantage of established departments within their parent organisation to take care of other administrative duties, such as HR, payroll, etc., Whereas PDCs will have to employ a staff member for this role, outsource the tasks to another organisation (incurring further costs) or assign the tasks to one of the company directors, which reduces the productivity of that director. Furthermore, NPD teams are responsible for the development of products within the portfolio of their parent organisations. This offers two distinct advantages to NPD teams. First, the ranges of potential products that NPD teams are likely to face are significantly smaller than PDCs, enabling NPD teams to apply the findings of previous projects in the planning and execution of future projects. Secondly, NPD parent companies are more likely to have the financial means to invest in research towards their business practices, and therefore NPD teams can benefit from the advantages that such research can offer.

Table 1 PDC and NPD team comparison

	Product Design Company (PDC)	**New Product Development (NPD) team**
Organisation	• Typically SME	• Part of a larger organisation
Financial	• Responsible for all finances (income, investment, etc.) • Less financial buffer for project failure	• Backed by a larger organisation • Financially protected in case of project failure
Administration	• Directly employed staff • Outsourced to 3rd party • Company director task	• Tasks performed by parent organisation’s departments.
Project Diversity	• Highly diverse	• Limited to the organisation’s product portfolio
Project Planning	• Carried out by designers	• Carried out by Project Managers

1.1.a Why focus on the Product Design industry?

There are two main personal motivations for this study. Firstly, as a subject of academic study, product design, specifically the practices of product design companies, is significantly under-researched, especially when compared to fields like design engineering. There has been extensive research (and investment into research) within the fields of manufacturing, engineering and business management areas, with large businesses (with available budgets) contributing their time and money to improve aspects of their operations. Even when we look more specifically into the fields of design engineering and project management, the research and publications in these areas are rich and diverse.

Yet even at the nexus of these subjects, the narrower field of *design management* (the management of design processes and practices), which this thesis ostensibly contributes to, the body of literature, although sizable, becomes much less bountiful. This is further compounded when one considers design management within the previously mentioned context of product design companies. This is illustrated through a search of peer-reviewed publications using the Scopus search engine for "product design" or "industrial design" business, company, agency, or consultancy within publications' title, abstract or keywords returns a total of 111 documents. Although it can be acknowledged that publications might indeed not have the correct keywords within their publications, it is doubtful that this oversight leaves hundreds of publications out of a search return. If one considers the likely correlation between peer-reviewed publications and investment in research, then clearly the PDC field is lacking.

When considering the £16.3bn contributed in GVA to the UK economy in 2019 (Hay et al., 2022), it is clear that product and industrial design is a highly valuable sector in the UK, but is all but ignored by research. It is simpler to focus investment efforts on larger organisations where greater change can be affected. Whereas these SME PDCs are too many and too small to be an effective target for funding and have less financial flexibility to sponsor research into their practice.

This leads to the other personal motivation for this research relating to the background of the researcher. I am a product designer by training and by experience. I have friends and former classmates who work in the product design industry. I was presented with an opportunity to conduct research with them and for them, which can benefit them and their industry. In effect, I wanted to provide something of use and value to practising designers that are often overlooked.

So why PDCs?

PDCs are an under-represented industry within academic study and literature, this is not least of all due to the lack of budget and staff availability to facilitate lengthy studies. PDCs face the unique challenge of planning and executing a diverse variety of projects which are exempt from direct comparison to previous projects and are not subject to any specialised planning model. This makes PDCs an ideal target for research, with designers with a broad sense of their craft and what influences it.

1.2 The factors influencing product design projects

Although the breadth of research conducted specifically for PDCs is limited, broadening the search may provide some benefits that can be applied to the PDC use case. Research has been published on several methods which may offer potential approaches to aid the PDC industry, or at least provide some insight. Many of these studies discuss the existence of factors which influence the design space, with their approaches based on this understanding. This research study identifies and analyses such approaches to gain insight from them and determine their possible suitability in a product design company context. Based on this review, this research develops a method which builds upon the insight accrued and develops a means of identifying these influential factors and providing product design company teams with a greater understanding of their own design space and the factors that influence it.

Thesis Structure

This thesis is broken into three parts, outlined in Figure 1.

Part 1 provides context for the study, along with this introduction covering the background and motivation for this research project, a literature review and a chapter outlining the methodology for the research. The literature review considers product design project planning literature, taking a funnel structure to look at the issues faced by product design teams, and the methods they take to overcome such issues. The findings of the literature review conclude with a set of research questions which act to guide research. The research approach outlines both the philosophical standpoint taken for this research and the practical research methodology for an evolutionary multiple round case-based approach.

Part 2 covers the methods and outputs of three cases as part of a evolutionary multiple round case-based approach. Conducted with UK-based product design companies, the analysis of each case informs improvements to the research approach. With each case analysed to aid the development of a method to identify and model the factors most influential to design effort demands of design projects and the insight that such modelling offers.

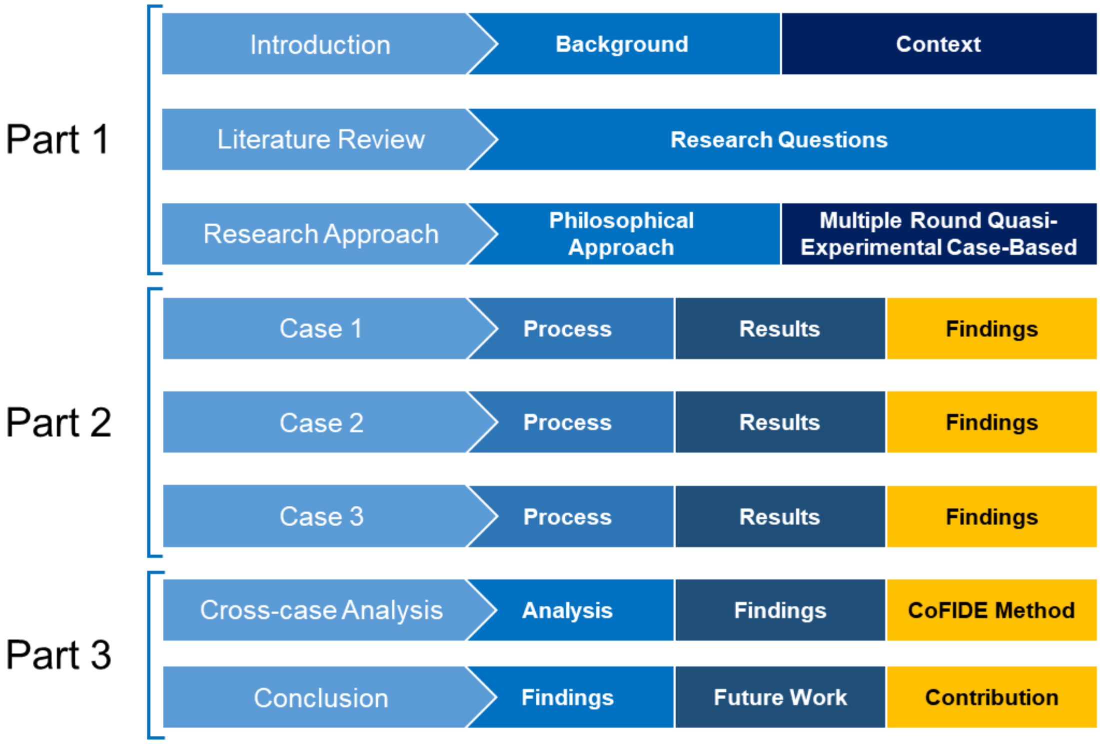


Figure 1 Thesis Structure

Part 3 presents the results and findings of the evolutionary multiple round case-based approach, conducting a cross-case analysis. There are four outputs of this cross-case analysis, including a deep investigation into the factors influencing design effort needs in PDC projects, the identification of novel factors not mentioned in literature and culminates in the presentation of the Collaborative Factor Identification for Design Effort (CoFIDE) method. CoFIDE is a method to identify and model the behaviour of the factors which have the greatest influence over design effort levels of product design projects.

Research Aims & Objectives

The aims and objectives of this research are:

1. To determine if factors influencing design effort demands of product design company projects can be identified and modelled.
2. To understand the influence such factors have over design effort levels in a practical and understandable way.
3. To determine whether changes in these influential factors' behaviour throughout a project can be modelled to identify characteristics, such as where any given factor has the greatest influence.

4. To identify any discrepancies and agreements between the findings of literature and PDC designers.

This will be achieved by:

- Identifying and applying methods and techniques that can identify influential factors in a design project context.
- Adopting an evolutionary multiple round case-based approach, working with practicing designers within PDCs.
- Identifying and testing various modelling and communication approaches for the insight gained.
- Include and improve the visual communication tools used to convey the insight offered by such a method.

2. Literature Review

"Research makes it possible to do the right thing. You know who didn't do research? The stupid little pigs that built their houses out of straw and sticks. They made a great stew.
Build your house out of bricks."

-- Mike Monteiro, You're My Favourite Client

2.1 Introduction

With a diverse potential project range and a low survivability rate, PDCs face a significant and difficult challenge when planning their projects (Salam and Bhuiyan, 2016). Planning, undoubtedly the first step on any project (Jack, 2013a), is critical to project success, with those in planning roles having to overcome the high degree of uncertainty (Chalupnik et al., 2009; Dong et al., 2014; Eckert and Clarkson, 2010; Pich et al., 2002) inherent to design projects. One core action when planning design projects is design effort estimation. Design effort is the unit of measure used when considering the time required to complete a project and is measured in either person-hours or person-days (Salam et al., 2009; Salam and Bhuiyan, 2016). The demands for design effort are undoubtedly influenced by a wide range of potential factors (Bashir and Thomson, 1999) and a poor understanding of these factors can lead to poor project planning (Chatzoglou and Macaulay, 1997). Studying these factors, what they are, how they influence design projects and specifically the resource demands of projects would have significant value to industry and would contribute to their understanding in academia. A key observation has been made that a successful means of estimating design effort is designers utilising their tacit knowledge and experience (Brauers and Weber, 1988; Eckert and Clarkson, 2010; Jack, 2013b; Serrat et al., 2013), something which is widely used in PDC environments.

Therefore, this literature review identifies the methods that consider the factors influencing design project resource demands, analyse their processes to determine their viability and suitability in a PDC environment, and collate the factors that such studies consider identifying any commonality or trends in their findings. From this, several gaps in knowledge can be identified and a series of research questions can be formulated.

2.2 Methodology

This review will explore the challenges and issues associated with project planning in the PDC industry, as well as other analogous industries (i.e. industrial design, engineering design, etc.), develop concepts and ideas and identify suitable gaps in research (Jesson et al., 2011). The research conducted and described in this thesis explores the issues stated in the initial remarks of this chapter and investigates the processes for estimating design project resources (design effort) to identify trends in the processes adopted in such methods, and the factors identified in such studies to establish trends in which factors are considered influential.

As this review seeks to identify gaps in knowledge and determine the direction the study should take by formulating research questions from its outcomes, this review takes the form of a scoping literature review. As such this review identifies all relevant papers on specific topics (discussed below), the contents of which are then assessed for relevance and insight. From which gaps in knowledge can be identified and research questions synthesised.

2.2.a Sourcing suitable literature

As described in chapter 1, this research study considers the PDC industry (a subsector of the design economy), to aid these organisations in their project planning. Also discussed in chapter 1 is the lack of peer-reviewed publications with a focus on PDCs, with "product design company" or alternatives. For this review, various search terms were used when conducting this literature review to identify suitable peer-reviewed papers. This process, along with a depiction of their subsequent analysis is summarised in Figure 2.

The terms used to conduct an initial literature search, shown in Table 2, were included due to the various terminologies used to describe what this study has classified as a product design company (PDC). In the UK, the term "product design" typically relates to the design of artefacts, however, in other countries, this term can relate to software design. In such instances, the term "industrial design" is commonly used. Similarly, PDC businesses may choose to define themselves as either a "company", a "business", a "consultancy", an "agency" or a "firm". As a result, many combinations of search terms have been used. The search has been extended to include the title, abstract or keywords, producing a total of 111 results when using the search engine Scoups. When considering the breakdown of these results by subject area, as shown in Table 3, most of these papers are written for the *engineering* field, with *Business, Management and Accounting* taking a large proportion of the remaining results.

A follow-on search, using the previously used terms, as well as those relating to estimation (forecasting, etc.) was also conducted to identify peer-reviewed literature covering estimation in PDCs, the number of results returned quarters to 25, shown in Table 3. The results of this search have a narrower diversity of subject areas (shown in Table 4), with engineering remaining the most common subject, computing science second and business management and accounting being the third most common.

With a lack of depth within this field, the search terms used to gather potential sources had to be expanded to include peer-reviewed papers that consider design within the engineering subject area. The researcher selected the Scopus search engine to conduct this literature search, as it has links to many publishers and their publications across a divrse range of subject areas. Using the Scopus search engine, a search for peer-reviewed papers was conducted using the keywords outlined in Table 5, searching within the title, abstract and keywords

Table 2 Search terms for PDC-related research on Scopus

Search Terms	No. Results
"product design company" OR "product design business" OR "product design consultancy" OR "product design agency" OR "product design firm" OR "industrial design company" OR "industrial design consultancy" OR "industrial design agency" OR "industrial design business" OR "industrial design firm"	111

Table 3 Subject areas of PDC-related research on Scoups

Subject Area	No. results
Engineering	52
Business, Management and Accounting	36
Computer Science	28
Social Sciences	27
Materials Science	13
Mathematics	11
Arts and Humanities	9
Economics, Econometrics and Finance	9
Environmental Science	8
Chemical Engineering	4
Physics and Astronomy	4
Agricultural and Biological Sciences	2
Chemistry	2
Decision Sciences	2
Energy	2
Medicine	1
Multidisciplinary	1
Psychology	1

.

Table 4 Search terms for estimation within PDC-related research on Scopus

Terms	No. Results
"product design company" OR "product design business" OR "product design consultancy" OR "product design agency" OR "product design firm" OR "industrial design company" OR "industrial design consultancy" OR "industrial design agency" OR "industrial design business" OR "industrial design firm" AND "planning" OR "plan" OR "resource" OR "estimat*" OR "forecast*"	25

Table 5 Subject areas for estimation within PDC-related research on Scopus

Subject Area	No. results
Engineering	14
Computer science	10
Business, management & accounting	8
Mathematics	6
Social sciences	5
Economics, econometrics and finances	3
Materials science	2
Physics and astronomy	2
Arts and humanities	1
Energy	1
Environmental science	1

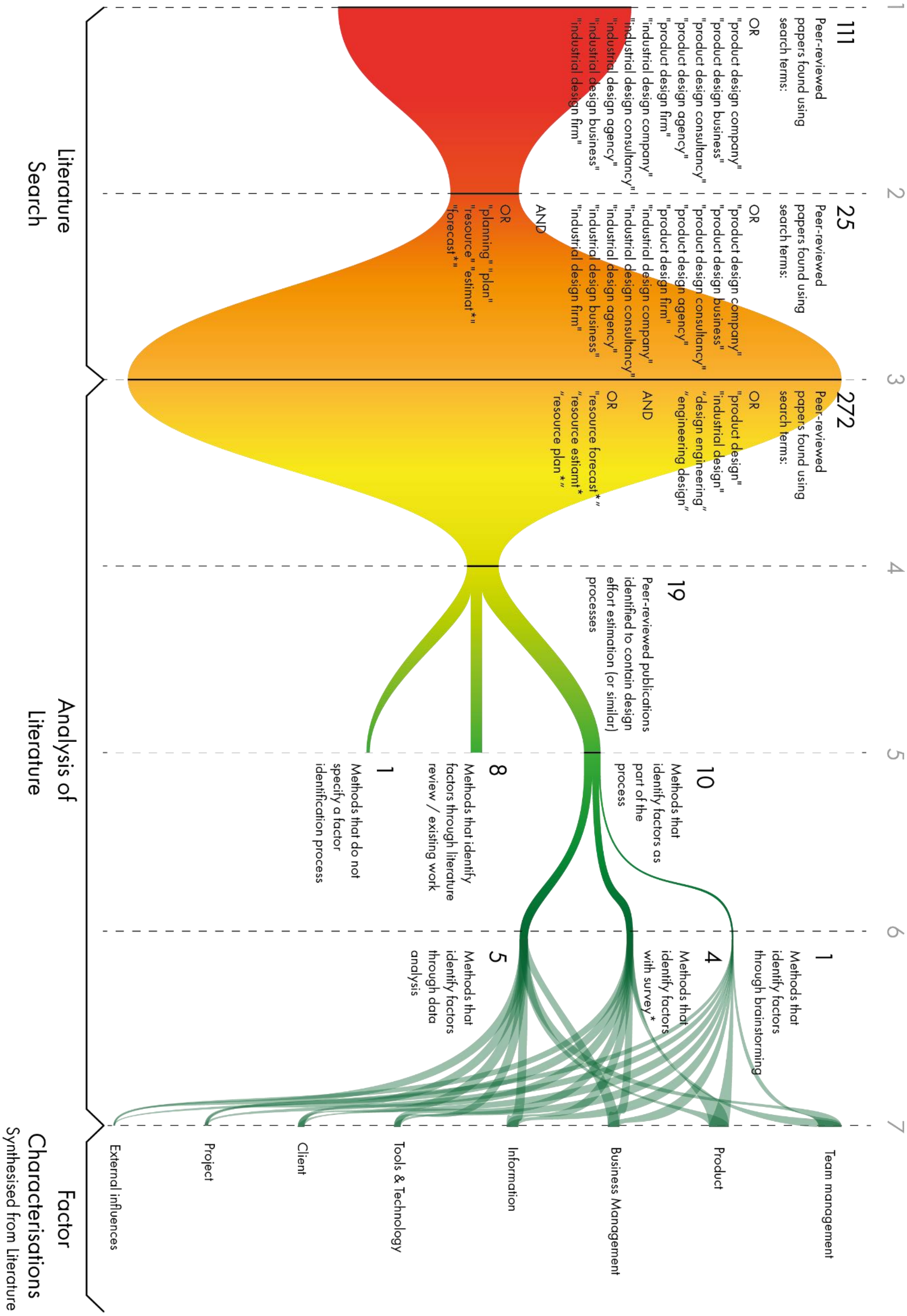


Figure 2 Literature Review Process & Findings

Table 6 Search terms for estimation within Product Design research on Scopus

Terms	Subject area	No. Results
"product design" OR "industrial design" OR "design engineering" OR "engineering design" AND "resource forecast*" OR "resource estiamt* OR "resource plan*"	Engineering	272

Of the results found, many were eliminated based on their title, as they discussed topics unrelated to the estimation of resources in product design. Of the relevant papers identified, several referred to other relevant publications, and these were included in the study. Additionally, the studies that referred to those publications returned in the search with high citation counts were also reviewed for relevancy. A small number of papers returned in the search were written in a language other than English, which were therefore eliminated.

Of course, there are many textbooks and other publications which cover design management and other related fields, including project management. However, like the peer-reviewed publications previously discussed, very few of these texts discuss the specifics surrounding PDCs. Rather, these texts consider procedural approaches to the management of projects, particularly in the execution of such projects. As such, their discussion on planning, resource estimation, etc. are generalised, suggesting the "preparation of a schedule" as adequate instruction. Bodies of knowledge on project management texts from organisations such as the Project Management Institute (PMI) (2021) and the Association for Project Management (APM) (2012) discuss the estimation of a project's resource needs through the summation of best guesses of the duration of constituent activities, as it is assumed that all activities are known at the planning stage. Such estimations are accomplished through various models and activities such as the creation of Activity on Node diagrams (Maylor, 2010), or referring to the records of previous tasks for comparison (Lock, 2013; Wells, 2019). Likewise, bodies of knowledge from organisations, such as the Project Management Institute list a plethora of potential estimation approaches, including multipoint, function point and parametric estimating (2021), yet, like the textbooks, the methods they cover are predicated on having a clear understanding of project outcomes, knowing what activities are to be included in a project and, in some cases, having some past project to act as a basis for estimations. Therefore, such textbooks and reference books have not been included in this literature review.

2.3 Estimation in Design Project Planning

"Prediction is very difficult, especially if it's about the future." *--Nils Bohr*

As the understanding of the factors influencing resource demands of product design projects is key to the successful planning of such projects (Chatzoglou and Macaulay, 1997), a study into the methods described in peer-reviewed literature was conducted. It is assumed that such publications may discuss possible factors and means of identifying them. The following section will discuss various approaches to estimate design effort for product design projects and how these approaches and how they identify the factors which influence design effort levels. This section is an adaptation and expansion of a literature review section of a paper titled "A Matter of Factor: A Proposed Method for Identifying Factors that Influence Design Effort Levels in Product Design" presented at the International Conference on Engineering Design 2019.

Based on the issues highlighted at the start of this chapter, identifying suitable peer-reviewed studies, thirty-six studies were identified where the estimation of product design project time as either the focus of the method covered or as a function of a broader method. After review, sixteen of these papers were either identified as being generic project management methods and therefore not specifically tailored to the estimation of design effort; or were identified as being an abstracted theory, with no specific links to product design. The remaining twenty papers are varied in their scope, from specific areas of product design such as the design of manufacturing tooling to more generic product design project time estimation, each is shown in Table 7. Papers were sorted into five categories based on their consideration of influential factors (IF):

- Papers that identified influential factors as part of their process through **participant involvement**
- Papers that identified influential factors as part of their process through **data analysis**
- Papers that **build upon** the theoretical existing work from **design fields**
- Papers that **build upon** the theoretical existing work from **other sources**
- Papers whose methods **do not include factors** at all

The following sections will discuss each of these categories in detail.

2.3.a Estimation in Design Project Planning: Methods that identify factors

Any method which produces its own (potentially unique per use case) list of factors, by various means, has been considered to identify factors. Of the methods identified and reviewed, ten (52.6%) included IF identification in their processes. Four identify IF's through statistical analysis, such as Yan & Shang (2015). A further four methods identify IF's by engaging with experts through either brainstorming activities, or surveys/interviews. A final publication embraces a combination of both.

Table 7 Design Effort in product design project estimation methods that consider influential factors

	Does the method identify the factors	Theory / Existing Work	Brainstorming	Survey / Interview of Industry	Analysis of Data	Factorless / Unjustified Factors
Bashir & Thomson, (2004)	•		•			
Hird (2012)	•			•		
Andersson et al., (1998)	•			•		
Shang & Yan, (2016)	•			•		
Benedetto et al., (2017)	•			•		
Griffin, (1993)	•	•			•	
Yan & Shang, (2015)	•				•	
Hellenbrand et al, (2010)	•				•	
Cho & Eppinger, (2005)	•				•	
Eppinger et al., (1997)	•				•	
Bashir & Thomson, (2001a)		•				
Bashir & Thomson, (2001b)		•				
Xu & Yan, (2006)		•				
Yan & Xu, (2007)		•				
Salam et al., (2009)		•				
Pollmanns et al., (2013)		•				
Wang et al., (2015)		•				
Jacome & Lapinskii, (1997)						•
Yan et al., (2010)						•
	10	8	1	4	5	2
	52.6%	42.1%	5.3%	21.1%	26.3%	10.5%

Data Analysis to Identify Influential Factors

Data analysis is used to identify IF's in five papers covered in this review. The method by Cho & Eppinger (2005) is a variant of Steward's Design Structure Matrix (DSM) (1981) which identifies system variables (factors) and relationships, modelling information transfer patterns, resources conflicts overlapping and sequential iterations; and task concurrency. The model created considers that the system variables can evolve over time.

Data analysis IF identification methods commonly involves regression analysis. Some, like Hellenbrand et al. (2010) use regression analysis to identify influential factors to train a Monte-Carlo simulation for product development cost estimation. Developed to overcome the uncertainty found at the start of a project, this method focuses on project cost, although the authors identify a strong correlation between cost and effort (time). Yang & Shang (2015) also identify factors through data analysis to develop a forecasting tool using a support vector regression with probabilistic constraints (PC-SVR).

Worker Interviews to Identify Influential Factors

Various methods adopt interviewing, surveying and brainstorming with workers as a means of identifying IF, relying on their experience and knowledge to build an understanding of their design practices (Brauers and Weber, 1988; Eckert and Clarkson, 2010; Jack, 2013b; Serrat et al., 2013). A method for obtaining product development cycle time performance baselines through the application of regression analysis on historical data is proposed by Griffin (1993). Uniquely, this method identifies IF's which affect cycle time from both a literature review and existing study data analysis. For Andersson, Pohl & Eppinger (1998), an extension to the signal flow graphs method, outlined by Eppinger et al. (1997), IF's are gathered through worker interviews. Industry workers also provide details of IF's and their relationships for the method described by Bashir & Thomson (2004) through brainstorming.

Questionnaires, interviews and brainstorming are common approaches to identifying IF's from the perspective of industry experts. Shang & Yan (2016) suggest a method which has been developed to overcome small samples and heteroscedastic noise found in design time forecasting. This method identifies IF's (referred to as time factors and engineering characteristics) through self-administered questionnaires, based on a survey-based methodology.

In-depth interviews are the source of information on IF's in the method discussed by Benedetto et al. (2018), taking a work breakdown structure (WBS) and producing a project network standard to create a guide for the successful completion of design activities. Their study uses data from 13 design professionals, discussing what influences the design project quotation process and identifying four dimensions (factors) influential to the design process.

A notable study that was found from this review is that of Dataless Forecasting by Hird (2012), which presents a resource forecasting tool development method created specifically for New Product Development (NPD) teams. Hird identified that resource information is a critical and fundamental issue in resource demand planning processes, relying on the quality of the data gathered and analysed. Hird observed that although there are numerous modelling approaches available, the major limitation for the majority was the lack of past-project data; In effect identifying the need for a novel method which required little past-project data while remaining accurate, transparent and repeatable.

Based on the theory that experts and experienced practitioners have the greatest understanding of project resource demands, Dataless Forecasting captures the tacit knowledge of experts and reproduces said knowledge to produce accurate, transparent and repeatable resource forecasts in a fraction of the time that conventional estimation processes take. Hird's method is a five-step process which closely follows Fisher's Design of Experiments (DOE) (1949). This method has three main differences from that of traditional DOE, shown in Figure 3: physical experiments (or simulated) are replaced with expert estimations about hypothetical scenarios; the objective and measurable experimental inputs are replaced with the tacit and subjective knowledge of experts to become the subject of modelling; and results of the analysis are used for prediction, rather than optimisation.

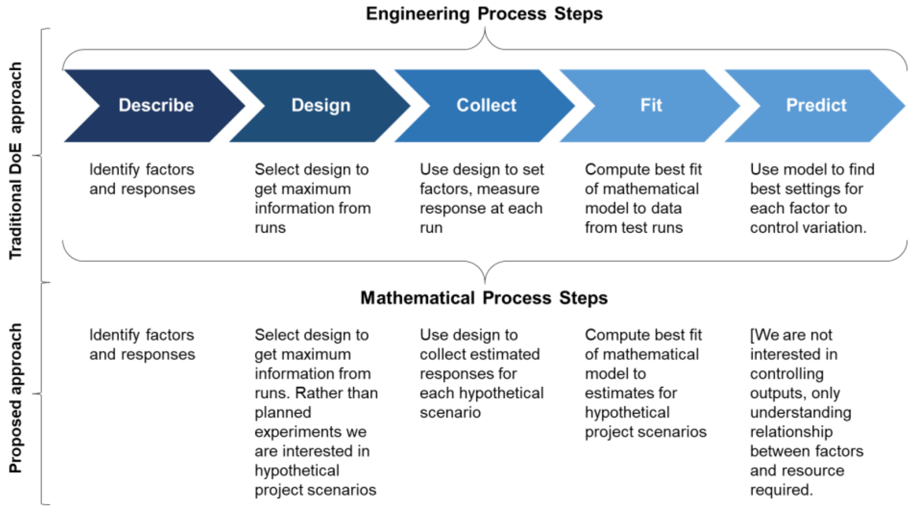


Figure 3 A New Product Development Resource Forecasting Method. Adapted from Hird (2012)

2.3.b Estimation in Design Project Planning: Finding factors in the literature

The other common method for identifying factors to use in developing an estimation tool is through the analysis of literature. Of the methods reviewed, eight methods (42.1%) based their assumptions of IF's on pre-existing research or models; or synthesise a list from a literature review.

The method proposed by Bashir & Thomson (2001a) takes evaluations of past project productivity and the factors (taken from Bashir & Thomson (1999))which affected that productivity, applying them to an eigenvector approach (based on Saaty (1980)). Based on a literature review, Bashir & Thomson propose a shortlist of project length IF's, and although each is prescribed into the method, they acknowledge that each design team that the method is applied to, may result in different factors from said shortlist becoming the most influential. In that way, it is neither a method which explicitly identifies IF's, like those in the previous section nor a method which exclusively uses a de facto list of pre-determined factors. The widely-cited paper by Bashir & Thomson (2001b) proposes two models for estimating design effort and time. Both methods use historical data with the jackknife resampling method and regression analysis to develop estimation models. Both models consider product complexity to be a major contributing factor. The other factor suggested is the Severity of requirements: how extreme are the limits imposed on the project deliverables?

Xu & Yan (2006) developed a "Fuzzy measurable house of quality (FM-HOQ)" by taking the House of Quality from the Quality Function Deployment (QFD) and applying a fuzzy neural network (FNN) to the process. The researchers take factors from the literature to set the parameters of the FNN, taking historical data to train the FNN to identify relationships between factors, etc.

Another Fuzzy-based approach is proposed by Yan & Xu (2007). This method uses a fuzzy nu-support vector machine (Fnu-SVM) to forecast design efforts. First introduced by Vapnik et al (1995), SVM is a supervised learning model designed for classification and regression analysis. Yan & Xu use an SVM as the basis for their model, building on other research findings and literature to infer relationships for effort estimation. The authors cite another paper when referring to IF's (or input variables, as referred to in the paper) (Xu and Yan, 2004) when listing four types of input variables for a Fnu-SVM: product characteristics, design process, design condition, and design team.

An example of a method which is developed for a specific use case is proposed by Salam et al. (2009), for the design of aircraft engine compressors by Pratt & Whitney to estimate design effort. Using a multiple linear regression model (MLRM) to facilitate a parametric modelling technique, the method considers three factors: type of design, degree of change, and experience of departmental personnel.

Pollmanns et al. (2013) propose a method of devolving an information model to evaluate design projects against a series of IF's (identified through a literature review) to develop design effort estimates. Such information models require historical data to establish relationships between stages, IF's, etc.

A tool for variant design time predictions is proposed by Wang et al. (2015), using a combination of the chaos particle swarm optimization (CPSO) and FNN. This theoretical method builds an FNN from the established relationships between product factors (this paper covers printer design, so all factors relate to the performance characteristics and features of a printer) with their influence weighting established by correlation degree. The authors do not specify the source of these printer factors, however, in their literature review, they discuss general factors which impact design project time.

2.3.c Estimation in Design Project Planning: Other Factored Methods

Factors without justification

Two of the papers reviewed make use of factors, or some other term for factors, in their methods without justifying their use, assuming their influence over project length.

Jacome & Lapinskii (1997) refer to a Nonrecurring Engineering (NRE) project which they define in similar terms to a design project (based on the nonrecurring nature of design projects). They propose a method to produce an NRE project cost estimation tool to be used within the electronic product design industry. Like Hellenbrand et al. (2010), the authors draw a direct correlation between project cost and duration. This tool bases its estimates on the IF's: product size, product complexity and factors relating to productivity, although the source of these factors is not specified.

Zhi-gen & Yan (2011) proposes a model for identifying relevant project parameters and predicting time with those parameters. This is achieved through the use of Gaussian Margin Regression (GMR) analysis and is specifically developed when even a small data set is available. The factors used for the regression analysis are assumed without any literature-based justification discussed.

2.3.d Estimation in Design Project Planning: Factorless Methods

Participation Factors

Eppinger, Nukala & Whitney (1997) propose a method for modelling the design process to be analysed using signal flow graphs. This model can also be used to calculate project duration distributions and predict significant project metrics, such as the expected mean and variance of lead time. Additionally, this model can provide insight into the iterative structure of the projects and the sensitivity of the lead time to the parameters of the model. This process requires the participation of the designers/engineers of the company that the model is intended for. This method does not explicitly identify IF's, instead identifying "participation factors", commonly used in linear system theory.

The Phenomena, not the factors

Some methods cover similar phenomena to the effect of IF's on project length, but do no specify which factors. Smith & Eppinger (1997) propose a method for developing a DSM-based extension model to estimate design project duration and to recommend coupled design order of tasks to minimise project time. Using the pre-existing theories of DSM and Reward Markov Chains, data collected from a company's managers and engineers are analysed to determine the probability of task repetition. This method does not explicitly identify IF's, but rather produces a general understanding of the calculated effects and their likelihood.

Another study which does not consider IF's, as previously defined, is Yan et al. (2010), who proposes a method to reduce product development time based on the DSM (Steward, 1981) method. This method includes the observations of Krishnan et al. (1995) (upstream information evolution and downstream information change sensitivity) and Carrascosa et al. (1998) (extended concepts of change and impact probability). This method requires modelling the entire product development process, analysing relationships and establishing dynamic characteristics of information flow with the statistical optimisation method of Sequential Quadratic Programming (SQP) (Yuan and Sun, 1997). Using data gathered in other studies, this is a theoretical method which has not been tested or validated, in industry. This method is designed for product development optimisation - specifically development time and cost.

2.3.e Analysis of Factor identification within product design project length estimation methods

Bespoke Influential Factor Identification

42% of the design project estimation tool creation methods covered in this review identify project time IF's on a case-by-case basis; Finding the IF's each considered influential by each design group that undertakes the method. Of these methods, half gather information directly from the practising designers, engineers, managers, etc.; The other half gather their data through some form of statistical analysis. It is reasonable to assume that there are clear advantages to each method. Both, in their way, process historical data to synthesise their conclusions on projects and factors.

Working with design industry professionals, it is possible to obtain a level of understanding afforded to those who have years of experience. It is this experience, and the earned tacit knowledge from past experiences that form perceptions held around design projects and the IF's which influence them. Therefore, it is the perceptions of these IF's that inform the thought processes behind the creation of estimations, quotations, etc. for new projects (Serrat et al., 2013). Yet for all the lessons learned through experience and the wealth of knowledge accrued over a lifetime in the industry, estimates made by experts can still be affected by influences, such as bias (Bashir and Thomson, 1999). Therefore, it is reasonable to assume that, so too are the perceptions on project length IF's. Similarly, any discussion of factors may lead to disagreement between parties, leading to further impact on what factors are truly influential.

Conversely, the analysis of data through simple, or sophisticated means can highlight patterns in past project performance and uncover which IF's have influenced project length in the past. When considering facts, rather than opinions (albeit from experts), there is no opportunity for bias from these experts to taint the results. However, these statistical approaches require some basic understanding of IF's, or typically in these cases variables, to identify which are exerting influence. Therefore, such methods are dependent on the knowledge of the practitioner to program, train, etc. their analytical tools. Furthermore, such methods require accurate records of past projects, ideally in significant quantities, to conduct a robust analysis. For many companies, such record-keeping has not been possible. Additionally, such analysis tends to need sophisticated software, or at least a competency in analytical methods to perform such investigation; Neither may be accessible to those businesses within the product design industry.

Identification of Influential Factors from Existing Research

42% of the papers covered in this review discuss methods that base their assumptions of IF's on either a literature review or from another study. This approach has the clear advantage of a rigorous foundation of peer-reviewed research. Yet, the reliance on past research has the potential of overlooking the possible changes in trends, attitudes or approaches to product design, as research takes time to be conducted, analysed and published. 84% of papers covered use IF's as the critical variables when estimating design effort. Clearly, the identification and comprehension of IF's a critical part of design effort estimation. Yet, only half of these papers (42%) use some form of IF identification to inform their methods.

2.3.f Estimation in Design Project Planning - Summary

Many of the methods developed to estimate resources (design effort) in design projects rely on the understanding of various factors which have influence on such projects. Those methods that find factors in the literature consider such factors to be universally applicable to any suitable use case, and therefore are not contextually specific. The alternative is to identify IFs on a case-by-case basis. Such methods enable users to identify those IFs that are specific to their needs and use cases. Many of these approaches adopt some form of data analysis, which require some combination of large sets of homogeneous data, or sophisticated data analysis approaches. These approaches have either highly specific use cases or need analysis expertise; neither of which are viable for PDCs. The alternative IF identification approach is through consultation with design team members. These approaches include interviews, surveys, and brainstorming activities. Such methods are much more viable to PDCs, requiring none of the specific needs of the other approaches. Therefore, any approach to identify IFs within a PDC context should utilise these methods.

2.4 Factors Influencing Design Project Planning

"The future influences the present just as much as the past." -- Friedrich Nietzsche

This section provides an analysis of the factors found to influence product design projects, specifically the planning of such projects and the resources needed to complete them. There are many factors which influence the planning of projects, specifically when considering the design effort required to complete tasks, phases and the project in its entirety. This section discusses the factors identified in the development of design effort estimation methods, as well as others that are discussed in other publications. This will be followed by an analysis of potential categories that each of these factors refers to, based on the definitions provided by the authors of their source publications.

2.4.a Factors Influencing Design Project Planning: A note on factors

Factors influencing the design project resource of time (and its variations) and the contexts in which they are considered are varied. Discussions range from factors concerning specific parts of the product design process, such as tooling design for manufacture, to broader discussions on so-called "creative" projects, such as construction, new product development projects, etc. There has been limited writing on such factors from the perspective of the PDC.

2.4.b Factors Influencing Design Project Planning: Factors in Literature

Considering lists compiled by other researchers, Xu & Yan (2006) synthesize a list of seven factors (each with its own elements) to create a conceptual model of factors that influence design time (design effort) from 4 sources: Zirger & Hartley (1994), Ittner & Larcker (1997), Tatikonda & Rosenthal (2000) and Ali et al. (1995). The following paragraphs will cover the factors that these authors cover.

Zirger & Hartley (1994) investigates "acceleration techniques" to increase the speed of product development. These techniques look to address individual factors, or "constructs", which influence this speed both negatively and positively. The range of factors that have been identified from various sources of literature, with each factor having a range of contributing different elements. The factors they consider are: Project Complexity, Information Processing Capability and Motivation.

By examining the contributing elements, it is clear that Zirger & Hartley (1994) have established categorisations for each of the factors. Project Complexity - with the elements of uncertainty, coordinative complexity and component complexity - relates to constructs around the project and the tasks within, rather than qualities of the product – the output of the task. This is particularly notable with the element of component complexity, which refers to the complexity of each constituent activity of a task. Taken from Wood (1986), these elements are defined in the context of the task and refer to several psychology studies relating to the relationships between training and task success.

Information Processing Capability – with the elements of the extent of information sharing, timeliness of information processing, and the speed of decision-making - relates to the efficiency of communication between teams and team members; and Motivation – with the elements of explicit goals, goal congruence, linking performance measures and rewards to goals, and control - relates to the management of the development team.

Ittner & Larcker (1997) take a business management perspective when identifying 5 "organizational practices" that enhance the performance benefits from accelerated product development (particularly in new product development). The arguments for each of these practices: Fit with the Organization's Strategy; Greater Use of Cross-Functional Development Teams; Customer and Supplier Involvement in the Development Process; Use of Advanced Design Tools; and Higher Perceived Product Quality are drawn from several other sources and research. Although this paper addresses business issues and practices, such as profitability, rather than product considerations, some of these practices can be considered relevant factors, as they influence the speed of product development.

With the characteristic of Fit with the Organization's Strategy, the authors suggest that to develop products quickly, the business strategy must reflect this, making quick product development a key component of their business plan. This characteristic can be adapted into a factor by considering the level of fit of rapid product development within an organisation's strategy, or type of product development business strategy.

For the Greater Use of Cross-functional Development Teams characteristic, Ittner & Larcker (1997) cite Brown and Eisenhardt (1995); Clark and Fujimoto (1990); and lansiti (1993) as evidence that the diverse backgrounds found in cross-functional development teams can improve the range of information available to design products, improving efficiency and effectiveness, thus reducing development time. A factor can be gleaned from this characteristic, with a phase such as Product Development Team Diversity.

Ittner and Larcker address the *customer* and *supplier* involvement of the "Customer and Supplier Involvement" in the Development Process characteristic separately. Citing Stalk & Webber (1993), they observe that brining the customer into the product development process can result in the development of products which fulfil customer requirements. Although included as one of the "organizational practices", it is not one considered to improve development speed. However, the discussion of supplier involvement in NPD does discuss potential improvements in development speed to be gained. As a result, the factor of Supplier Involvement can be created.

When suggesting that the Use of Advanced Design Tools as an "organizational practice", Ittner & Larcker (1997) refer to tools (such as the quality function deployment "house of quality" (QFD), and Failure Mode and Effects Analysis (FMEA)) which 20 years later, are more commonly found in product development environments. Therefore, the factor of "Up-to-date Development Tools Used?" as a factor, although due to the increased ubiquity of these development tools, one could potentially disregard this as a factor.

From the analysis of studies (e.g., Zirger and Maidique (1990)), Ittner & Larcker (1997) observe that there is a correlation between accelerated product development and the perceived higher level of quality of a product. Therefore, for the characteristic of *Higher Perceived Product Quality*, one can consider the factor of "Level of Perceived Product Quality."

Ittner & Larcker (1997) also identify 3 "organizational practices" that can limit the potential benefits of said beneficial practices: Lower Conformance Quality; Less Innovation in Product Designers and Diminished Returns to Scale for Additional Resources, some of which can also be modified into factors.

The discussion around Lower Conformance Quality characteristics considers the impact that increasing product development speed can have on the resulting products. Citing several sources, Ittner and Larcker state that the benefits of saving time can be nullified by product defects, unintended manufacturing problems, etc. Therefore, the factor of the "Number (or level) of Quality Measures" could be considered, although this relates to manufacturing as much as development.

Citing lansiti (1993) and Mansfield (1988), Ittner & Larcker (1997) note that although less innovative products require less development time, this can result in oversights of innovations which can lead to profit and the creation of products that will make a company more competitive. From the perspective of improving development speed, there are no suitable factors which can be gleaned from this argument, although the "Level of Desired Product Innovation" can be considered a potential factor.

When considering the *Diminished Returns to Scale for Additional Resources* characteristic, Ittner and Larcker consider the negative financial impact that some steps to reducing development time can have. Most notably the issue covered by Brooks (1975) that of adding more people to a task does not exactly reduce the task duration. As this discussion considers the cost of including additional personnel to a project, rather than a factor which can influence project development speed, one has to consider the only relevant factor to be the number of staff on a project as a factor, based on Brooks' (1975) argument.

Drawing their conclusions from 12 studies, Tatikonda & Rosenthal (2000) consider "Technology Novelty" and "Project Complexity" as the two dimensions to determine project success. Each dimension has several factors, two and three factors respectively. These two dimensions are calculated from the sum of their contributing elements. The Technology Novelty dimension is the sum of the measures for "Product Technology Novelty" (the level of novelty the final product will have); and "Process Technology Novelty" (the level of novelty in the technology used or developed to produce the product). The Project Complexity Dimension is calculated from the sum of three elements: "Technology Interdependence" (how dependent each technology required in the product, or to produce the product); "Objectives Novelty" (how novel are the product's objectives); and "Project Difficulty" (how challenging will the project be to accomplish).

A range of factors has been identified and placed into one of three categories (Context, Process and Outcome) by Bryson and Bromiley (1993). The *context* category has eight factors (Involvement, Planning Staff, Technology, Time available, Impact/Required, Stability, Prior Coalitions, Power) which consider the environment in which the project is being conducted, including the people, deadlines, product influence, and external conditions and agreements. The process context has three categories (Communication, Forcing and Compromise) which consider how effectively information is communicated internally and externally, the use of forcing and compromise to resolve conflict among the stakeholders. For the outcome category, there are two factors (Success and Learning) which consider project success and the amount of information gathered that will influence future projects. Although these factors are all undoubtedly influential, many can only be assessed upon project completion.

An alternative categorisation scheme of *Socio-economic Environmental*, *Degree of innovation* and *Cultural Value* has also been suggested. Rondinelli, Middleton and Verspoor (1989) identify a range of factors for each categorisation. The *Socio-economic Environmental* category (Political and administrative systems, Economic systems, and Organisational Environment) considers the systems and environment (both political and business) which may influence a project. The *Degree of innovation* category (Task variety, Task Analysability, Scale of Innovation, degree of deviation of innovation) is project-focused, looking at the tasks required to accomplish the projects and the range and levels of novelty needed to realise the product. Whereas the *Cultural Value* category (Power distance, Uncertainty avoidance, Individualism-collectivism and role differentiation) considers how the design team organises and manages itself and the overall business as a whole

Goal and *Technology* have further been suggested as two "variables" that can be used to assess a project, each with two value levels (Christensen, 1985). A technology can be known or unknown; a goal can be agreed upon or not agreed upon, leading to four potential combinations, referred to as "problem conditions": Programming (Agreed goal, known technology), Bargaining (Not agreed goal, known technology), Experimentation (Agreed goal, unknown technology), and Chaos (not agreed goal, unknown technology). Christensen suggests that these can be used to assess a project, with recommendations for each condition, however, these conditions are fewer factors per se, rather states that a project falls within. Therefore we can modify these variables as the factors of the states: level of understanding of technology (the technologies used within the product), and clarity of goals (the agreement of project goals).

In their paper discussing the estimation of non-recurring engineering cost estimation in electronics design, Jacome & Lapinskii (1997) identify three factors which influence the duration of a design project (which they consider to directly correlate to cost); *Product Size*, *Complexity* and *Productivity*. Jacome & Lapinskii measure the size of the product based on the number of gates or transistors anticipated to be needed in the product. For this tool, complexity is considered to be a measure of the anticipated difficulty in producing a particular design. The example given is that of a product with "unusually stringent speed and/or power requirements". In this paper, productivity is the anticipated pace at which a task can be completed, based on given staff availability, etc.

Several publications by Bashir & Thomson address the factors that influence design effort levels in product design projects. In their 1999 paper, they provide seven separate factors. "Product Complexity" is a product-based factor based on the number of functions expected of the design and the depth of the functional tree. "Technical difficulty" is divided into two sub-factors (severity of requirements, and use of new technology) and is a combination of the expectations of the client measured by how easy or difficult it would be to meet them, and the use of novel technologies in either the product or the process. "Experience, skill, and attitude of team members" is a team management-based factor, which considers the capabilities of the team, both from a knowledge and skills perspective, as well as attitude. "Team Structure" is both a team management and business management-based factor which considers the means that design teams are managed within the design agency, the size of the team and the tools used for communication. "Use of design-assisted tools" considers the use of technologies to aid development and "Use of a formal process" considers the processes used by the design agency and the design team to manage the project (Bashir and Thomson, 1999).

In their 2001 paper, Bashir and Thomson build upon the findings of their previous paper, identifying two factors: "Product Complexity" and "Severity of Requirements"; derived from their 1999 paper, these are based on the number of functions expected of the design and the depth of the functional tree, and the expectations of the client measured by how easy or difficult it would be to meet them respectively (2001b).

A further publication by Bashir & Thomson (2004) considers a range of four factors; "Product functionality" is based on the number of functions expected of the design. As shown in other publications reviewed, this can be linked to product complexity. "Technical difficulty versus team expertise" is related to two issues. Firstly the design team must consider whether a new technology is to be used in the development of the product; and secondly how strict are the requirements of the product (such as the tolerances expected)? In this context, the authors associate these issues with the level of experience each member of the design team has. The third factor, "type of drawings submitted to the customer", specifically addresses the expected level of detail required for the design drawings and is based on the expectations of the client and their demand for the exchange of information. The final factor, "involvement of design partners" refers to the number of stakeholders involved in the development of a design.

Another proposed collection of four factors is provided by Salam et al. (2009), Benedetto et al. (2018) and Rondinelli et al. (1989). Salam et al. (2009) propose: "Type of Design", "Degree of Change", "Concurrency", and "Experience of departmental personnel". "Type of Design" is product-based and asks the question: "Is the product completely new, or based on an existing product?" Also product-based, "Degree of Change" links to the "Type of Design" factor, further considering the level of change the new product will have. Again, is it a brand-new product, or is it closely, or loosely based on an existing product? "Concurrency" is a team management and business management-based factor, looking to determine whether different aspects or elements of the product being developed at the same time? "Experience of departmental personnel" is another clear team management and business management-based factor, measured in years, it simply asks how experienced is the design team in general?

The factors proposed by Benedetto et al. (2018) are "Knowledge", "Execution", "Design Method" and "Planning and Control". "Knowledge" is split into two types (explicit knowledge and tacit knowledge) and discusses the level of experience the team has in the subject area of the project. Derived from the design team knowledge level, "execution" refers to the skills possessed by the design team and their ability to apply their knowledge. "Design Method" considered the formal structures that the design team follow to design and develop a product, while "Planning and Control" address the design agency's ability to manage the team and the activities that are needed to complete the project.

The four factors proposed by Rondinelli et al. (1989) "Outcome", "Socio-economic Environmental", "Degree of innovation", and "Cultural Value" each with their sub-divisions. "Outcome" (sub-divided into success and learning) considers project success and the amount of information gathered that will influence future projects. However, this is a factor that can only be assessed retrospectively. "Socio-economic Environmental" (Political & administrative systems, Economic systems, and Organisational Environment) considers the (external) systems and environment (both political and business) which may influence a project. "Degree of innovation" (Task variety, Task Analysability, Scale of Innovation, and Degree of deviation of innovation) is project-focused, looking at the tasks required to accomplish the projects and the range and levels of novelty needed to realise the product. "Cultural Value" (Power distance, Uncertainty avoidance, Individualism-collectivism and role differentiation) is both team management and business management-based and considers how the design team organises and manages itself and the overall business as a whole.

Griffin (1993) proposed a range of eight factors influencing design effort levels in product design. These factors (referred to as variables) are divided into three categories: *product characteristic* (PC), *outcome variable* (OV), and *development process variable* (DPV). Like in many papers, and as discussed previously, "Complexity" (PC) is a notable factor that Griffin divides into two (Product complexity and Management complexity). This is both a product characteristic that is based on the number of functions expected of the design and a team-management factor relating to the number of specialists required for the project. "Amount of Change" (PC) is a product-based factor that is assessed by comparing the product to be designed to those that are similar already on the market (which makes it an external influence factor) or produced by the client (which also makes it a client-factor). "Process" (OV) considers the demands made of the design team, both time and cost-based, and can therefore be considered a team management, business management, client and information-based factor. "Product" is also an outcome variable which can only be assessed after the project is complete, and looks at the success of the product, both commercially and with the customer. "Strategic driver development" (DVP) also has sub-divisions (Deliver customer needs, Competitive reaction, and Technology-driven), look at the reasons why the project was commissioned: customer demand, reaction to a competitor, to take advantage of some new technology, or management decision. This makes it a product, client, stakeholder and external influences factor.

Griffin looks at the development process variables as factors which are based on the team management and business management approaches taken at a strategic, tactical and operational level. "Organisational Variables" considers the strategic organisational approaches used by the design agency. The employment of specialists within teams, team location and the use of other strategic management approaches. "Type of process used" considers the tactical team management approaches. The processes employed to generally manage the design team and other project management processes employed. "Tools and techniques used" considers the operational project tools and techniques used by the project team.

An even larger range of factors is proposed by Pollmanns et al. (2013) with eight factors: "Innovation", "Product size", "Employee experience", "Multi-site development and development outsourcing", "Difficulty of the design task", "Team aspects and working environment", "Criticality of the designed product", and "Educational level of the employees". The authors provide specific detail on "Innovation" and "Product Size". "Innovation" is also described in terms of "product newness", which relates to how novel the product is to the design team. "Product size" is another product-based factor which links the size of a product to its complexity. "Employee experience" is a team management-based factor that considers the overall knowledge and experience of the design team. Whereas "Multi-site development and development outsourcing" looks at the geographical locations of the design team (in relation to each other) and the location of other stakeholders. This may be considered a team management, business management and stakeholder-based factor. "Difficulty of the design task" refers to the perceived difficulty of the product. This can be considered a feature of the project and the product and is dependent on the experience of the design team members. "Educational level of the employees", a team management-based factor, is a factor based on the experience each member of the design team has from their time in education. The factors of "Team aspects and working environment" (perhaps referring to Team management and attributes, and the working environment of the design agency) and "Criticality of the designed product" (perhaps referring to the severity of requirements based on the brief and client expectations) were found by Pollmanns et al in German-language literature, and therefore will not be considered to avoid misinterpretation of the cited authors' intent.

2.4.c Factors Influencing Design Project Planning: Factor Analysis

This section will cover the analysis of the factors covered in the previous section, attribute a categorisation scheme based on common phrasings found in each factor's source and determine which (if any) are most commonly found in the literature.

From the analysis of the 59 factors found in the literature, ten factor categories were found based on similarities in the definitions given by the authors. These categories are: Project, Product, Team Management, Business Management, Client, Information, Stakeholder, Tools & Technology, External Influences and Retrospective-only. A further category of "Not Included" has also been provided, to acknowledge the instances where it was not possible to confidently determine the justifications or definitions of the term. The distribution of factor categories is shown in Figure 4 and the full list of factors found in the literature is shown in Figure 5.

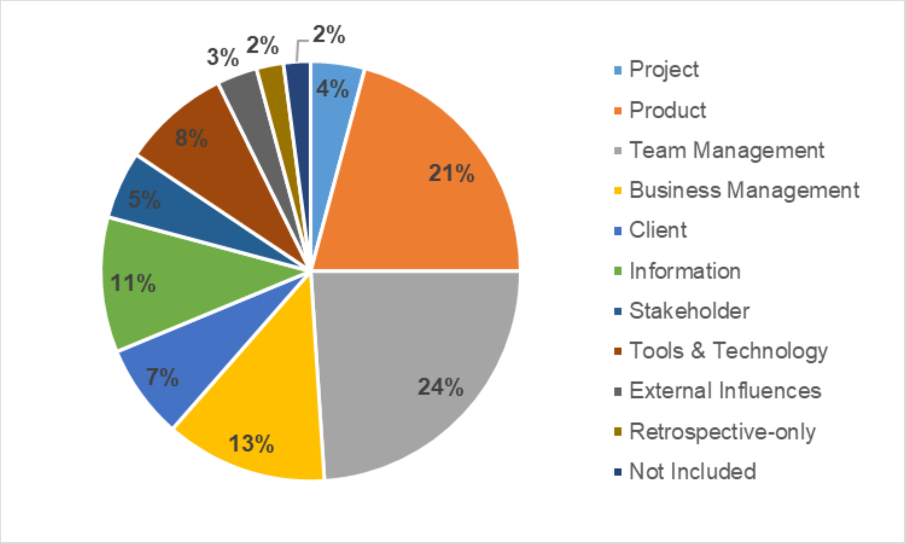


Figure 4 Factor Categorisation Analysis

Many of the factors identified within this review can be (and have been) categorised with more than one category. Each of the factor categorisations will be discussed in greater detail in the following sub-sections.

Project-based Factors

Project-based factors are any factors that refer to the project type. These include such terms as "difficulty of the design task" (Pollmanns et al., 2013) - which was also classified as product and team management classifications; and "Project Complexity" (Zirger and Hartley, 1994) which considers the overall perceived uncertainty and complexity of the project. Of the 59 factors that were found, four (6.8%) were categorised as project-based factors.

Product-based Factors

Product-based factors are any factors refering to the qualities or attributes of the intended product. These include such terms as "Severity of Requirements" (Bashir and Thomson, 2001b) – relating to the expected tolerances and other specifications that the product must be designed to; and "Product Complexity" (Bashir and Thomson, 2001b, 2001c; Griffin, 1993; Jacome and Lapinskii, 1997; Tatikonda and Rosenthal, 2000) which is one of the most common factors found in this category. 33.9% (20) of the factors found have been categorised as product-based factors.

Source	Term In Literature	Project	Product	Team Mgmt.	Biz. Mgmnt	Client	Information	Stakeholder	Tools & Tech.	Ext. Influences	Retrospective	Not Included
Pollmanns et al. (2013)	Difficulty of the design task	•	•	•								
Griffin (1993)	Strategic driver development	•				•		•		•		
Rondinelli et al. (1989)	Degree of innovation	•					•					
Zirger & Hartley (1994)	Project Complexity	•										
Bryson and Bromiley (1993)	Context		•	•			•	•	•			
Griffin (1993)	Complexity		•	•					•			
Bashir & Thomson (1999)	technical difficulty		•			•			•			
Bashir & Thomson (2001a)	Severity of Requirements		•			•						
Griffin (1993)	Amount of Change		•				•			•		
Tatikonda & Rosenthal (2000)	Technology Novelty		•						•			
Ittner & Larcker (1997)	Higher Perceived Product Quality		•									
Ittner & Larcker (1997)	Lower Conformance Quality		•									
Tatikonda & Rosenthal (2000)	Project Complexity		•									
Bashir & Thomson (2004)	Product functionality		•									
Bashir & Thomson (2001a)	Product Complexity		•									
Bashir & Thomson (1999)	Product Complexity		•									
Salam et al. (2009)	Type of Design		•									
Salam et al. (2009)	Degree of Change		•									
Pollmanns et al. (2013)	Innovation		•									
Pollmanns et al. (2013)	Product size		•									
Jacome & Lapinskii (1997)	Product size		•									
Jacome & Lapinskii (1997)	Product Complexity		•									
Christensen (1985)	Level of understanding of technology		•									
Griffin (1993)	Process			•	•	•	•					
Pollmanns et al. (2013)	Multi-site development and dev. outsourcing			•	•			•				
Griffin (1993)	Tools and techniques used			•	•				•			
Bashir & Thomson (1999)	Team structure			•	•				•			
Benedetto et al. (2018)	Design Method			•	•							
Benedetto et al. (2018)	Planning and Control			•	•							
Griffin (1993)	Type of process used			•	•							
Griffin (1993)	Organisational Variables			•	•							
Bashir & Thomson (1999)	Use of a formal process.			•	•							
Salam et al. (2009)	Concurrency			•	•							
Jacome & Lapinskii (1997)	Productivity			•	•							
Rondinelli et al. (1989)	Cultural Value			•	•							
Bryson and Bromiley (1993)	Process			•		•	•	•				
Christensen (1985)	Clarity of goals			•		•	•					
Bashir & Thomson (2004)	Technical difficulty versus team expertise			•			•		•			
Benedetto et al. (2018)	Knowledge			•			•					
Benedetto et al. (2018)	Execution			•			•					
Ittner & Larcker (1997)	Customer/Supplier Involvement in Dev. Pro.			•				•				
Zirger & Hartley (1994)	Information Processing Capability			•								
Ittner & Larcker (1997)	Greater Use of Cross-Functional Dev. Teams			•								
Ittner & Larcker (1997)	Diminished Returns to Scale for Adtl. Resources			•								
Bashir & Thomson (1999)	Exp., skill & attitude of team members			•								
Salam et al. (2009)	Experience of departmental personnel			•								
Pollmanns et al. (2013)	Employee experience			•								
Pollmanns et al. (2013)	Educational level of the employees			•								
Ittner & Larcker (1997)	Fit with the Organization's Strategy				•							
Bashir & Thomson (2004)	Type of drawings submitted to the customer					•	•					
Zirger & Hartley (1994)	Motivation						•					
Bashir & Thomson (2004)	Involvement of design partners							•				
Ittner & Larcker (1997)	Use of Advanced Design Tools								•			
Bashir & Thomson (1999)	Use of design assisted tools								•			
Rondinelli et al. (1989)	Socio-economic Environmental									•		
Griffin (1993)	Product										•	
Rondinelli et al. (1989)	Outcome										•	
Pollmanns et al. (2013)	Team aspects and working environment											•
Pollmanns et al. (2013)	Criticality of the designed product											•
		4	20	23	12	7	10	5	8	3	2	2

Figure 5 Analysis of Factors Found in Literature

Team Management-based Factors

Team management-based factors are any factors that refer to the makeup and management of design team members. This includes the processes that are used by the team during the development of a product (Bashir and Thomson, 1999; Bryson and Bromiley, 1993; Griffin, 1993; Ittner and Larcker, 1997) and the experience of each member of the design team (Bashir and Thomson, 1999, 2004; Benedetto et al., 2018; Pollmanns et al., 2013; Salam et al., 2009). 39% (23) of the factors identified have been categorised as team management-based factors.

Business Management-based Factors

Business management-based factors are any factors that refer to the overall management of the design company (or similar), the business plan, strategies, etc. that are used business-wide. These include the majority of the team management-based factors, such as team structure (Bashir and Thomson, 1999), as there is some cross-over, but also factors including "Fit with the organisation's strategy" (Ittner and Larcker, 1997) which considers the how the business's strategy may influence the project. 12 factors (20.3%) have been categorised as business management-based factors.

Client-based Factors

Client-based factors refer to any issues or characteristics that are displayed by the client. These include the factors that consider the levels of information being provided to the design team (in this case by the client) (Christensen, 1985). 7 factors (11.9%) have been categorised as client-based factors.

Information-based Factors

Information-based factors refer to any factors relating to the exchange of information. This category also includes considerations of existing products on the market that can aid product development – "amount of change" (Griffin, 1993). Many factors categorised as information-based, have other categorisations, including team management and product-based. 16.9% (10) factors were classified as information-based.

Stakeholder-based Factors

Stakeholder-based factors refer to any factors that involve other stakeholders (other than the client) such as suppliers (Ittner and Larcker, 1997); the processes to resolve conflict with stakeholders (Bryson and Bromiley, 1993) and the geographical locations of stakeholders (Pollmanns et al., 2013). 5 factors (8.5%) were categorised as stakeholder-based.

Tools & Technology-based Factors

Tools & Technology-based factors refer to the use and availability of equipment or other technologies to aid in the development of a product (Bashir and Thomson, 1999; Ittner and Larcker, 1997), and technologies needed by the design team for a specific project (Tatikonda and Rosenthal, 2000). Eight of the factors identified in the literature (13.6%)

External Influences-based Factors

External Influences-based factors refer to any non-stakeholder external body that may influence a design project. These include political influences "Socio-economic Environmental" (Rondinelli et al., 1989) and market-based influences (Griffin, 1993). Only 3 of the 59 factors identified (5.1%) were classified as external influence factors.

Retrospective Factors

Retrospective factors refer are factors proposed by authors but can only be assessed after a project has been completed. Two (3.4%) were identified which are the commercial success and customer satisfaction described by Griffin (1993), and the "outcome" factor proposed by Rondinelli et al. (1989).

Factors Not Included

Two factors were proposed by Pollmanns et al. (2013) which have not been included in the analysis. This is because the authors source these factors from another publication, which has been written in German. Therefore, to not misinterpret the intentions of the authors of either paper, these have been disregarded for this study.

Factors Influencing Design Project Planning: Analysis Conclusion

In this literature, a clear link has been shown between a designer, or design team understanding the design effort levels needed for a project, and their understanding of the factors which influence such levels. There is therefore a clear need to enable designers to better understand these factors and facilitate their discovery of them. The studies reviewed have investigated these factors in broad and narrow terms and in cases where the development of a design effort estimation method has been the outcome, rely on either the previously observed understanding of factors through their own literature review, or have gained their own insight into these factors through experimentation or data analysis.

2.4.d Factors Influencing Design Project Planning - Summary

There are a range of factors which influence the planning of design projects. This section presents an analysis of the terms found in literature to catagorise factors based on their characteristics. This analysis has found that, of all the categories (Project, Product, Team Management, Business Management, Client, Information, Stakeholder, Tools & Technology, External Influences, Retrospective-only), Product (21%), Team Management (24%), Business Management (13%) and Information (11%) based factors are the most commonly occurring in the literature. However the range of other factor categories identified indicate that there is a lack of a definative consensus within the literature.

2.5 Literature Review: Conclusion

Designing is an activity at the core of a range of creative roles (Harfield, 2007), each of which may benefit from studies into improved planning of design activities especially as there is limited understanding of design planning (O'Donovan et al., 2005). Understanding resource demands is key to planning, and for design activities, the universal resource is Design Effort. Design Effort can be influenced by a host of factors and phenomena, therefore understanding these factors and phenomena, and how they influence Design Effort, is key to understanding design planning.

2.5.a Conclusion: Design Effort Estimation in Product Design Project Planning

To effectively estimate design effort for a product design project, a designer has to evaluate the project brief. There are several proposed methods to project brief evaluation, either in isolation or as part of a method to estimate design effort in product design projects. These methods vary significantly in terms of scope and conclusions, but each approach has one similarity: projects can be categorised against various factors. This study reviewed 19 proposed methods to design effort estimation, each stating a range of factors as a core element to their performance. Seventeen of these papers (89.5%) identified several factors which influenced design effort project needs, of which ten (52.6%) include factor identification within their process. This shows a clear need for design teams to understand the factors which influence their projects to estimate design effort. Furthermore, by including factor identification in their processes, the authors of each method have tacitly stated that such factors may indeed vary on a case-by-case basis. This need for a case-by-case approach is further emphasised by the fact that in each example given, there are differences in the factors that have been identified.

Additionally, half of the factor-identifying methods use analysis of past project data to identify these factors, which, although undoubtedly a suitable approach, may not be viable for PDCs. This is for two main reasons. Firstly, as stated in the opening chapter, such businesses rarely have the vast datasets required to conduct a robust analysis, in contrast to many of the industries or partners of the studies reviewed, who are, in most cases, large engineering organisations. Secondly, such large organisations can afford to either recruit, or train, specialists in such analysis approaches (artificial neural networking, etc.) and provide the specialist software required to conduct analysis. This option is not as readily available to PDCs, as they may not be able to afford such an expense – and what data would they analyse anyway? The remaining half of these studies, discuss methods which use interviews and brainstorming as means to identify factors, taking advantage of the participants' experiences and knowledge. This approach, unlike the data analysis-based studies, requires little-to-no technical speciality, nor any large datasets. It has been shown that the use of experience and tacit knowledge to estimate design effort for a design project is successful (Brauers and Weber, 1988; Eckert and Clarkson, 2010; Jack, 2013a; Serrat et al., 2013), and with the majority of the studies reviewed (89.5%) utilising an understanding of factors to produce estimates, it is clear that designers are using their experience and tacit knowledge of influential factors as part of the process to estimate design effort.

One method reviewed offered an approach which specifically addresses experience and tacit knowledge is that of Hird (2012). This approach also includes data analysis, by collecting data on factors both directly, via interviews/surveys; and indirectly through a tailored project estimation process. The latter requires a degree of simple data analysis, based on a Design of Experiments approach, not requiring any sophisticated software or training. In effect, offering a "best of both worlds". This use of Design of Experiments offers a potential approach to generate and gather "project" data at the same time, which offers a potential means to have quantitative values for the typically qualitative values of such factors.

2.5.b Conclusion: Factors Influencing Design Project Planning

As stated previously, the majority of the approaches covered in this review were developed for engineering design, or similar. There is little-to-no published research into PDCs and the specific challenges that they face when planning their projects. Thiers is a design space that is broad and varied, full of uncertainty and complexity. Their businesses are small and their survivability is limited; They need all the help that they can get. To improve the understanding of the design space of PDCs, what (and how) factors influence design effort levels in product design projects, one must improve one's understanding of the factors which influence design effort demands. The designer's experience and knowledge are critical elements throughout this study. Having have been shown to mitigate uncertainty and manage complexity and iteration in product design. This same experience and knowledge contribute to the understanding of the factors that influence design effort in product design projects. It is through their experience and knowledge that designers can evaluate a project brief against their understanding of these various factors, using their chosen design process to provide context.

This review has considered a range of factors which have been identified in the literature to be influential. There are some factors which are commonplace in these studies, such as product complexity. Yet there are many more which are all but unique to their corresponding study. This illustrates that there is no universal set of factors that influence design projects, therefore for every design team, and every PDC, there is a unique, personal set of factors, which may have as varied a level of influence as the list of factors are varied. Therefore, a process which can identify factors on a case-by-case basis would be the most viable option to consider.

There is a clear need and gap in knowledge when considering the issues surrounding PDCs and the specific set of challenges they face. This gap will be addressed through this research, utilising a design of experiments-based approach to the identification, modelling and understanding of the most influential factors of product design projects conducted by product design companies.

2.5.c Gaps in Knowledge

From this review, there are clear gaps in knowledge which can be addressed through this study.

Knowledge of Which Factors

From the discussion on factors which influence design project resources, it is clear there is a diverse range of these factors, rather than a unified agreement on which factors have influence. This subjectivity is possibly related to the means of identification that the studies considered used. Regardless, there is a need to increase the knowledge of these factors to identify if those considered in literature reflect those considered by practising designers, in particular within a PDC context.

Knowledge of Factor Behaviour

A continuation of the first knowledge gap; It is not just what factors have the most influence which is valuable, but how their influence behaves, and how that behaviour changes during a project. Published methods do not consider explicitly state whether they can model such behaviour, yet this understanding of factor behaviour is utilised by practising designers who perform resource estimates within their roles. Therefore, there is a gap in the knowledge around the capture of influential factor behaviour.

Knowledge of Factor Behaviour Modelling

Building upon the preceding knowledge gap; As there are no published processes for capturing influential factor behaviour, there cannot be any methods for modelling that behaviour. Therefore, there is a gap in the knowledge around the modelling of influential factor behaviour within the PDC project context.

2.7 Research Questions

This review has indicated that there has been a clear need to understand the factors which influence design projects. Additionally, it has shown that for PDCs, whose need is arguably more critical to the survivability of their business, there are no specific approaches that have been developed; Many of those approaches developed for engineering design are too time-consuming and resource intensive for such PDCs to use and are for design effort estimation, rather than addressing factors specifically. As such, this review has shown that there is a clear need for developing an approach which identifies the factors which influence design effort in product design projects and models their behaviour throughout a project.

Considering all of this, the following research questions have been posited and will be addressed in this research:

2.7.a RQ1

As shown in this review, there are various factors which influence design effort demands of product design projects. Each study considers a combination of factors, with limited agreement on which factors have the greatest influence. There is a clear need for this insight, as evidenced by the number of resource estimation methods developed which have influential factors as a key component. Compounding this is the lack of research into PDCs specifically, where the need is high, but research interest is low. It is unclear whether the findings in existing research. covering the engineering subject area, correlate with the viewpoints held by members of the PDC industry. Therefore, RQ1 asks:

> *RQ1: What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in the literature?*

2.7.b RQ2

Building upon RQ1, understanding which factor, or factors, have the greatest influence has value, yet it asks a follow-up question: How does the influence of such factors change? How does it behave? The means to understand not only which factors have the greatest influence, but how that influence behaves throughout a project, could offer significant advantages to PDCs. As such, and as a direct continuance from RQ1, RQ2 asks:

> *RQ2: How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?*

2.7.c RQ3

It has been shown that successful estimates of project resources can be made using designers' own tacit knowledge and understanding of their design practice and the factors which influence it. Therefore there is value to be gained from capturing this tacit knowledge and experience and modelling it to effectively communicate each individual's perceptions. Doing so through a process that mimics the collaborative methods used by design teams in their design process, it may be possible to complement the work of design teams by offering a means of modelling such insight. Therefore RQ3 asks:

> *RQ3: How might PDC teams enhance their understanding of the project planning process and of their own teams through the collaborative capture and modelling of their own understanding?*

3. Research Approach

"If we knew what it was we were doing, it would not be called research, would it?" -- Albert Einstein

3.1 Research Approach Introduction

From the analysis of literature in the previous chapter, it has been shown that due to the complex and uncertain nature of product design and design engineering activities, there are many factors influencing a design team's practice with various degrees of influence. Understanding these factors is key to design project planning, as shown by their inclusion in many design effort estimation (planning) methods. Such methods identify these influential factors (IF) by:

1. Asking experts, through interviews, surveys, etc. to create methods that have highly specific use cases and do not apply to general PDCs.
2. Analysing large sets of past project performance data using machine learning, or similar, which are not viable for PDCs who neither have the expertise to conduct such analysis, nor the data sets to analyse; or
3. A combination of both using a Design of Experiments-based method, which generate the data to analyse, and identify factors through questionnaires with select staff.

The latter approach has been applied in the new product development space, a limited use-case in comparison to PDCs (as discussed at length earlier in this thesis), but offers a viable approach to act as a starting point for this research study.

This chapter has three over-arching sections. The first discusses the philosophical perspective adopted by the researcher, including discussions of the appropriate ontology and epistemology perspectives incorporated within the adopted philosophy. The second will discuss the research approach and the method used throughout this study. The third section will discuss the practical application of the adopted research method, including its structure and other issues, including participant recruitment, etc. This structure is summarised in an adaptation of the research onion, shown in Figure 6.

3.2 Philosophical Perspectives

This section discusses the philosophical perspectives adopted by the researcher for this study.

3.2.a Philosophy

What is a research philosophy? The term refers to "the development of knowledge and the nature of that knowledge", according to Saunders et al. (2015). Understanding the philosophical issues surrounding research can help clarify research designs and enable the selection of suitable designs (or the need to create a new one if necessary) (Easterby-Smith et al., 2012). There are several research philosophies that can be adopted for such a research study, namely positivism, post-positivism and constructionism, details of which are described by Hatch (2002) and are shown in Table 8.

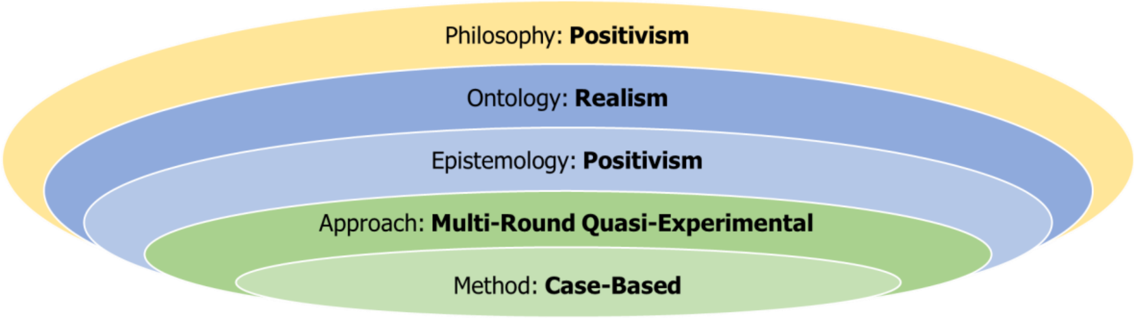


Figure 6 Research Approach Diagram. Adapted from Saunders et al. (2015)

Table 8 Summary of Research Relevant Paradigms. Adapted from Hatch (2002)

Research Paradigm	**Positivism**	**Postpositivism**	**Constructionism**
Ontology (Nature of reality)	Reality is out there to be studied, captured and understood	Reality exists, but is never fully apprehended, only approximated	Multiple realities are constructed
Epistemology (What can be known; relationship of knower to known)	How the world is really ordered; knower is distinct from the known	Approximation of reality; researcher is a data collection instrument	Knowledge as a human construction researcher and participant co-construct understandings
Methodology (How knowledge is gained)	Experiments, quasi-experiments, surveys, correlational studies	Rigorously defined qualitative methods, frequency counts, low-level statistics	Naturalistic qualitative methods
Products (Forms of knowledge produced)	Facts, theories, laws, predictions	Generalisations, descriptions, patterns, grounded theory	Case studies, narratives, interpretations, reconstructions

To answer the research questions stated in chapter 2, a method requires testing. This will be achieved through experimentation. The perspective held for this research is that there are factors influencing resource demands, therefore the method being tested is set to determine how the world is ordered, with the identification of these factors and how their influence behaves being facts and theories. Therefore, this research adopts a **positivist philosophy**.

Such a philosophy can collect various data types, including qualitative data collected from research conducted from a positivist philosophy can include observations, videos and critically interviews (Patton, 2014).

3.2.b Ontology

The nature of reality and existence, referred to as Ontology (Easterby-Smith et al., 2012) is seen to have four different forms, described in Table 9. This study adopts the position of ***Internal Relativism***, suggesting that although there is a truth to be identified, it is obscure as the nature of perceptions can be described as vague with people not necessarily capable of articulating or expressing them. Similarly, the perspectives of different people has a degree of consistency on the topic of product design project planning at a macro level, these can vary on a granular level. As such, the truth is present, but challenging to observe. To overcome this, various participant groups of different people and different organisations have been experimented with to capture their differing views and opinions that broader, and also the macro truth.

Table 9 Four different ontologies (Easterby-Smith, et al., 2012)

Ontology	**Realism**	**Internal Realism**	**Relativism**	**Nominalism**
Truth	Single Truth	Truth exists but is obscure	There are many "truths"	There is no truth
Facts	Facts exist and can be revealed.	Facts are concrete but cannot be accessed directly	Facts depend on the viewpoint of the observer	Facts are all human creations

3.2.c Epistemology

When considering the levels of engagement made with the subject, a research epistemology (the means of enquiry and enquiring into the nature of the physical and social world (Easterby-Smith et al., 2012) must be decided. That is to say, does the researcher remain independent and objective, or be completely engaged with the subject (Easterby-Smith et al., 2012))? This study gathers a mixture of qualitative and quantitative data, but due to the collection methods, the researcher must gather and interpret the data. Therefore the researcher is part of the research process itself, to similar levels as the participants and their data, as discussed by Corbin & Strauss (2015).

Based on this, the selection of an ontology of internal realism, and the adoption of positivist epistemology, there are various methodological implications that had to be considered, which have been summarised in Table 10. From Table 9, Easterby-Smith et al. (2012) highlights that facts, although concrete, cannot be accessed directly, therefore the task of the researcher is to use several means, such as workshops, interviews, etc. to better understand these various perspectives (Robson, 2011). This correlates with many knowledge and experience-gathering approaches covered in the literature review, where various participant engagement approaches were adopted, including interviews, surveys and workshops.

Table 10 Methodological implication of different epistemologies (Easterby-Smith, et al., 2012)

Ontology **Epistemology**	**Realism** **Strong Positivism**	**Internal Realism** **Positivism**	**Relativism** **Constructionism**	**Nominalism** **Strong Constructionism**
Aims	Discovery	Exposure	Convergence	Invention
Starting Points	Hypothesis	Propositions	Questions	Critique
Designs	Experiment	Large surveys; multiple cases	Cases and surveys	Engagement and reflexivity
Data Types	Numbers and facts	Numbers and words	Words and numbers	Discourse and experiences
Analysis / Interpretation	Verification / Falsification	Correlation and regression	Triangulation and comparison	Sense-making; understanding
Outcomes	Confirmation of theories	Theory testing and generation	Theory generation	New insights and actions

However, considering the implications shown in Table 10, specifically the design implications, the decision to adopt for internal realism and positivism is completely discrete. The research processes discussed and adopted in this study, covered in the following section, do not adhere exclusively to the selected ontology and epistemology, rather they deviate as both quasi-experimental and case-based research has been included within the study. This is discussed in greater detail in the following sections.

3.3 Research Processes

3.3.a Considered Research Processes

This section will review and discuss the applicability of processes suitable for this research study and identify and justify which were used.

Co-operative inquiry is an approach that works with people who have similar interests in order to both: 'understand your world, make sense of your life and develop new and creative ways of looking at things"; And "learn how to act to change things you may want to change and find out how to do things better'" (Heron and Reason, 2006). This sits comfortably within the aims of this study, as an investigation into influential factors effectively provides a new way of looking at design project planning. Additionally, this approach expects the full involvement of all active subjects, acting as co-researchers (Heron and Reason, 2006), which suits the application of a research approach as PDC workforces are small (they are SMEs after all) and therefore easily managed.

There are several research approaches which can be applied to the context discussed in this thesis. Each will be discussed in this section, with their merits and limitations presented.

Experiments

A major strength of conventional experimentation is the need to rigidly control various variables studied to create suitable conditions for testing. One common approach for experiment-based research is the hypothetico-deductive method (McNeill and Townley, 1986), shown in Figure 7, where a phenomena is observed, leading to the creation of a testable hypothesis, which is then systematically tested with data collected and analysed. This analysis allows for a hypothesis to be tested, leading to either its revision or rejection, or confirmation and subsequent formation of a theory. This is a relatively straightforward consideration for laboratory-based experimentation, however becomes significantly more challenging in the field, with faulty randomization, lack of validity, ethical issues, lack of control and types of experiment all being potential problems to be faced by a researcher (Walliman, 2006a).

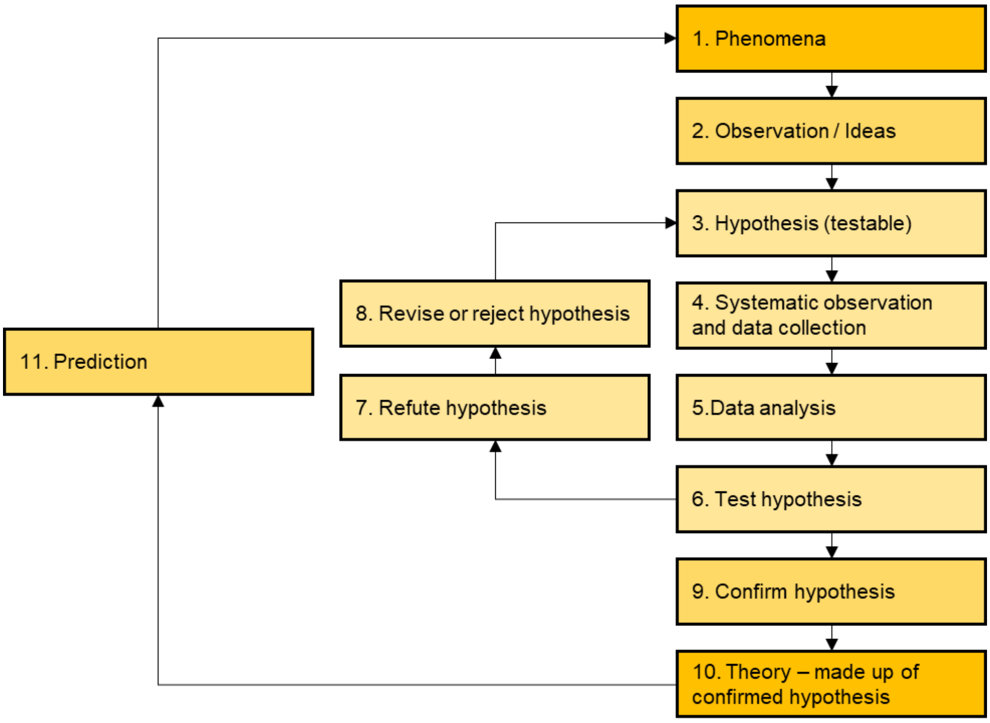


Figure 7 The hypothetico-deductive method. Adapted from McNeil & Townley (1986)

However, this can also be a limitation when exploring processes where the participants are active in the research process, such as that adopted in this research project. Robson (2002) describes the various features of experimentation. Stated below are each of these along with an explanation of why experimentation is not the most procedure in the context of this research study:

> *Experimentation research involves the assignment of participants to different conditions.* (Robson, 2002)

Experimentation can be used to develop a method for the identification and modelling of design-effort level influencing factors in PDC projects, like that adopted in this study. The development of a process for the collaborative identification of factors most influential in the design effort demands of PDC projects requires each participant within a phase of the research to be subjected to the same series of activities. The collaborative nature of design (Dong, 2005) requires all participants to work together to take advantage of the social cognition present in design teams (Busby, 2001).

> *Experimentation research involves the manipulation of one or more variables (called "independent variables") by the experimenter.* (Robson, 2002)

The approach for the research is open to the identification of potential changes to the process to optimise the results, however, this is done on a case-by-case basis, not within each phase of research. To develop and test a method for the identification and modelling of design effort-influencing factors in PDC projects, changes cannot be made to the procedure during a research phase.

> *Experimentation research involves the measurement of the effects of this manipulation on one or more other variables called "dependent variables"* (Robson, 2002)

The research method does not observe the effects of manipulation of independent variables, rather it will consider refinements of a proposed method and test such refinements with a new PDC during a different research phase.

> *Experimentation research involves the control of other variables. (Robson, 2002)*

By retaining the same steps of the method being developed that have not been identified as potential points of improvement, indeed if one were to consider each step a discrete variable, then it may be considered that control is being exerted over it. However, when viewed from this perspective, many variables cannot be controlled. Such as those based on the willingness and availability of PDCs and their team members, the education and experience levels of each participant and many, many more.

Quasi-Experiments

A quasi-experimental approach shares many similarities to that of the experimental approach, notably excluding the practice of randomisation (Saunders et al., 2016). Quasi-experimental designs help us test for casual relationships in situations in which a classical design is difficult or inappropriate (Neuman, 2013) and require less organisation and support than experimental approaches (Horváth, 2016). In general, the research has less control over the independent variable than in the classical design (Neuman, 2013).

Of the various types of quasi-experimental designs, the most viable is the *non-equivalent groups quasi-experimental design*. The non-equivalent groups quasi-experimental design takes two or more groups of participants that are not randomly assigned, rather are previously formed, in this case, the PDCs. As previously discussed, each PDC has their own way of working, their own perspectives on the factors influencing their projects, etc.

Case Studies

A case study can be considered a naturalistic evidence-gathering approach (Yin, 2003), and is one of the most prominent methodologies related to positivist qualitative research (Su, 2018), which therefore aligns with the positivist philosophy adopted by this study. Case studies use particular types of evidence, such as ethnographic, clinical, non-experimental, process tracking, non-survey based, participant observation, historical, textual, or field research (George and Bennett, 2005; Gerring, 2006; Gomm et al., 2000; Hamel, 1993; Yin, 2003). Yin (2018) defines the features of a case study with three key points, which are presented with a contextualisation for this research study:

> *A case study copes with the technically distinctive situation in which there will be many more variables of interest than data points.* (Yin, 2018)

This study intends on identifying and modelling multiple factors which influence the design effort needs of PDC projects. These factors (which can be considered also as variables) are broad in number, as they are unknown to the researcher at the outset of each given case.

> *A case study benefits from the prior development of theoretical propositions to guide design, data collection, and analysis…* (Yin, 2018)

From the literature review, various methods and their constituent techniques were identified which can act as cornerstones for this study, themselves adapted from previously developed.

3.3.b Chosen Research Process

When considering the aims of this study, the approaches discussed are suited for some, but not others. Therefore, this research uses a combination of experimental and case study-based research processes.

Aim 1 of this research study is to "determine if factors influencing design, effort, demands of product, design company projects can be identified and modelled"; to achieve this, a data collection method needs to be conceived and tested. The testing of this method can be considered experimentation, with necessary variations to this method being identified an implemented for each subsequent experimental run. However, as the experimental subjects, referred to in this study as "participants" cannot be randomised; and the experiments are being conducted in the field, this ad adopts elements of a **quasi-experimental** research process.

However, Aims 2 and 4 of this study consider the factors that are identified in this method and their influence. With different PDCs and participants being used, the collected data from each experiment provide insight beyond the success of the method, which has more of a grounding in **case study research**, allowing for comparison in outcomes of each round. Working with discrete groups of participants from which data on product design project influencing factors is collected, this collection requires the active, collaborative participation of the members of each product design team. In addition, the data collected from each round of research provides additional insight which has been considered within this study that extends beyond the Therefore, each round of data collection, interacting with a new design team, is referred to as a "**case**".

In summary, this study takes a hybrid approach, incorporating aspects of experimental and case study-based research: an evolutionary multiple round quasi-experimental case-based approach: evolutionary, as the findings of each round informs changes to the experimental design for subsequent rounds; experiment-based, as the research develops and tests a method; quasi-experimental, as certain aspects of the experiment cannot be randomised (i.e. the participants); and case-based, as the data collected from each experimental round itself provides insight and contribution to knowledge. This approach can be summarised in an adaptation of the hypothetico-deductive experimental method, shown in Figure 8.

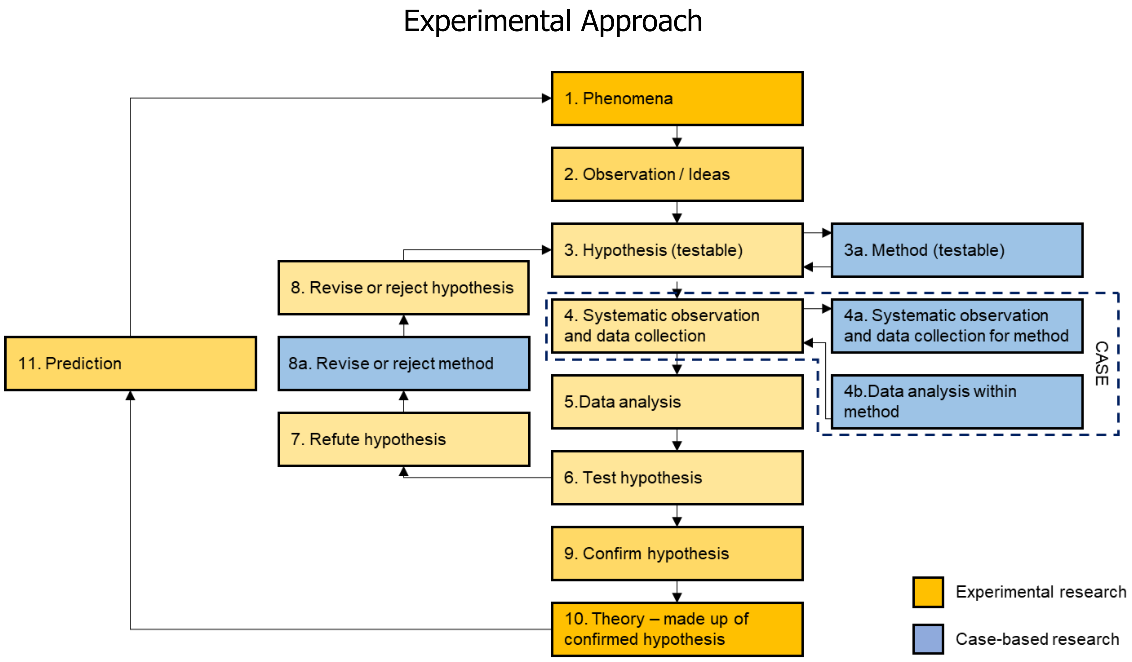


Figure 8 The hypothetico-deductive experimental method with case-based research.

3.4 An Evolutionary Multiple Round Quasi-Experimental Case-Based Approach

The purpose of this case-based strategy is similar to that of a case study approach, providing opportunities to both develop or build theories (Layder, 1993) and test theories (Yin, 2014). The purpose of a case-based approach is to "understand the complex relationship between factors as they operate within a particular social setting" (Denscombe, 2017). In this instance, the social setting is design teams within PDCs. The setting of specific companies also provides a distinct case for each study. These distinct cases have self-contained boundaries because these are separate businesses, based in separate locations.

Each case study conducted had the opportunity to highlight the need for changes in protocol, to develop and refine the method under investigation. Furthermore, every participating organisation faces the same, or similar, challenges in its operations, while each of its members has unique perspectives on their work. Yet these groups also are professionally creative, and through their engagement with this research are presented with further opportunities for development and refinement of the process. Therefore, an evolutionary multiple round quasi-experimental case-based approach was adopted to capitalise on the potential opportunities afforded by working with creative organisations.

This section will discuss the specifics of the organisation of the cases, including the selection of cases, the data collection approaches considered and selected, and the research strategies adopted and will conclude with a discussion of validity.

3.4.a Researcher Involvement in Cases

During each case, the researcher acted as a facilitator for each of the constituent workshops, acting as a guide for the participants, answering any questions that arise and keeping discussions during the workshop on-topic. As discussions on factors covered subjects and causes of frustration, it was anticipated that there would be instances when the discussion may deviate from its intended course. As the time offered to participate in the study was limited, an effort was made to ensure that such deviations are kept to a minimum.

3.4.b Case Selection

Having chosen a case-based approach as being the most appropriate to address the research questions, as well as maintain the constructivist philosophy and relativistic ontology chosen, cases need to be selected. There are various types of cases, summarised by Clark (2021), for the purpose of this research study, the type of case considered is a "representative case". A representative case in this instance is where the researcher operates under the assumption that a PDC can be considered a stand-in for any PDC within the industry, providing suitable context for certain research questions to be answered. Although there are undoubtedly nuances in the ways any given PDC operates, they all follow a general means of working, taking some brief and applying creative processes to develop new or novel ideas.

As covered in both chapters 1 and 2 to various degrees, as well as in the previous section of this chapter, the time available is a precious resource for PDCs, which limits their willingness to participate in any study. Therefore, the selection of specific organisations for this study was based on their availability and willingness to participate. The researcher found the recruitment of PDCs for this study to be a significant challenge, and as such had to adopt a "beggars can't be choosers" philosophy. This is, however, advantageous to the research, as testing a new variation of a method with a new set of participants provides the opportunity for a broader range of feedback and comment from said participants. Furthermore, by using different PDC teams for each case of this evolutionary multiple round case-based approach, a lack of familiarity with the process prevents the possibility of participant collusion prior to a given workshop, resulting in unadulterated results. Additionally, as the purpose of this study is to develop a method for identifying and modelling the influential factors of design effort needs in PDC projects, the use of different participant groups will not impact the outcome, as it is understood that the results of each use of such a process would differ case-by-case. The data collected during each case will be used for testing various elements of the developed method, with each dataset of estimate values, regression equation values and other data analysis results being used within their own case only. This study aims to conduct three cases, to develop a method in the first, to test and identify refinements in the second, and validating the method in the third. This is outlined in Figure 9.

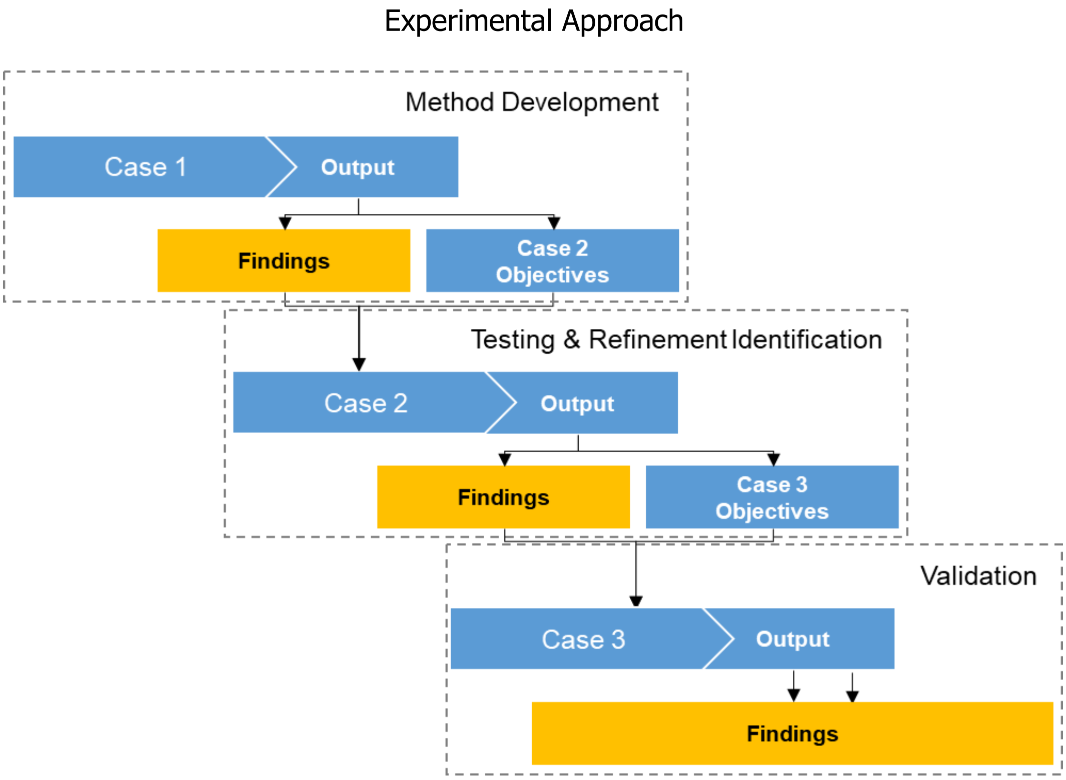


Figure 9 Proposed Case-Based Process Purpose

3.4.c Participant Recruitment

The method covered in this study has potential applications in a range of different industries, however, this study focuses on the application of this method within the design field, specifically product design, industrial design, or similar. This study will work with entire groups of industry workers, therefore the entire staff of product design companies are needed.

Identifying potential participants

To be viable for this study, potential participating product design companies had to fulfil the following requirements. Potential participants must:

- Have a team of designers or other workers who contributed to the development of new products based on briefs supplied by clients.
- Have experience working for more than one specific client (i.e. companies cannot work exclusively for a particular company, etc.)
- Have experience designing products for various markets (i.e. furniture, medical devices, food & drink, etc.) and not specialise in one specific field.
- Allow all members of the design team to participate in the study.
- Allow for anonymised data from past projects to be used during the evaluation of forecasting tools.

Recruiting participants

Participant recruitment was conducted by approaching the design directors, managing directors, or similar, with the key advantages were emphasised to these points of contact. The researcher has several contacts with product design companies across the UK and these were the first to be approached.

Recruiting participants – Potential Issues & Solutions

The possible issues anticipated during participant recruitment, in particular when the researcher was engaging with the senior management of product design companies. Although ultimately not required, these were considered and have been outlined in Table 11 along with potential solutions.

Table 11 Participant Recruitment - Potential Issues & Solutions

Potential Issue	**Potential Solution**
Management unwilling to stop work for hours at a time	Emphasise potential savings in resources (time) made through estimation tool use
Management unwilling to participate in university research	Emphasise the success in previous trials.
Lack of availability due to workload	Unknown

3.4.d Data Collection

Data Collection Approach

This section will discuss the types of data to be collected in this study and the data collection processes to be used.

Having chosen a suitable research paradigm, suitable datatypes were identified. Each possible influential factor had its own definition, etc. as illustrated by the literature review. These data types were either (or both) qualitative and quantitative, although the majority are qualitative. The other datatype was the estimates made by each member of the PDC team. These, as discussed in the literature review, are units of design effort, which can be seconds, minutes, hours, days or months. With the adoption of cooperative inquiry, each member of a product design company is a co-researcher, therefore this unit was determined by them, based on what suits their perspectives and their current work practices.

Yin (2003) identifies six distinct sources of data, shown in Table 12, of which this study made use of several. Quasi-experimental and case-based research typically includes a combination of both quantitative and qualitative research activities (Clark, 2021; Yin, 2018) using a variety of data sources as part of a mixed methods approach. Some of these can be considered their own research approach and have been evaluated for suitability for the development of the method for the identification and modelling of design effort-influencing factors in PDC projects.

Table 12 Six Sources of Data. (Adapted from Yin, 2003)

Data source	Description
Documents	Any media relating to ongoing practice within an organisation
Archival records	Formal records and external data sources
Interviews	Structured or unstructured discussions with actors
Direct Observation	Non-participatory observation of the phenomena and its context
Participant Observation	Active involvement of the researcher in the phenomena of interest within its context
Artefacts	Inspection of the physical context or result of the phenomena

Questionnaires

A **questionnaire** approach was considered. As a research method, it has many advantages (and disadvantages) as proposed by Walliman (2006b), shown in Table 13. Certainly, they would allow a broad perspective of the research area, incorporating multiple sources of data. However, the observed reluctance to engage with surveys without incentive being high in any industry, is only multiplied by the lack of available time had by product design companies making the use of questionnaires less than ideal. Additionally, the depth of detail needed and the responsiveness needed to address viewpoints and findings as they arise eliminated questionnaires as a viable option for this study.

Table 13 Questionnaire Advantages and Disadvantages as a Research Tool. Adapted from Walliman (2006)

Advantages	Disadvantages
They are cheap to administer.	They require a lot of time and skill to design and develop.
They are quick to administer.	They limit the range and scope of questioning – questions need to be simple to follow and understand so complex question structures are not possible.
They are an easy way to question a large number of cases covering large geographical areas.	Yet more forms to fill ini They can be unpopular, so they need to be as short as possible.
The personal influence of the researcher is eliminated.	Prompting and probing are impossible, and this limits the scope of answers and the possibility of getting additional data.
Embarrassing questions can be asked with a fair chance of getting a truthful reply.	It is not possible to ascertain if the right person has responded.
Variability between different researchers or assistants is eliminated.	Not everyone is able to complete questionnaires.
They are convenient for respondents.	Response rates can be low.
Respondents have time to check facts and think about their answers, which tends to lead to more accurate information.	
They have a structured format.	
They can be designed to assist in the analysis stage.	
They are particularly suitable for quantitative data but can also be used for qualitative data.	

Interviews

Structured interviews, defined by Walliman (2006b) as those with standardised read-out by an interviewer according to an interview schedule were also considered. However, for a similar reason to the questionnaire, the need to be responsive to the responses of participants and “deviate from the script” to uncover more detail would not be possible with a rigid schedule. Furthermore, the experience had by participants of such interviews can feel closer to an interrogation, which may be unappealing and underproductive.

Semi-structured interviews contain structured and unstructured sections with standardized and open-format questions (Walliman, 2006b) and offer a degree of flexibility that structured interviews do not. This flexibility opens further avenues for investigation as, and when, they are presented. As the participants were active in the research process, the research design had to accommodate the insight and opportunities that are offered by such an approach.

Observations

Observations of participants provide a means of collecting both quantitative and qualitative data (Walliman, 2006b) and can have various levels of researcher engagement, as defined by Gold (1958), shown in Table 14.

Table 14 Research Observer Types. Adapted from Gold (1958)

Observer Type	Description
Complete observer	the observer takes a detached stance by not getting involved in the events, and uses unobtrusive observation techniques and remains ‘invisible’ either in fact or in effect (i.e. by being ignored).
Observer-as-participant	the researcher is mainly an interviewer doing some degree of observation but very little participation.
Participant-as-observer	the researcher engages fully in the life and activities of the observed, who are aware of his/her observing role.
Complete participant	the researcher takes a full part in the social events but is not recognized as an observer by the observed. The complete participant is a covert observer.

Chosen Data Collection Process

Several data collection processes were adopted in this research study. Each is discussed in detail in the following section:

Semi-Structured Interviews

Semi-Structured Interviews were held with selected members of PDC teams who have significant involvement in the management of design projects, typically senior management and project managers, but was kept open to whichever specific members were involved per case. These interviews followed a semi-structured format and gathered the initial data required to set up the other phases of the method being tested. It was planned that additional interviews would also be held with each participating member of the PDC to present the visual models of the identified factors. These too were to have a semi-structured format to provide the opportunity for the broadest range of observations from participants.

Two forms of interviews were conducted: a preliminary conversation with senior members of the PDCs, and follow-up interviews with each member of the PDC teams. The preliminary interviews were informal discussions of an exploratory nature, with written notes captured. The second set of interviews followed a more rigid semi-structured approach, as suggested by Yin (2003), and sought to gather the vital details that informed the data collection of future steps within the case study.

Observation

Observation and **Participant Observation** were conducted during the group activities as part of the method, with the researcher taking notes as required. This allowed the researcher to identify behaviours, and other phenomena, as well as provide an opportunity to record participant views, comments, etc.

3.4.f Research Strategy

A research strategy, according to Densombe (2017), is a plan of action designed to achieve a specific goal. Qualitative research is typically associated with observing phenomena in reality, or context (Denscombe, 2017; Silverman, 2013). It is a holistic approach allowing for various factors and relationships to be considered. This makes this approach appropriate for this research as the researcher will construct the data, carry out interviews and analyse their findings. Furthermore, according to Flick (2009), there are four main features of qualitative research: "the correct choice of appropriate methods and theories, the recognition and analysis of different perspectives, the researchers' reflections on their research as part of the process of knowledge production, and the variety of approaches and methods". The analysis of qualitative data is iterative and thus evolves as the collection and analysis of data happen at the same time (Denscombe, 2017). As such, during this study, the analysis of data from one case study occurred before the start of another. From this analysis, adjustments, improvements and additions can be identified in both the method itself and the case study approach to maximise utility.

3.4.g Validity & Reliability

Yin (2014) states that concerns relating to validity and reliability can be addressed by giving particular attention to their structure.

Validity refers to the integrity of the conclusions produced from the findings of the research (Bryman, 2012), while reliability refers to the "degree of consistency with which instances are assigned to the same category by the same observer on different occasions" (Silverman, 2013). The intended validity of this study is found in the data collection approach and working with PDCs. Through collaborative qualitative data collection processes such as semi-structured interviews and questionaires, the answers provided remained the same upon repeated application with the same participants. The reliability of data and its collection is determined by whether the process is suitably documented to enable successful repetition (Silverman, 2013) and whether the data itself is repeatable and consistent (Sim and Wright, 2000). To ensure that the data collected is reliable two major criteria must be met, according to Silverman (2013):

- The research strategy, process and analysis methods are described with sufficient detail to ensure transparency.
- A clear theoretical position must be clearly stated from which all interpretations are made and how each interpretation was made.

3.5 Proposed Case-Based Approach

This section will cover the case-based approach adopted for Case 1. Changes made to the approach for the subsequent cases will be discussed in their corresponding chapter.

3.5.a Design of Experiments Process

A notable finding in the literature review was that the use of a Design of Experiments (DOE) based approach to capture the experience and tacit knowledge of managers for new product development projects (Hird, 2012). Such a method has the potential to capture the very same experience and tacit knowledge of product design company design teams, to investigate the factors influencing their design space. Additionally, a DOE approach has the versatility of bypassing the limits faced by product design companies of large past project data sets as well as the expertise in sophisticated statistical analysis and its accompanying software.

The DOE process (1949) was developed by Sir Ronald Fisher while working for the Rothamsted Agricultural Field Research Station in the UK to explore the effect of several fertilizers on various plots of land. A direct response to the "traditional" One-Variable-At-a-Time (OVAT) approach, DOE allows many factors to be assessed in tandem, using the fewest experiments (known as experimental runs) possible; Using statistical analysis to calculate the effects of each factor. This is an economical, as well as practical advantage for researchers in any discipline, maximising the insight per experimental design (Antony, 2014). In most instances, DOE is used for process optimisation and has been adopted in many use cases, including production engineering (Davim, 2016), and pharmaceutical and food research (Carrillo-Cedillo et al., 2019). Yet, similar to the issues previously highlighted in this review, the use of Design of Experiments in the Product Design, or Industrial Design company field is unrecorded in peer-reviewed publications.

The DOE method has a five-stage process, as shown in Figure 10. This process is typically used for the creation of specific combinations of practical experiments, known as experimental design, to identify optimal conditions for a desired outcome, through the creation of a regression equation(s). This is achieved by establishing how each factor and the interaction between each factor influences the response value for an experiment through a process of statistical analysis derived from analysis of variance, or ANOVA.

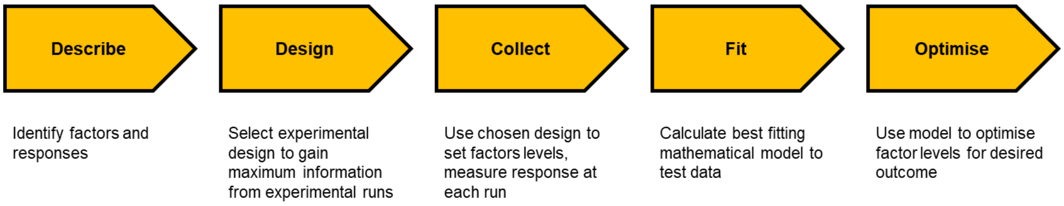


Figure 10 Design of Experiments Process

The *describe* stage is used to identify the values needed to build an experimental design, factors which will act as the variables for the experiments, and the responses which are the output of an experiment to be measured. *Levels* for each factor are also identified, the DOE process needs a minimum of two levels, which are commonly a maximum and minimum level, although more between those values may also be included.

The *design* stage is used to select the most suitable experimental design for the number of factors and the number of corresponding levels identified. An experimental design will have several experimental runs, incorporating all of the factors identified. Each experimental run will have a specific combination of levels for each factor. The common experimental designs for the DOE process are *full factorial* (where every combination of levels is included) and *half factorial* (where only half of the possible combinations are included). The number of experimental runs required for a full factorial experimental design is calculated through the following equation:

$$No.of\ experimental\ runs\ = No.of\ factor\ levels^{No.of\ factors}$$

Equation 1

A full factorial experimental design offers the greatest degree of insight, as a response to every combination will be recorded. However, as the number of factors measured increases, the number of experimental runs increases exponentially. For example, with 6 factors, the number of experimental runs is 64, 9 factors need 512 runs, etc. This volume of experimental runs quickly becomes cumbersome and challenging for researchers. As such, half-factorial experimental designs provide a more viable option for researchers who are considering more than three factors in their investigations. As the name suggests, the number of experimental runs required for a half-factorial experimental design is calculated through the following equation:

$$No. of\ experimental\ runs\ = \frac{No. of\ factor\ levels^{No.of\ factors}}{2}$$

Equation 2

However, a drawback of a half-factorial experimental design is in the analysis of interactions between factors, which cannot be calculated for every factor equally based on the response values of the experiments conducted and the analysis alone. For that reason, researchers will select the factor to be under the closest scrutiny As a result, researchers may conduct several sets of experiments, the first acting as a screening process, to identify which factors require further investigation. At this point, three or more levels will be included to add rigour to a study, while removing any variation in factors which have little-to-no influence.

As an example, consider an experiment with three factors, set at two levels. The number of experimental runs required for a full factorial experimental design will be eight, and a half factorial will be four. It is common to illustrate such an example in a cube plot, a three-dimensional graph with each possible combination of factors and levels shown as the corresponding corner, shown in Figure 11. Each axis represents a factor and each point represents the minimum or maximum level of each factor. Minimum and maximum values are often represented as "-" or "low" and "+" or "high" respectively.

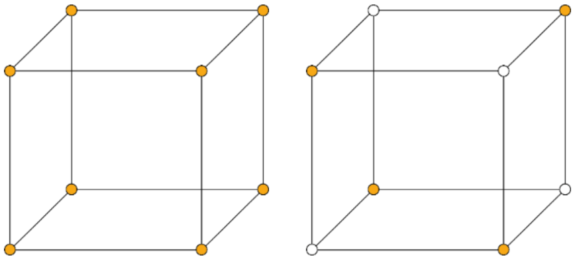


Figure 11 Experimental Design Cube Plots, Full Factorial (L), Half Factorial (R)

Each experimental run is described in a table, which can be generated by statistical analysis software, such as Minitab, or can be created manually in spreadsheet software. Using the same example as before, the experimental runs for a 2-level, 3-factor experimental design as a full factorial is shown in Table 15, and half factorial in Table 16.

The *collect* stage of the DOE process is when researchers use their experimental designs to prescribe their experimental procedure. Typically, researchers will randomise the order they conduct their experiments and repeat the measurements, or the whole experiment, to minimise the noise in the data.

The *fit* stage of the DOE process sees the researcher take all the collected data and input it into a Design of Experiments analysis. This is typically done using software such as Minitab, but can also be done in spreadsheet software, such as Microsoft Excel. From this analysis, regression equations are created, modelling the factors and their influence over the response value. An example of a regression equation is shown in Equation 3Equation 3 where a constant (c) is added to the sum of the products of each factor's influence (a, b, c, d) and their level (w, x, y, z).

Table 15 Full Factorial Experimental Runs Example

Experimental Run	Factor 1	Factor 2	Factor 3
1	-	-	-
2	+	-	-
3	-	+	-
4	+	+	-
5	-	-	+
6	+	-	+
7	-	+	+
8	+	+	+

Table 16 Half Factorial Experimental Runs Example

Experimental Run	Factor 1	Factor 2	Factor 3
1	+	-	-
2	-	-	+
3	-	+	-
4	+	+	+

$$y = c + (a \times w) + (b \times x) + (c \times y) + (d \times z)$$

Equation 3

From this regression analysis, it is possible to determine what factor(s) are most influential and what level they should be set to achieve the desired outcome. This is the process of the *optimise* stage of the DOE process.

3.5.b Design of Experiments in this study

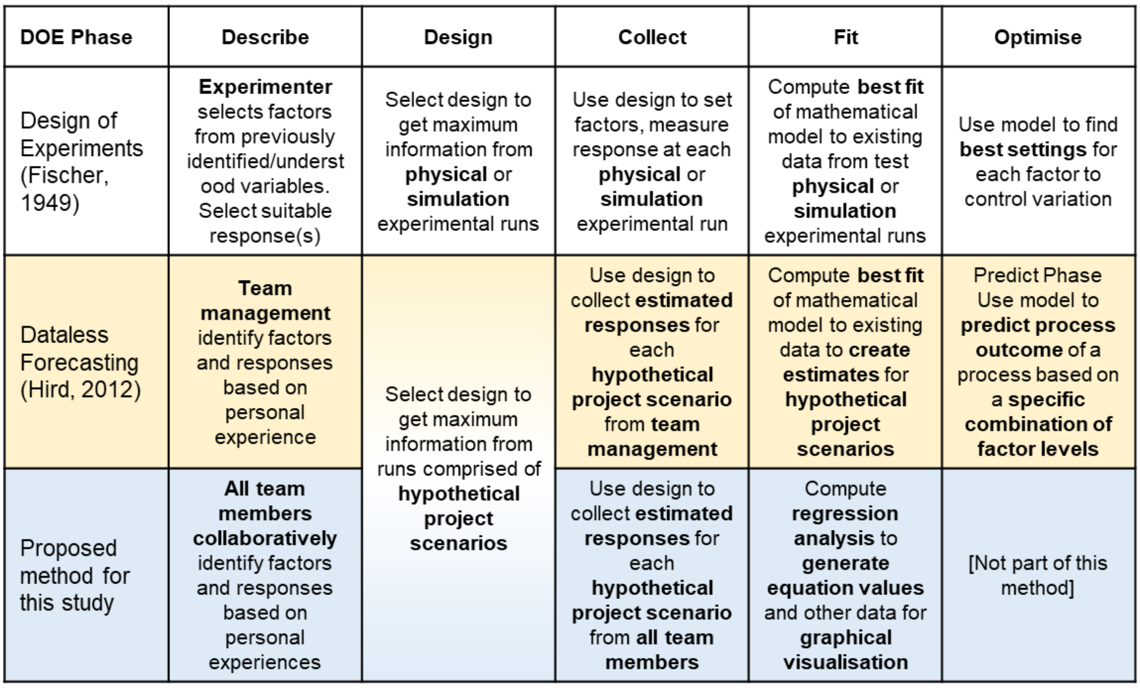
This evolutionary multiple round case-based approach applied a variation of this DOE approach to address the research. Using various collaborative techniques typically used in product design companies, this variation of the DOE process identifies the most influential factors of design effort demands of product design projects for that design team. Based on the success of this implementation and the observations of both the researcher and the case participants of Case 1, recommendations and adjustments are made to the approach, which were in turn tested in subsequent cases.

Differences to Conventional DOE and Dataless Forecasting

In broad strokes, the DOE process was developed to determine the optimal configuration of variables for a desired outcome, for process optimisation. Yet, at its core, DOE is for the prescribed collection of data to provide an overall understanding of how variables affect an outcome. As such, Hird's Dataless Forecasting (DF) (2012) capitalises on this understanding to predict a process's outcome, based on specific conditions. Both DOE and DF rely on a sample of past project, or past experimental, data, to "tune" their equations to create the best fit for optimisation and estimation. DOE also provides several charts through its process, like mean effect plots, which provide the average response value when a specific variable is at each level determined in the experimental design. Although generated, this data is not typically considered in the DF process, nor are the equations generated as part of the regression analysis scrutinised for further insight, beyond the potential for prediction.

More specifically, Hird made several changes to DOE for their DF process, and likewise, the method described in this chapter had several changes made to it, making it distinct from the DF process. All these differences have been described in detail in Figure 12.

When gathering tacit knowledge and experience to model factor behaviour firstly these factors needed to be determined. Based on the discussion in the literature review, the design effort-influencing factors are not controllable by the design team before any design project, but they are understood by the team. Highlighted in the literature review was a resource estimation approach by Hird (2012), who observed this issue, offering a process whereby select team members (typically management) answer questionnaires or interviews to identify factors, this doesn't lend itself to the highly collaborative environment of product design companies. Therefore, the initial factor identification used in this method was achieved through a collaborative processes that was familiar to the participating design teams (discussion, debate, brainstorming, sticky dot selection, etc.). Specific processes were selected for this stage to identify the factors to be considered and their minimum and maximum values.



DOE Phase	Describe	Design	Collect	Fit	Optimise
Design of Experiments (Fischer, 1949)	**Experimenter** selects factors from previously identified/understood variables. Select suitable response(s)	Select design to get maximum information from **physical** or **simulation** experimental runs	Use design to set factors, measure response at each **physical** or **simulation** experimental run	Compute **best fit** of mathematical model to existing data from test **physical** or **simulation** experimental runs	Use model to find **best settings** for each factor to control variation
Dataless Forecasting (Hird, 2012)	**Team management** identify factors and responses based on personal experience	Select design to get maximum information from runs comprised of **hypothetical project scenarios**	Use design to collect **estimated responses** for each **hypothetical project scenario** from **team management**	Compute **best fit** of mathematical model to existing data to **create estimates** for **hypothetical project scenarios**	Predict Phase Use model to **predict process outcome** of a process based on a **specific combination of factor levels**
Proposed method for this study	**All team members collaboratively** identify factors and responses based on personal experiences		Use design to collect **estimated responses** for each **hypothetical project scenario** from **all team members**	Compute **regression analysis** to **generate equation values** and other data for **graphical visualisation**	[Not part of this method]

Figure 12 Differences between "Classic" DOE, Dataless Forecasting (Hird, 2012) and this study's proposed method

Experimental designs used in this study

Several different experimental designs are available to an experimenter based on their aims for their experiments. Experimental designs are comprised of specific combinations of experimental runs, which are experiments where each of the factors is set to specific combinations of levels. Each experimental design, be it full factorial, half factorial, Taguchi, etc., will have a differing number of experimental runs. Furthermore, it is best practice to repeat experiments in a randomised order to eliminate noise, so the number of individual experiments conducted can be quite high. The limitations on the number of experiments are normally based on resource availability, i.e. experimenter's time, raw materials, equipment availability, etc.

In this tacit knowledge and experience capture use case, the experimental runs are hypothetical design projects described by their factors. The experimental design was chosen based on the number of experiments it requires. Rather than an experimenter conducting practical experiments, each participant estimated the design effort for each experimental run. This had the potential to be cognitively taxing for the participants as the estimation activity had to be completed in a single sitting.

Fit and Optimise Stages

As this research is focused on identifying and modelling factors, there was no need to follow, nor modify, the optimise stage of DOE, as they are based on optimising experimental conditions to achieve a desired outcome. A regression analysis was conducted in the "fit" phase to produce mean effect values and regression equations.

3.5.c Experimental Process

NB: This section will include the terms "stage" and "phase" in terms of the DOE process and the experimental process. For clarity, the term "stage" will refer to the DOE process, and "phase" will refer to the experimental process.

This approach has been developed based on the first three stages of the DOE process. To accommodate the businesses participating in this study, the activities included in some DOE stages were split between different case phases, while others were combined. Table 17 outlines the purpose of each case phase, the individuals required to participate, and the anticipated outcomes. The output of each case phase had the potential to influence the subsequent courses of action to be taken. In such cases, these changes will be discussed in their corresponding chapter. Each case phase will be depicted in an IDEF0 model, found in the appendices.

Table 17 Experimental Process

Case Phase	Purpose	People Required	Outcomes	IDEF0 Model	Mapped DOE Stage
1. Preliminary Discussion	Identify key elements of product design projects at participant company.	R / M	Suitable key resource(s) of future design projects. The design process followed by participant company.	Figure 13	*Describe*
2. Workshop 1	Identify key influential factors on project resource and their maximum / minimum values.	R / M / T	Key factors which influence resource(s) level Hypothetical viable max/min factor levels.	Figure 13	*Describe*
3. Interim Phase 1	Generate experimental design with identified factors and levels	R	Template experimental design	Figure 14	*Design*
4. Workshop 2	Collect experimental data (participant estimates) using template	R / M / T	Participant estimates (1)	Figure 14	*Collect 1*
5. Interim Phase 2	Generate regression equations for participants Create regression models for each participant based on regression equations Build comparison graphs of regression models	R	Regression equations, Participant regression models, Comparison Graphs	Figure 16	*N/A*
6. Workshop 3	Gain insight into participant's views on comparison graphs	R / M / T	Feedback on process Feedback on comp. graphs	Figure 16	*N/A*

Persons involved in study coded as: Researcher (R), Company Director & Office Manager (M), & Design Team (T)

Experimental Process: 1 Preliminary Discussion

Shown in Figure 13, the purpose of the first phase was to gather some of the fundamental information and data needed to plan the remaining phases of the case. This includes data that contributed to the building of the experimental design in Interim Phase 1. For the "Design Project Stages Recording" stage, shown in Figure 13, preliminary discussions were held with the company leadership, including at least one director and the office manager. These participants were instructed to identify the key phases work of their product design projects. This could have been based on an existing design process, such as the Design Council's Double Diamond, a variant of such processes, or their own design process. It was also during these discussions that the specific product design project resource, or resources, were identified. In this case "design effort", although PDCs used person-hours, or person-days as their term for resources.

Experimental Process: 2. Workshop 1

Workshop 1 concludes the remaining stages of the Design Process and Factor Identification IDEF0, shown in Figure 13. The workshops were conducted with every member of the design company in an informal brainstorming session. The participants were tasked with identifying the key influential factors on project resource(s) and devising viable maximum and minimum values for these factors. As an example, one such factor could be the "Number of Expected Functions". In this case, the minimum value would be "1"; and the maximum value could be "4+". The factor identification task was structured as a brainstorming activity, with all participants encouraged to suggest factors. Once an exhaustive list was generated, the participants voted for those which they think are most influential. Hypothetical maximum and minimum values for the top-voted factors were then identified, again through an open discussion between every member of the design team.

Experimental Process: 3. Interim Phase 1

The first interim phase, outlined in the first stage of Figure 14, had the researcher selecting a suitable experimental design, based on Design of Experiments (Fisher, 1949). The researcher used the factors and levels to set the parameters of the experimental design, an example of which is shown in Table 18. This experimental design was used to describe a series of hypothetical design projects, each described by their own unique combination of hypothetical minimum and maximum factor values. As an example, we can consider that each run shown in Table 18 is a design project; then for Project 6 (Run 6): factors 1, 3 and 5 are set to high, and factors 2 and 4 are set to low. These combinations were provided to the participants in a template for data collection Workshop 2.

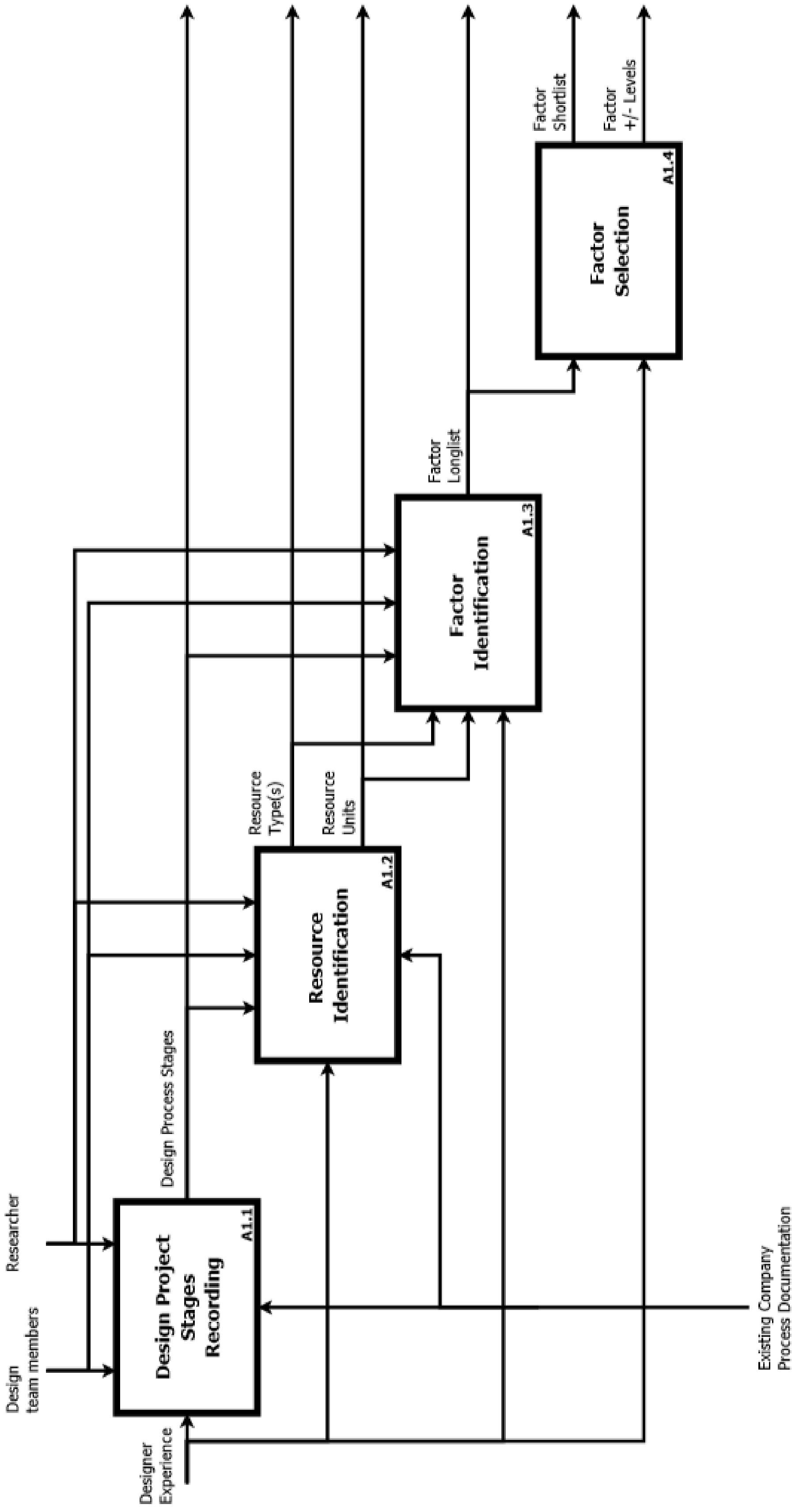


Figure 13 Case Design Process and Factor Identification Process IDEF0

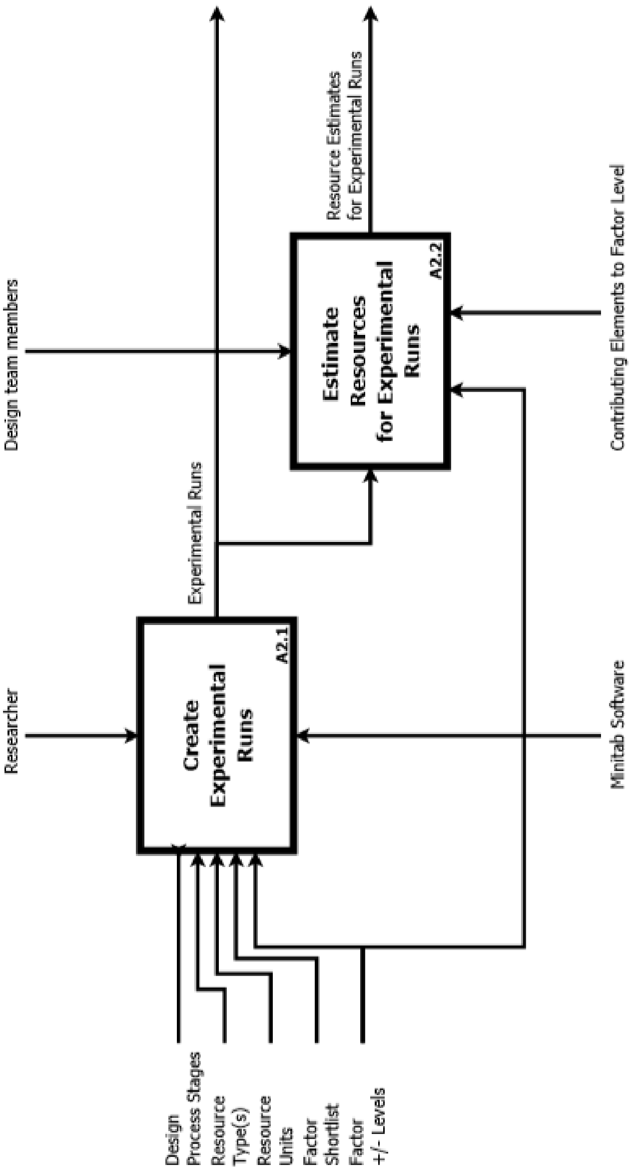


Figure 14 Case Estimation Collection Phase IDEF0 Model

Experimental Process: 4. Workshop 2

Workshop 2 completes the second stage outlined in Figure 14. All members of the design company were to be present for Workshop 2, during which each participant was instructed to estimate the duration of each project phase based on the levels of each factor. Participants were provided with a form to complete, shown in Figure 15, which outlines all these combinations.

Table 18 - Example of Experimental Design

Run	Factor				
	1	2	3	4	5
1	Low	Low	Low	Low	High
2	High	Low	Low	Low	Low
3	Low	High	Low	Low	Low
4	High	Low	Low	Low	High
5	Low	Low	High	Low	Low
6	High	Low	High	Low	High
7	Low	High	High	Low	High
8	High	High	High	Low	Low
9	Low	Low	Low	High	Low
10	High	Low	Low	High	High
11	Low	High	Low	High	High
12	High	Low	Low	High	Low
13	Low	Low	High	High	High
14	High	Low	High	High	Low
15	Low	High	High	High	Low
16	High	High	High	High	High

Run	Factor					Design Phase			
	1	2	3	4	5	1	2	3	4
1	Low	Low	Low	Low	High				
2	High	Low	Low	Low	Low				
3	Low	High	Low	Low	Low				
4	High	Low	Low	Low	High				
5	Low	Low	High	Low	Low				
6	High	Low	High	Low	High				
7	Low	High	High	Low	High				
8	High	High	High	Low	Low				
9	Low	Low	Low	High	Low				
10	High	Low	Low	High	High				
11	Low	High	Low	High	High				
12	High	Low	Low	High	Low				
13	Low	Low	High	High	High				
14	High	Low	High	High	Low				
15	Low	High	High	High	Low				
16	High	High	High	High	High				

Figure 15 - Example of Workshop 2 Estimation Sheet

Experimental Process: 5. Interim Phase 2

The work assigned to Interim Phase 2, both stages shown in Figure 16, includes the collation of the data entered into the estimation sheets during Workshop 2. Regression equations were created from each of the participant's estimation data, using statistical analysis software, such as *Minitab*. A set of regression equations will be created for each participant, reflecting their perceptions of how the resources of each project phase will be affected by changes in influential factors. An example of such a regression equation can be shown in Equation 4

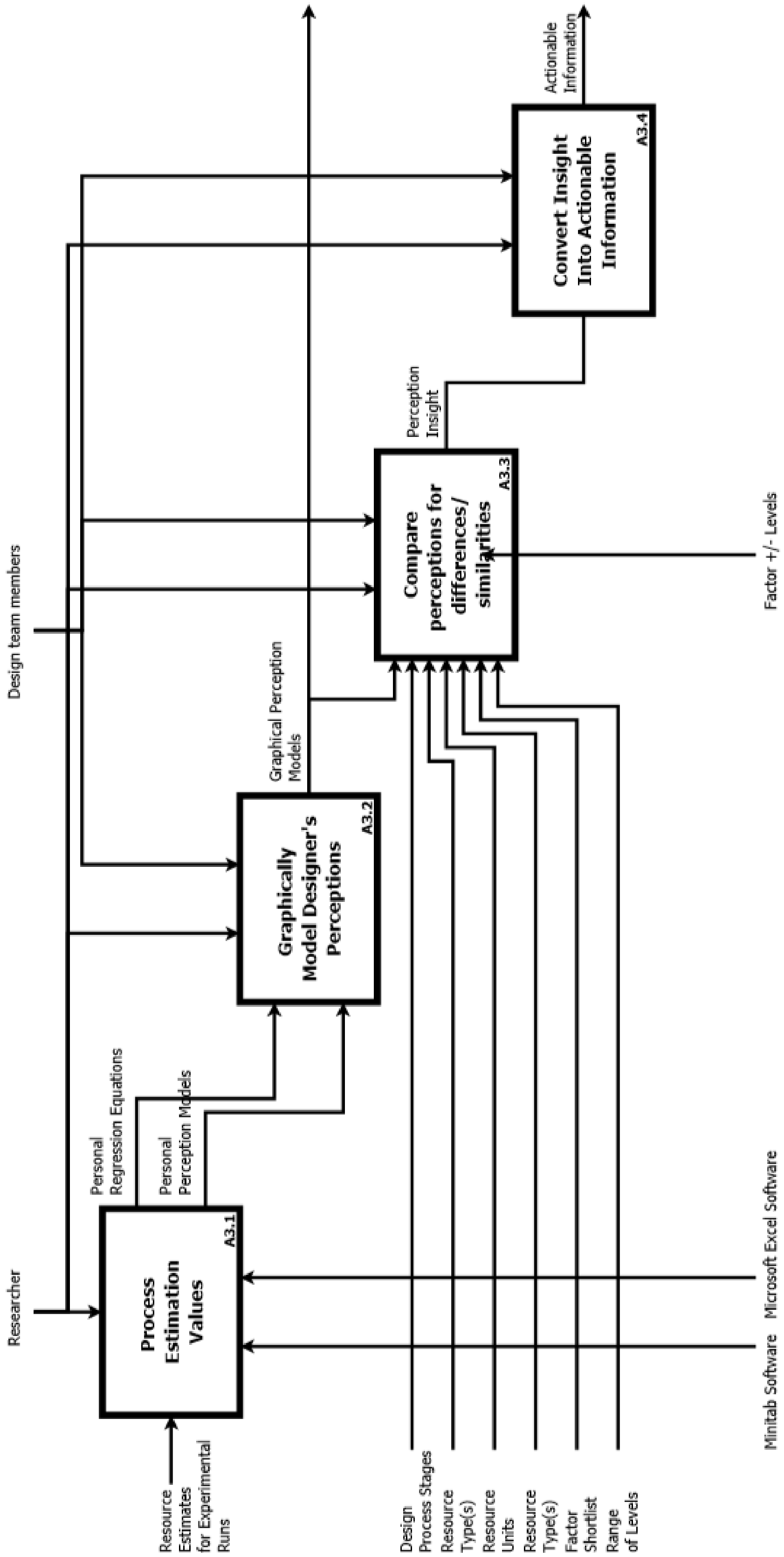


Figure 16 Gather Actionable Information from Designer Perceptions IDEF0

$$Output = Constant + (a \times w) + (b \times x) + (c \times y) + (d \times z)$$

Equation 4

Using the coefficients of each factor as input data it was be possible to identify suitable graphs or other diagrams to represent and effectively communicate the perceptions of each factor by each participant. This is an area of investigation for all cases in this research.

Factor Influence

Using the coefficients from each regression equation as input data, it is possible to calculate the percentage of influence each factor has over product design project resources. These percentages can be collated by participant and then be plotted on a graph, with the project phases on the x-axis and percentages of total influence on the y-axis. The corresponding trend lines generated by such a graph illustrating how each participant perceives how each factor's influence changes during a design project. An example of such a graph is shown in Figure 17. The coefficients are converted into percentages so that they can be directly compared between participants with the magnitude of influence disregarded as all, or some, of the project factors vary between participants.

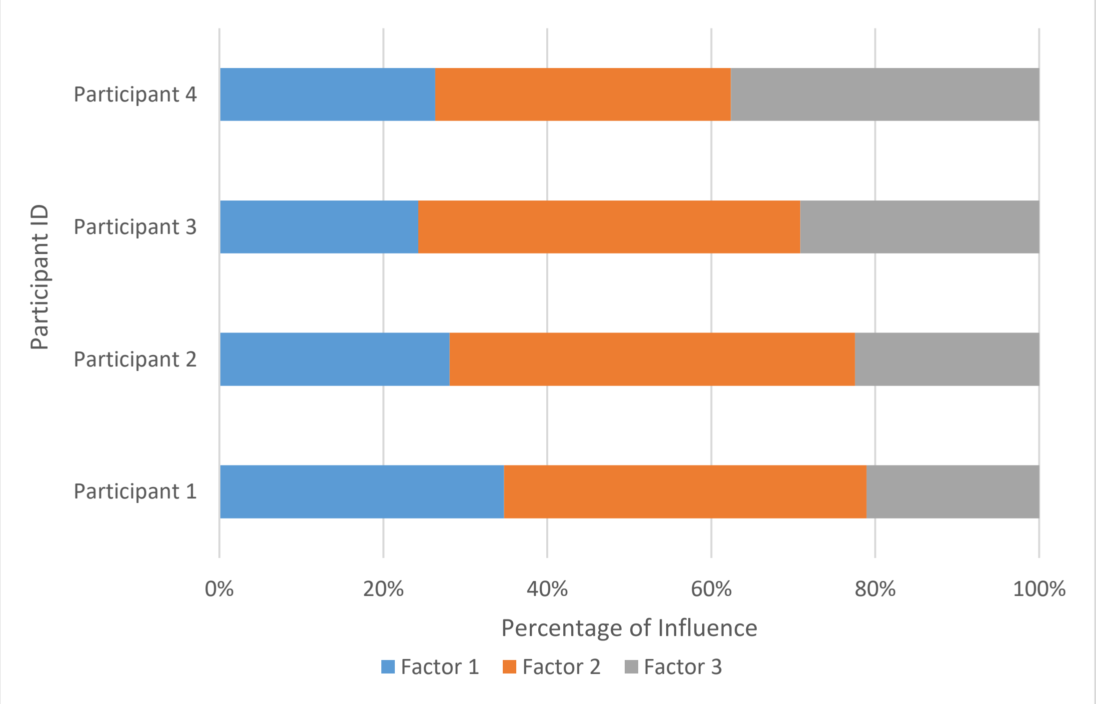


Figure 17 Example of Factor Influence Percentage Change

Percentage influence graphs can be analysed to identify trends in perceptions towards factors; and consensus (or disagreement) between participants. These graphs can also allow participants to see how their perceptions of factors change throughout a project. As an example, consider the graph in Figure 17, it illustrates that the perceived percentage of the overall influence of the particular factor reduces as the project progresses.

The statistical software used for data analysis can also generate the mean effects plots for each participant, each factor and each project phase. Collecting this data allows for the mean effect plots of each participant can be gathered into the same factors and phases, an example of which is shown in Figure 18. Such graphs can be used to directly compare the perceptions of the factors held by each participant, again allowing the researcher to identify a consensus in perceptions.

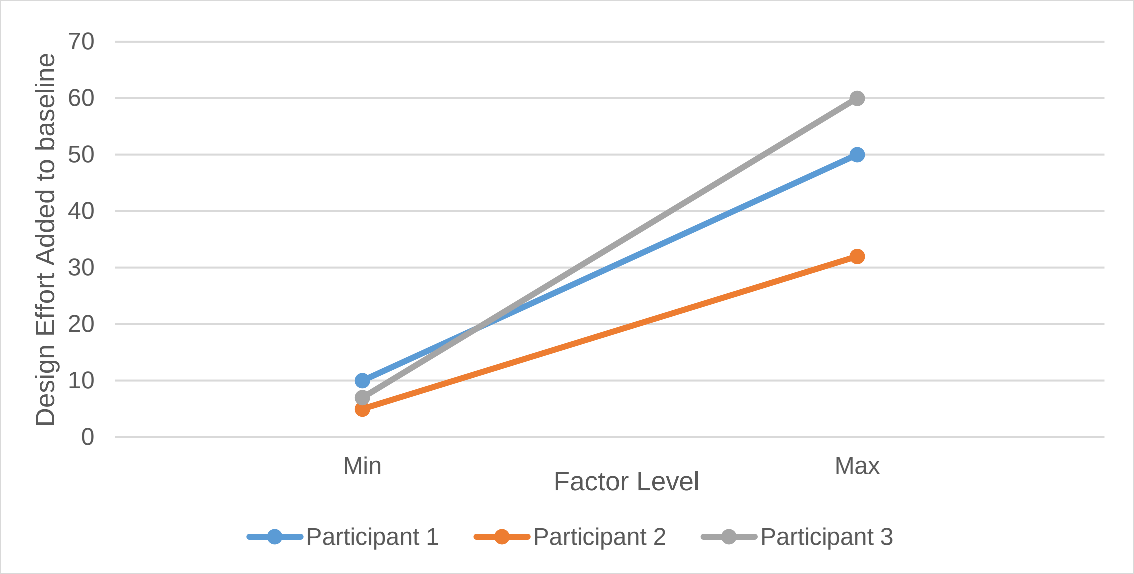


Figure 18 Example of Collated Mean Effects Plots of Factor

Experimental Process: 6. Workshop 3

Workshop 3 covers the remaining two stages of the Gather Actionable Information from Designer Perceptions IDEF0 phase, shown in Figure 16. All members of the design company were required for Workshop 3 to gain insight into each participant's modelled perceptions. The graphs/diagrams produced during Interim Phase 2 are presented to the participant to act as the focus of discussion on the factors, influences and other phenomena illustrated by the graphs/diagrams. This workshop aims to determine the extent to which each participant agrees with the graph of their perceptions, both in isolation and when compared to their colleagues.

Data Analysis

The data collected from the processes discussed in the previous section was analysed in various means. Figure describes each of the data types that were collected, their purpose within the context of the research, what analysis was conducted on them, what phase of the case they were collected and analysed (more detail of that is found in Table 17), or what out-of-case chapter the analysis is discussed.

Figure 19 Research Data Types & Analysis

3.6 Summary

This chapter focuses on the discussion of research approaches and presents the approach adopted by this study. This approach can be summarised by an adaptation of the research onion (Saunders et al., 2016), shown in Figure 6. In this study, the research philosophy followed is one of Positivism, with an ontology of Internal Realism. The capture of various participant perceptions from different, discrete design companies which leads to there being an obscured truth, therefore an epistemology of positivism has been adopted. Due to the hybrid nature of this research study, an evolutionary multiple round quasi-experimental case-based approach has been adopted which enables for the testing of a process with a quasi-experimental, framed within the context of case-based research. The findings of each case will inform changes and improvements to the method, which will, in turn, inform improvements to future applications.

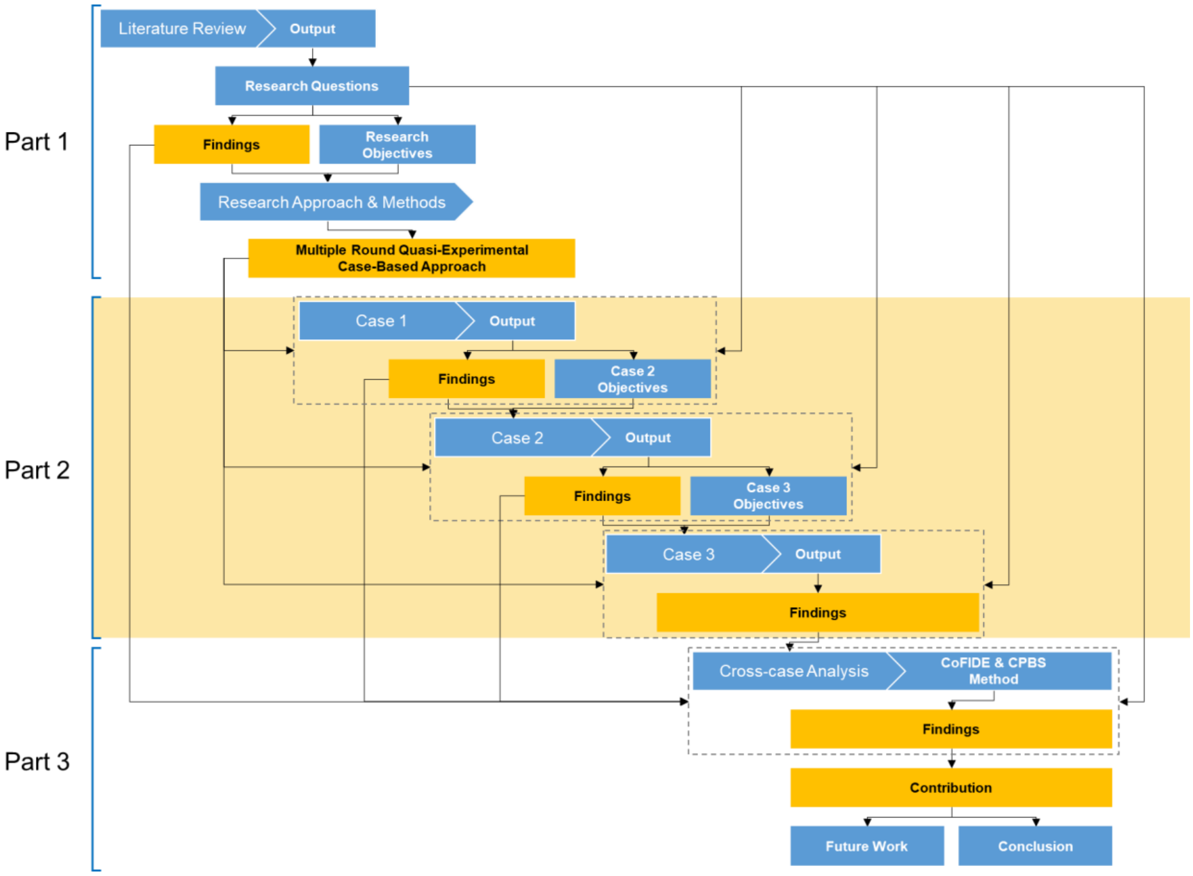


Figure 20 – Multiple Round Quasi-Experimental Case-Based Approach

PART 2

Part 2 Introduction

"I love deadlines. I like the whooshing sound they make as they fly by." —Douglas Adams

Introduction

This part of the thesis presents three individual cases. Each was conducted with a product design company based in the UK, working wherever possible with the entire design team. Within each case is a description of any changes made to the experimental process and its rationale, a presentation of the data collected and its analysis, and discussion on the findings derived from said analysis.

4. Case 1

"I love it when a plan comes together." – John "Hannibal" Smith, the A Team

4.1 Introduction

Case 1 was conducted between April 2017 and May 2017 with a Glasgow-based Product Design Company with experience in developing products in a diverse range of fields, referred to in this study as Design Company A (DCA). DCA was established by a husband and wife, and was incorporated in 2005. At the time of this study, DCA had a team of eight product design engineers with varying levels of experience in the industry, with degrees in Product Design Engineering or Product Design. The majority of the design team attended higher education in Scotland, predominantly attending The Glasgow School of Art for Product Design Engineering (in partnership with the University of Glasgow). It was these eight design team members who were the participants of this case, with no company director involvement. DCA's past work has been diverse, ranging from sub-sea and off-shore products to explosive atmosphere environments (ATEX) and medical equipment. Day-to-day project management is undertaken predominantly by senior members of the design team, with the company directors operating the business.

This study is comprised of the initial six-phase experimental process and two further phases outside the initial plan, details of which will be covered in this chapter. All workshops were conducted in the offices of DCA. The number of participants included in each workshop was determined by the types of data gathered, with initial background information (design process, resource types, etc.) and estimation tool evaluation only requiring the participation of the senior designers. All participants participated in each workshop of the case.

4.2 Results

The description of the results of applying the experimental method will be accompanied by a corresponding IDEF0 model that will depict the process followed, rather than the intended approach. These IDEF models can be found in Appendix 4.1 – 4.6.

This section will discuss the approach initially adopted in this case, referred to as Approach 1 and shown in the subheadings as "A1". A subsequent approach was adopted in order to explore the influence of a specific factor, which will be referred to as Approach 2, shown in the subheadings as "A2".

4.2.a A1: Resources and Project Stages (Preliminary Discussion)

Preliminary discussions were held with two senior designers at the offices of DCA. During these discussions, it was agreed that the best resource for the case would be "person-hours" as this matched the resource used to manage projects and when billing clients. When asked to describe their design process, the participants identified four phases of work as part of any product design project: *Discover, Define, Develop, and Deliver* based on the Design Council's "Double Diamond" design process. DCA had adopted this process but added to it, embellishing each phase with its own specific series of tasks and in some cases, with sub-tasks. All phases, tasks and sub-tasks are outlined in Table 19Table .

Table 19 – Case 1 - Product Design Project Phases, Tasks and Sub-tasks

Project Phase	*Project Task*	*Project Sub-task*
Discover	Gather Interviews	Observation Marketplace research
	Process	Workflow mapping Stakeholder profiling
	Imagine	"What if" statements
Define	Creative & Strategic	Ideation / Concept Generation (Modelling & Sketching) User Feedback
	Documentation	Requirements capture Standards assessment Preliminary BOM Indicative manufacturing proposals & cost Usability specification Confidence in performance
Develop	Refinement	Simulation / User testing Prototyping Verification testing DFM – CAD Detailing Manufacturing route defined Full manufacturing data package (cost) Compliance assessment
Deliver	Manufacture	First production batch Manufacturing & Supply chain setup Validated production process Validate production
	Documentation	Notified body submission Certification Technical file

4.2.b A1: Factors (Workshop 1)

The task of identifying factors required participants to create an exhaustive list of every factor that may influence the number of person-hours a project would require for any or all phases of a design project. Unprompted by the researcher, the participants discussed the design process as a means of contextualising their understanding of the design process. The participants identified seventeen potentially influential factors during the workshop, as outlined in Table 20. Using all these factors and following a standard half factorial design of experiments approach to create an experimental design in the following interim phase would not be practical for the workshop participants; As many of the factors would not have a statistically significant influence on resource requirements and participants would be unable to finish the estimation tasks in a reasonable time due to the high number of experimental runs. Therefore, a shortlist of five factors was selected as the most influential through a process of dot-selection. However, with each participant receiving five "votes".

Table 20 Case 1 - Longlist of potentially influential factors

Number of key stakeholders
Accessibility of key stakeholders (geographically)
Accessibility of key stakeholders (availability / willingness)
Accessibility of client (geographically)
Accessibility of client (availability and willingness)
Accessibility of manufacturers (geographically)
Accessibility of manufacturers (availability and willingness)
Personality & Relationship with clients
Prior knowledge (Background & Experience)
Materials Budget
Availability of staff (holidays, other projects, etc.)
Product complexity
Project Scope
Need for subcontractors
Equipment availability
Space to work
Testing Complexity

The voting results (Table 21) show that although there is clearly a top four list of factors, three factors each received an equal number of votes in joint fifth place. Therefore, to determine which of these factors should be included in the experimental design, a second round of blind voting was conducted, with each participant voting for one of the three factors. This resulted in "Materials Budget" being voted for fifth place.

Table 21 Case 1 - Influential Factor Participant Votes

Group Factor	**Votes**
Product Complexity	5
Project Scope	4
Regulatory complexity	3
Prior Knowledge	3
Materials Budget	2
Geographic Accessibility of key stakeholders	2
Availability of staff	2

Table 22 Case 1 – Influential Factors with High & Low Levels

Project Influential Factor	**Factor High Value**	**Factor Low Value**
Project Scope	Defined	Ambiguous
Product Complexity	One Part	100+ Parts
Regulatory Complexity	No Regulations	Highly Regulated
Prior Knowledge	Expert Knowledge	No Knowledge
Material Budget	High Budget	Low Budget

To build the experimental designs, high and low levels for each of the top factors had to be established. Participants brainstormed this for each factor level with the results shown in Table 22.

4.2.c A1: Experimental Design (Interim Phase 1)

The data gathered from Workshop 1 was collated and analysed using statistical analysis software "Minitab 17". Using the Design of Experiments tools within Minitab to produce an experimental plan based on a five-factor, two-level half-factorial experimental design, shown in Table 23. The experimental runs in this table have not been randomised, as it has been observed in workshop testing of estimation sheets, that participants locate and estimate the resources required for the experimental run that they have experience with, from which they base all their other estimations.

Table 23 Case 1 - Experimental Design

Run	1	2	3	4	5
1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	-1
4	1	1	-1	-1	1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	1
8	1	1	1	-1	-1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1

The experimental plan was combined with the eight tasks identified in Workshop 1 to create the Estimation Sheet for Workshop 2, shown in Table 24. Although sub-tasks were identified, it was determined that eight tasks would be the maximum to estimate, as otherwise, the time required to complete the exercise may lead to the participants' fatigue and poor results.

4.2.d A1: Estimation Data Collection (Workshop 2)

The second workshop was used to gather resource estimation values from each of the participating members of the design team, the results for which are outlined in Appendix 4.7 and 7. Eight members of the design team participated in the estimation process. While seated in PDC1's studio, printed copies of the estimation sheet were handed to each participant for them to record their estimates. These were collected by the researcher once each participant was complete.

4.2.e A1: Data Analysis – Regression Equations (Interim Phase 2)

This phase saw the creation of regression equations to describe the relationships between the project factors and design effort levels, following a structure shown in Equation 1. Each participant's estimation values (recorded by hand on their estimation sheets) were added to a spreadsheet and using the Design of Experiments regression analysis tool within the statistical analysis software Minitab, 64 regression equations were created, eight for each participant, one for each phase of the project shown in Appendix 4.8, with an example shown in equation 2 from Participant 1's estimates for the manufacturing phase.

Table 24 Case 1 - Workshop 2 Estimation Sheet

Run	Project Scope	Product Complexity	Regulatory Complexity	Prior Knowledge	Material Budget	Gather	Process	Imagine	Creative & Strategic	Documentation 1	Refinement	Manufacture	Documentation2
1	Ambiguous	100+ Parts	Highly regulatory	No Knowledge	£££								
2	Defined	100+ Parts	Highly regulatory	No Knowledge	£								
3	Ambiguous	One part	Highly regulatory	No Knowledge	£								
4	Defined	One part	Highly regulatory	No Knowledge	£££								
5	Ambiguous	100+ Parts	No Regulations	No Knowledge	£								
6	Defined	100+ Parts	No Regulations	No Knowledge	£££								
7	Ambiguous	One part	No Regulations	No Knowledge	£££								
8	Defined	One part	No Regulations	No Knowledge	£								
9	Ambiguous	100+ Parts	Highly regulatory	Expert Knowledge	£								
10	Defined	100+ Parts	Highly regulatory	Expert Knowledge	£££								
11	Ambiguous	One part	Highly regulatory	Expert Knowledge	£££								
12	Defined	One part	Highly regulatory	Expert Knowledge	£								
13	Ambiguous	100+ Parts	No Regulations	Expert Knowledge	£££								
14	Defined	100+ Parts	No Regulations	Expert Knowledge	£								
15	Ambiguous	One part	No Regulations	Expert Knowledge	£								
16	Defined	One part	No Regulations	Expert Knowledge	£££								

$$Output = \ Constant \ + (a \times w) + (b \times x) + (c \times y) + (d \times z)$$

Equation 1

$$\begin{aligned} Design\ Effort = \ & 187.5 + (0 \times a) + (-50 \times b) + (-12.5 \times c) + (-25.0 \times d) + (31.3 \times e) \\ & + (0 \times \mathrm{a.b}) + (0 \times a.c) + (0 \times \mathrm{a.d}) + (12.5 \times a.e) + (0 \times b.c) + (0 \times \mathrm{b.d}) \\ & + (0 \times b.e) + (-12.5 \times c.d) + (0 \times \mathrm{c.e}) + (0 \times d.e) \end{aligned}$$

Equation 2

4.2.f A1: Graphical Representation of Data (Interim Phase 2)

The values for each of the regression equations was imported to a spreadsheet, separated by each project phase, and the coefficient values for each part of the equation were separated into columns. This data for each of the eight phases were used to create two graphs types, the first to compare the magnitude (modulus, rather than the true value) of each factor compared to the constant value for each participant's regression equation, an example of which is shown in Figure 21; the second graph totals the values of each coefficient and presents them as percentage of total influence each factor has over the regression equation of each participant, to compare factors, an example of which is shown in Figure 22. The remaining graphical regression values and percentage influence graphs are shown in Appendix 4.9 and 4.10 respectively.

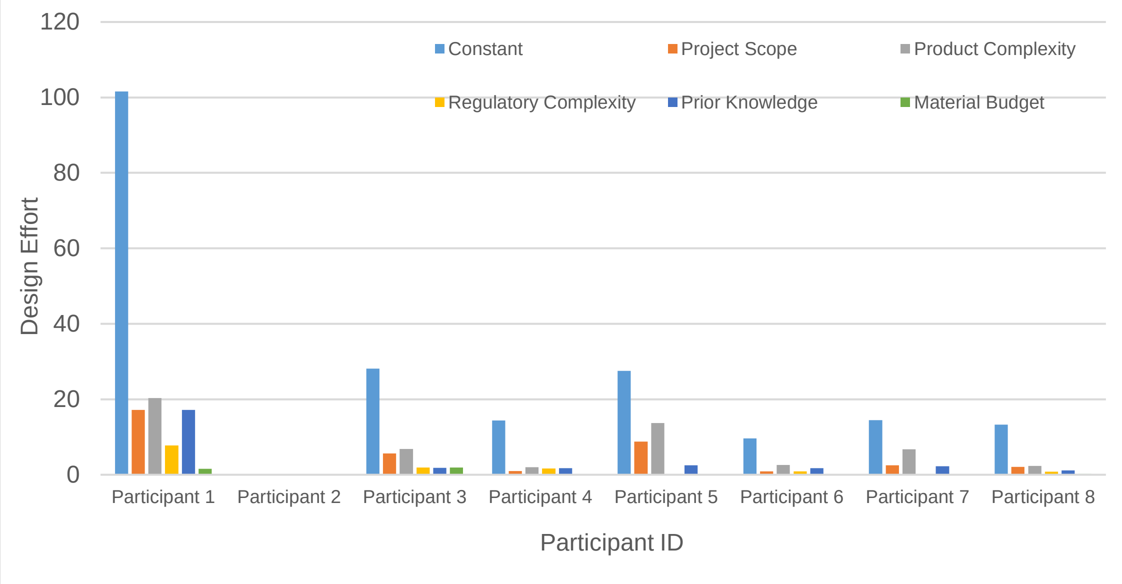


Figure 21 Case 1 – Graphical Regression Values Representation - Gather Phase

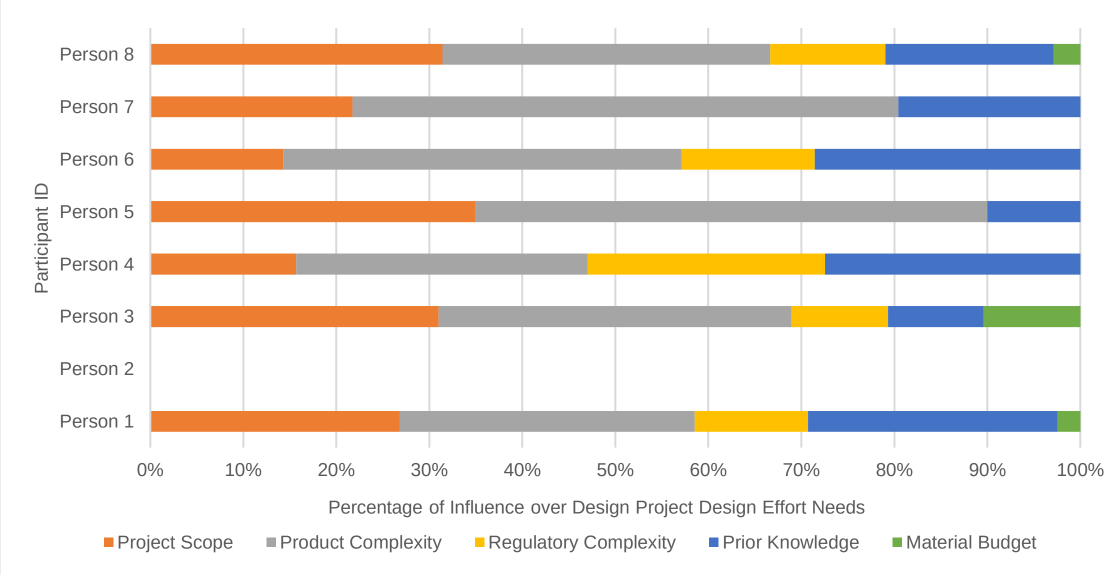


Figure 22 Case 1 Percentage Influence Graphs - Gather Phase

4.2.g A1: Mean Effect Plots (Interim Phase 2)

Using the Mean Effect analysis tool in Minitab, Mean Effect Plots were generated for each of the participants, project phase and factor, the values for which are included in Appendix

4.11. Each mean effect plot has been included in Appendix 4.12. The estimates for each of the eight phases collected in Workshop 2 were collated and combined into the four stages of the Design Council's Double Diamond (Discover, Define, Design and Deliver). This was to simplify the discussion during the participant interview stage, as the participants believed that the level of granularity in graphs would become confusing and overwhelming. To read mean effect plots, consider the gradient of the lines plotted. A positive gradient indicates a positive correlation between a factors level and the resource required; with a negative gradient being the opposite. The severity of the gradient of a mean effect plot indicates the magnitude of the difference in influence based on what level the factor is.

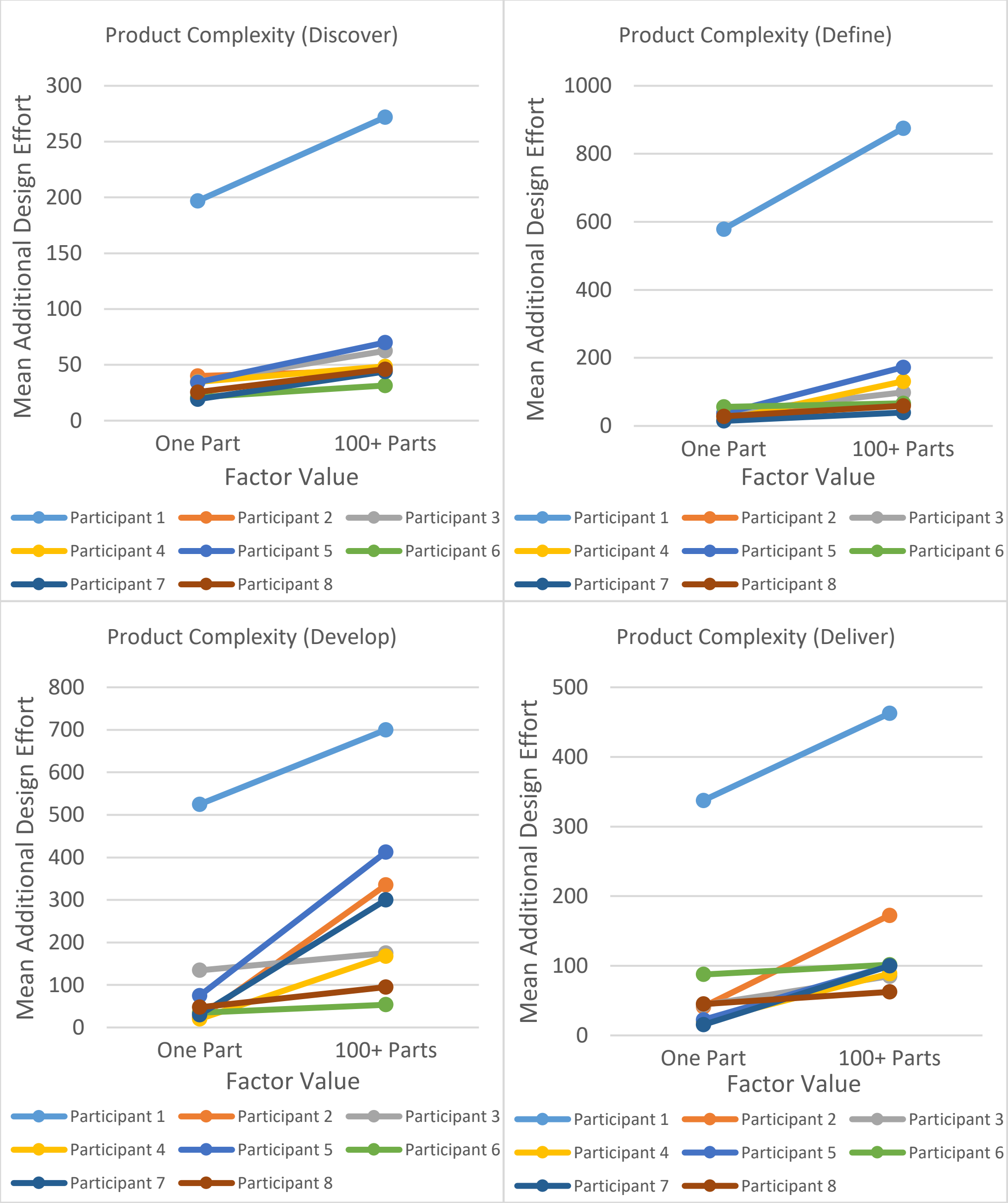


Figure 23 Case 1 - Mean Effect Plot of Product Complexity Factor

4.2.h Experimental Process Conclusion

As the factor of *Product Complexity* holds a clear majority of influence over design effort, with all other factors exerting limited influence, it was determined that there may be value to the study and the participants to establish the nature of the relationship between product complexity and design effort needs. To determine whether there is a linear relationship, or if the relationship is on a curve, exponential, etc. Therefore, a second round of estimation was required, with product complexity given four levels. To reduce the number of experimental runs, the least influential factor identified (*materials budget*) was removed.

4.3 Approach 2

To incorporate "Product Complexity" at four levels, a Taguchi-based experimental design is required, as it was developed to scrutinise one factor at multiple levels, while including other factors at a two level state. By adopting this Taguchi-based approach, it was possible to investigate whether the relationship it (product complexity) has with design effort needs is linear, exponential or other, while maintaining a two-level design for the remaining factors.

The numbering of the workshops and interim phase continues from the first round of this case to distinguish them from those that preceded them.

4.3.a Adopted Approach

7. Workshop 4

Workshop 4 is a variation of the activities of Workshop 1, and as such all members of the design team were needed to participate in brainstorming and group discussion activities. The purpose of this workshop was to identify the most influential factor(s) from those used in the previous phases. The participants produced a multi-level classification system for each of the influential factors, replacing the minimum/maximum values established previously with a multi-point scale, also created by the participant. This allowed for the creation of multi-level experimental designs during Interim Phase 3.

8. Interim Phase 3

The multi-level classification system created during workshop 4, was used to generate a Taguchi-based experimental design using the same statistical analysis software used in previous phases. Like with the previous examples, this newly-created experimental design was used as the template for data collection during Workshop 5. This would reduce the number of estimates each participant was required to do to model factor behaviour and therefore minimise participant inconvenience and fatigue.

9. Workshop 5

Workshop 5 was similar to Workshop 2 and required all the participants for an estimation task. Using new estimation sheets to record their estimates, each participant was instructed to estimate the duration of each project phase based on the levels of each factor.

10. Interim Phase 4

Regression equations were created from each of the participant's estimation data collected, which reflected each of their perceptions of how the resources of each project phase will be affected by changes in influential factors. A similar suite of graphs were produced to those produced in the initial approach (Mean Effects, Percentage Influence Change, etc.) to identify the types of relationships each factor has with project phase length.

11. Workshop 6

The graphs generated in Interim Phase 4 were designed to be presented to the participants to determine what can be offered and their potential value to be gained through analysis and data visualisation. A series of semi-structured one-to-one interviews (recorded with the permission of each participant) was planned to allow each participant to discuss their estimations and the insight offered by the graphs and diagrams.

4.4 Case Results (Approach 2)

4.4.a A2: 4-Level Classification of Product Complexity Factor (Workshop 4)

In a brainstorming workshop, the participants were presented with an example of a product complexity classification system, developed by Hubka & Eder (1988), and shown in Table 25. The design team at DCA did not use Hubka & Eder's categorisation of complexity, rather opting to create their own, 4-level complexity definition. A list of possible characteristics was identified through informal discussion between the participants, with seven potential characteristics identified: Number of parts, Geometry, Tolerances (Required accuracy), Number of disciplines, Modes of operation / Functional diversity, Frequency of interaction, and Ergonomics. Each of these characteristics was selected as they could be determined, to a degree, at the project's outset.

Each participant voted for what they considered to be the most influential characteristics of product complexity through dot selection, with the top four influential characteristics accruing the highest number of votes. These characteristics were identified as: *Number of parts for the product, number of disciplines required for the development of the product* (i.e. mechanical engineering, electrical engineering, bioengineering, etc.), *Functional Diversity* (i.e. the number of uses for a product), and *Frequency of product interaction with users*.

Case 1

Each factor has been considered to have equal influence with each assigned four levels, 1-4, with 1 being the lowest. These characteristics and their associated levels are shown in Table 26.

Table 25 Case 1 - Levels of complexity. Adapted from Hubka & Eder (1988)

Complexity Level	Technical System	Characteristic	Examples
I	Part, component	Elementary system produced without assembly operations	Bolt, bearing sleeve, spring, washer
II	Group, Mechanism, sub-assembly	Group, Mechanism, sub-assembly Characteristic: Simple system that can fulfil some higher functions	Gearbox, hydraulic drive, spindle head, brake unit, shaft, coupling
III	Machine, Apparatus, Device	System that consists of sub-assemblies and parts that perform a closed function.	Lathe, motor vehicle, electric motor
IV	Plant, Equipment, Complex machine unit	Complicated system that fulfils a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity.	Hardening plant, machining transfer line, factory equipment

To determine the product complexity ranking, based on the DCA Characteristics of Complexity, the products from each new project would be assessed against each characteristic and assigned the corresponding score. The sum of the scores is compared to the complexity ranking scales (Table 27) and the complexity ranking is established. It was considered by the participants that this scoring system would allow for projects that had high scores in one characteristic, to appropriately influence the complexity rank of the product.

Table 26 Case 1 – DCA Characteristics of Complexity

	Complexity Score			
Characteristic	**I (1)**	**II (2)**	**III (3)**	**IV (4)**
Number of Parts	1 – 5	6 – 30	30 – 99	100 +
Number of Disciplines	1	2	3	4 +
Functional Diversity	Single	Few	Many	Infinite
Frequency of Product Interaction	None	Occasional	Frequent	Constant

4.4.b A2: Experimental Design 2 (Interim Phase 3)

The data gathered from Workshop 4 was collated and using the Design of Experiments tool in the statistical analysis software “Minitab 17”, to produce an experimental plan based on a four-factor, mixed-level Taguchi-style Experimental design, shown in Table 28. As with the experimental design created in the first approach, the experimental runs in this table have not been randomised as the participants opted to complete the form in whichever way they deemed to be most appropriate and convenient to them.

Case 1

Table 27 Case 1 – DCA Complexity Ranking Scale

Complexity Ranking	Characteristics Point Scale
I	4 – 7
II	8 – 10
III	11 - 13
IV	14 - 16

The experimental design was combined with the four project phases in Workshop 1 – Describe Phase to create the Estimation Sheet (Table 29) for Workshop 2 – Collect Phase, shown in Table 28. Although in the previous study, eight tasks were identified, to further reduce participant fatigue, these tasks were reduced. The participants agreed that this reduction would not significantly reduce the insight offered from any analysis produced.

Table 28 Case 1 - Mixed level Taguchi Experimental design for hypothetical projects

Feature	1	2	3	4
1	1	-1	-1	-1
2	1	1	1	1
3	2	-1	-1	1
4	2	1	1	-1
5	3	-1	-1	1
6	3	1	1	-1
7	4	-1	-1	-1
8	4	1	1	1

Table 29 Case 1 - Workshop 2 Estimation Sheet

Run	Product Complexity	Project Scope	Reg. Complexity	Prior Knowledge	Discover	Define	Develop	Deliver
1	I	Many Parts	Highly Regulated	No Knowledge				
2	I	One Part	Not Regulated	Expert				
3	II	Many Parts	Highly Regulated	Expert				
4	II	One Part	Not Regulated	No Knowledge				
5	III	Many Parts	Not Regulated	No Knowledge				
6	III	One Part	Highly Regulated	Expert				
7	IV	Many Parts	Not Regulated	Expert				
8	IV	One Part	Highly Regulated	No Knowledge				

4.4.c A2: Project Data for Comparison (Collect 2)

Before completing the estimations for this round, the participants decided to evaluate four of the company's past projects to get examples of different projects rated at the different levels of the complexity scale. For confidentiality reasons, these projects have been assigned generic descriptor titles, these, along with their scores, can be shown in Table 30.

Table 30 Case 1 – DCA Past Project Complexity Analysis

Complexity Characteristic	Medical Device	Bottle Top	Ratchet	ATEX
Number of Parts	3	1	2	2
Number of Disciplines	4	1	1	2
Functional Diversity	3	2	1	2
Freq. of Product Interaction	3	2	3	2
Total Score	13	6	7	8
Complexity Rank	**III**	**I**	**I**	**II**

It is of note that the participants were surprised that the medical device project did not receive a level-4 complexity rating during this activity. Estimation data was collected from six participants, shown in Appendix 4.13. This change in the number of participants was due to the availability of staff at the time of the case. All available participants were issued with a print out of the estimation sheet (Table 29) to record their estimates.

4.4.d A2: Graphical Representation of Data (Interim Phase 4)

Each participant's estimation values (recorded by hand on their estimation sheets) were added to a spreadsheet and using the Design of Experiments regression analysis tool within the statistical analysis software Minitab, 64 regression equations were created. Using the Mean Effect analysis tool in Minitab, the mean effects of each factor were calculated, with their values imported into a spreadsheet so that Mean Effect Plot graphs could be produced. The values for these graphs are included in Appendix 4.15, with each mean effect plot graph has been included in Appendix 4.17.

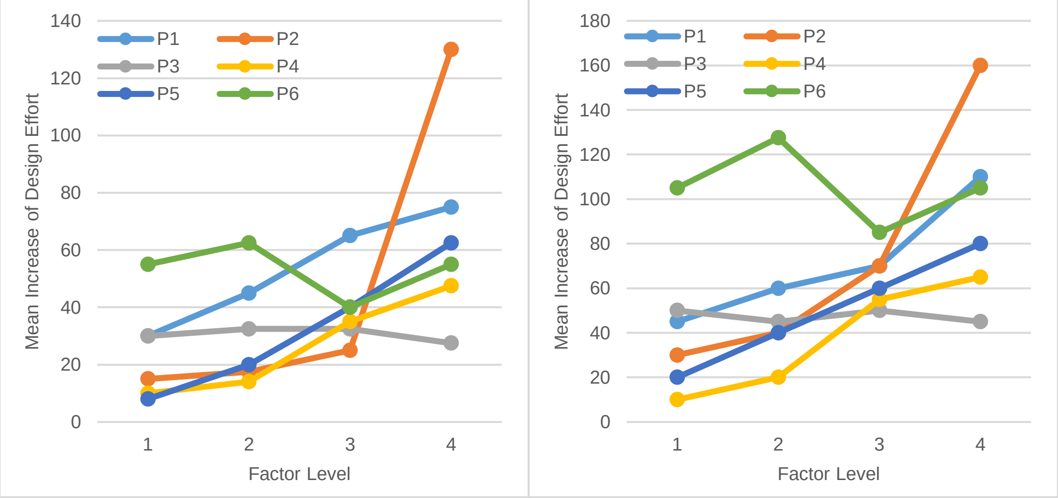


Figure 24 Case 1 - Product Complexity Mean Effect Plots (Discover (L) & Define (R) Phases)

Case 1

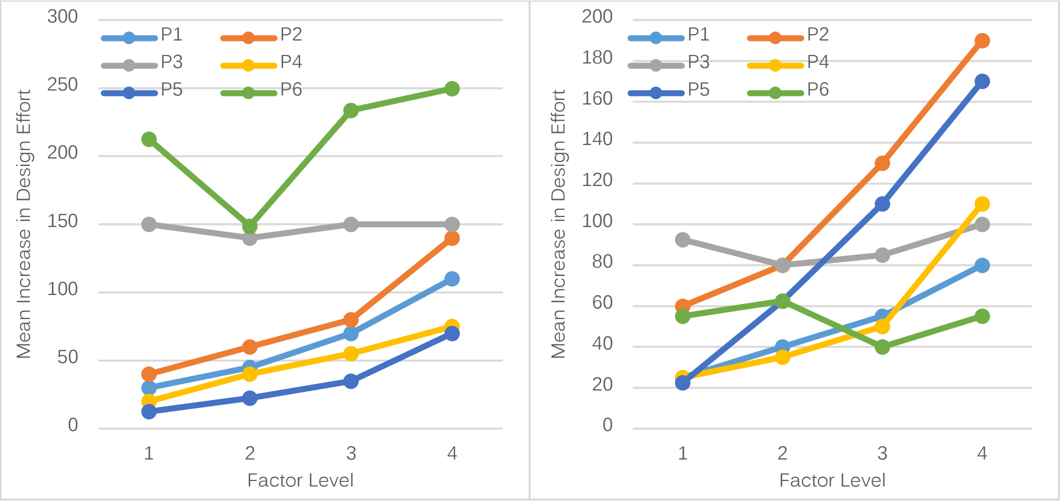


Figure 25 Case 1 - Product Complexity Mean Effect Plots (Develop (L) & Deliver (R) Phases)

Workshop 6 Note

Due to the workload and commitments of the individual participants of DCA, the participant interviews could not be held.

4.4 Analysis

This section presents an analysis of the data collected during Case 1.

4.4.a Analysis: Influential Factors

Of the seventeen factors identified by DCA1, seven groupings were made from which five were voted as being most influential.

Categorising Factors

From the literature review, nine categorisations of factors were synthesised, excluding those that were not practically valuable in the context of this study. These factor categorisations were, in order of frequency of occurrence: *Team management, Product, Business Management, Information, Tools & Technology, Client, External Influences* and *Project*. Definitions for each of these categories are stated in the literature review. In Table 31, the seven grouped factors identified in this case are mapped to the factor categories developed in the literature review. The frequency of each category has been calculated to determine the spread. Under the assumption that more importance is placed on categories that are mentioned with greater frequency. Table 31 indicates that Team management-based factors have the greatest significance, having been mentioned twice, while Product, Client, Project and External Influence factors are mentioned once. One factor identified by DCA does not correspond to a category from literature, that of "Materials Budget". It is unknown if this is an anomaly of this specific PDC or if this has some significance, which can only be determined through comparison of other case datasets.

Case 1

Product Complexity

As product-based factors refer to the qualities or attributes of the intended product, for which "Product Complexity" has already specifically been identified (Bashir and Thomson, 2001; Jacome and Lapinskii, 1997; Tatikonda and Rosenthal, 2000), assigning the "Product Complexity" factor identified by DCA's design team is clear.

Project Scope

DCA participants stated in informal discussions that the term "Project Scope" refers to the qualities of the project. As such, this factor can be categorised as a project-based factor.

Regulatory Complexity

The "Regulatory Complexity" factor refers to the volume and intricacies of the regulations and other legislation that the DCA design team will have to complete as part of the product development process. As these regulations (and similar) are mandated by external bodies, this is an "External Influence" factor.

Table 31 Case 1 Categorised Factors

	Team management	Product	Business management	Information	Tools & Technology	Client	Project	External Influences	Other
Product Complexity		1							
Project Scope							1		
Regulatory complexity								1	
Prior Knowledge	1								
Materials Budget									**1**
Geographic Accessibility of key stakeholders						1			
Availability of staff	1								
Instance	2	1	0	0	0	1	1	1	1
Case Percentage	28.57%	14.29%	0.00%	0.00%	0.00%	14.29%	14.29%	14.29%	14.29%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

Regulatory Complexity

The "Regulatory Complexity" factor refers to the volume and intricacies of the regulations and other legislation that the DCA design team will have to complete as part of the product development process. As these regulations (and similar) are mandated by external bodies, this is an "External Influence" factor.

Prior Knowledge

The "Prior Knowledge" factor refers to the depth of relevant knowledge the DCA design team has that will be required for the completion of a project. This knowledge is in part the result of effective team management. DCA management are responsible for the composition of their design team and therefore the skillsets and experience each member has. This mirrors the factors discussed in various sources within the literature review (Bashir and Thomson, 1999, 2004; Benedetto et al., 2018; Pollmanns et al., 2013; Salam et al., 2009).

Materials Budget

There was no specific factor category identified in the literature review that relates to the "Materials Budget" factor. Therefore it has been assigned to the "other category".

Geographic Accessibility of Key Stakeholders

Although the term defined by the DCA participants states the "Geographic Accessibility of Key Stakeholders", when asked to expand on this factor to define what they considered to be a stakeholder, the discussions would focus on the client. There would be mentions of other stakeholders, such as funders, but they were mainly about the client.

Availability of Staff

There is a clear link between the Team Management category and the "Availability of Staff" factor identified by the DCA participants. This factor relates to the workload of each member of the design team, as DCA would be working on multiple projects concurrently; as well as the scheduling of annual leave, and other absences, but scheduled and unscheduled.

Included in Table 31 are the corresponding percentages calculated from the literature review, form which it is possible to identify the differences in perspective between the literature and the DCA design team. There is agreement between both datasets when considering Team Management-based factors, both having the greatest percentage of instances. This is where the agreement between the literature review data and the case data ends. The spread of percentages is broader in the case data in comparison to the literature review findings, which can be explained by the limited dataset of the case. By gathering data from additional cases, a broader understanding of the perspectives of PDCs can be achieved.

Case 1

When considering exclusively the top-voted factors by DCA, shown in Table 32, the difference in distribution of categories remains similar to that when including all grouped factors. No category received more than one instance from the top-voted factors. The difference distribution of categories between the literature review and the factors identified by DCA indicate a degree of disagreement on which factors play a significant role in influencing design project resources.

Table 32 Case 1 Categorised Top Voted Factors

	Team management	Product	Business management	Information	Tools & Technology	Client	Project	External Influences	Other
Product Complexity		1							
Project Scope							1		
Regulatory complexity								1	
Prior Knowledge	1								
Materials Budget									**1**
	1	1	0	0	0	0	1	1	1
Case Percentage	20.00%	20.00%	0.00%	0.00%	0.00%	0.00%	20.00%	20.00%	20.00%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

4.4.b Analysis: Percentage Influence Graphs (PIGs)

Figure 22 shows that in the gather phase, the *project scope* and *product complexity* factors are the most influential. Note that Participant 2 believed that the gather phase was not influenced by any factor, but rather was a set duration and therefore required the same design effort regardless of the project. As such, their graph is blank.

From the graphs shown in Appendix 4.9 and Appendix 4.10, it is clear that Product Complexity is the factor with the overall greatest influence over the required resources for design projects. In contrast, Material Budget is the factor with the least influence, with many phases and participants not considering it to have any influence over resources at all.

4.4.c Analysis: Mean Effect Plots (MEPs)

This section will consider the Mean Effect Plots generated during Case 1 and what they indicate in their depiction.

Mean Effect Plots from Approach 1

The following analysis considers MEPs developed during Approach 1 (Section 4.2.g), the graphs for which can be seen in Appendix 4.12.

Product Complexity

From the graphs shown in Figure 23, there is a clear link between product complexity and each of the project phases, with the demands for design effort decreasing as the complexity decreases. The gradient of the plot line varies between participants, but the trend is still clear. This corroborates the attitudes of other research studies into product complexity, like those covered in the literature review chapter and its conclusions that Product Complexity is the most influential factor on product design project design effort level demand.

Project Scope

The mean effects graphs for the Project Scope factor, shown in Appendix 4.12, indicate that as the project scope is more clearly defined, the estimated design effort levels needed for a design project also decrease. This influence decreases as the project progresses, with the later "Design" and "Deliver" phases having minimal influence over design effort levels. This is likely due to the information shortfall experienced by an ambiguous brief is resolved over time.

Regulatory Complexity

The Regulatory Complexity mean effects graphs, shown in Appendix 4.12, indicate an anticipated reduction in design effort levels as the number and complexity of regulations decrease. There is some variation between participants, shown by some plotlines indicating an opposite correlation.

Prior Knowledge

The Prior Knowledge factor seems to have limited influence over project length, according to the Mean Effect Plots shown in Appendix 4.12. There is a slight trend which would indicate that as relevant knowledge increases, anticipated design effort levels decrease. As with the Project Scope factor, the influence of this factor is greatest at the start of the project, reducing as the project progresses. This is likely due to designers taking additional time at the project outset to familiarise themselves with the subject area.

Case 1

Material Budget

As a factor, Material Budget seems to have little influence over design effort levels in the main. This is illustrated by the graphs shown in Appendix 4.12, which suggest that material budget is only an issue during the latter half of a design project, where the anticipated project phase length decreases as the budget increases. This is likely because the designers will need to be more meticulous with their physical model/prototype design, as their budget is limited and don't have "cash to burn".

Mean Effect Plots from Approach 2

The following analysis considers MEPs developed during Approach 2 (Section 4.2.g), the graphs for which can be seen in Appendix 4.17.

Mean Effect Plots (Taguchi): Product Complexity

From the graphs shown in Figure 24 and Figure 25, there is a clear link between product complexity and each of the project phases, with the demand for design effort decreasing as the complexity decreases. As with the previous set of plots, the gradient of the plot lines varies between participants, but the trend is still clear. With a four-level plot, it is clear that some participants perceive this factor to have greater influence over design effort levels as the factor level increases beyond a linear relationship, towards an exponential curve. However, when considering the plots of all participants together, the relationship tends towards a linear one.

Project Scope (Taguchi)

The mean effects graphs for the Project Scope factor are shown in Appendix 4.17. Contrary to what was shown in the first set of plots for Project Scope, these graphs indicate that there may be some disagreement between design team members, with some perceiving that as the project scope is more clearly defined, the estimated design effort demands also decreases. Whereas others perceive the opposite. A consensus within the DCA design team is shown on the overall influence that Project Scope has over design effort levels; the gradient of the plot lines is shallow, indicating a limited difference between levels, and therefore limited overall influence over design effort levels.

Regulatory Complexity (Taguchi)

The second set of Regulatory Complexity mean effects graphs are shown in Appendix 4.17. Like the first set of plots, these graphs indicate an anticipated reduction in design effort demands as the number and complexity of regulations decrease. Unlike the first set, there is little variation between participants, with far fewer plotlines indicating an opposite correlation.

Case 1

Prior Knowledge (Taguchi)

Unlike the first set of mean effect plots for Prior Knowledge, the second set of plots indicates a greater level of influence over design effort levels. This is indicated by the gradient of the plot lines (shown in Appendix 4.17). These plots indicate a trend indicating that as relevant knowledge increases, anticipated levels of design effort required decrease. As with the Project Scope factor, the influence of this factor is greatest at the start of the project, reducing as the project progresses. This is likely due to designers taking additional time at the project outset to familiarise themselves with the subject area.

Mean Effect Plots Application

The use of Mean Effect Plots has been shown to effectively communicate the interactions between factors and project resources. These graphs require little explanation to understand and demonstrate the degree to which a factor influences resources, as the steeper the gradient, the greater the influence. The efficacy of mean effect plots can be influenced by the difference in estimates, where the estimates of Participant 1 are greater than those of the other participants, reducing the legibility of the other trend lines on the plot.

4.4.d Analysis: Modelling Factor Behaviour

If considered in combination, the Mean Effect Plots and Percentage Influence Graphs can be used to identify two key factor behaviours. The PIGs provide a per-phase perspective on which factor has the greatest influence. For example, Figure 22 indicates that the factors "Project Scope" and "Product Complexity" have the greatest influence in the Gather Phase of a DCA's design projects. While the MEPs indicate the directionality of each factor's influence, as shown in Figure 23, which indicates that as the "Product Complexity" factor increases, as too does the expected resource demand of a DCA projects. As there are sets of PIGs for each design project phase and sets of MEPs for each factor and each phase, this combination of graphs can model the behaviour of all the most influential factors and their influence throughout the duration of a design project.

For each of the five factors their behaviour can be determined:

Project Scope

The "Project Scope" factor is shown in the PIGs (Appendix 4.10) to have its greatest influence at the start of the project, with its influence diminishing over the course of the project.

Product Complexity

It is clearly shown in the PIGs that the "Product Complexity" factor has the greatest percentage of influence over design projects, with some phases, such as the Manufacture

Phase, almost exclusively showing product complexity as the sole influential factor. The PIGS also indicate that the influence of "Product Complexity" increases over the duration of a project. The MEPs for product complexity indicate that as complexity increases, as too does the anticipated demand of project resources.

Regulatory Complexity

From the PIGs of the "Regulatory Complexity" factor shown in Appendix 4.10, its influence peaks during the documentation phases of DCA's design process, with it having significantly less influence the rest of the design process. Perhaps unsurprisingly, the corresponding MEPS indicate that the greater the regulatory complexity, the more resource the design project will require.

Prior Knowledge

The influence of the "Prior Knowledge" factor varies significantly between each participant of DCA. Comparing the PIGs shown in Appendix 4.10, its influence subsides in the middle of a design project, peaking both at the outset and the later phases. The MEPs for "Prior Knowledge" indicate that as the relevant knowledge increases, the anticipated demand on project resources decreases.

Material Budget

The "Material Budget" factor has very little influence over the DCA's design projects, with no specific pattern being shown in the PIGs. Some participants consider it to have slightly more significance; Participant 3 considers it to hold over 20% of the total influence during the Refinement Phase, but this is an anomaly.

4.4.e Analysis: Identifying Contributing Elements for Factors

During discussions with the participants, it was established that each factor identified by the participants, (shown in Table 20) had several elements which contributed to the parent factor's effect. Except for Product Complexity (Table 26 & Table 27), these contributing elements were not recorded at the time of the study. The exercise of discussing how to quantify a factor provided an opportunity to discuss the factor in greater depth and to share insight and opinions.

Consider the Product Complexity factor. Without a range of elements, how does one quantify complexity? In isolation, the term is abstract within the product design milieu. What does a product complexity level of 4 mean? How is it measured? For that matter, what does product complexity even mean? By identifying a series of measurable elements which each contribute to an overall state of complexity, it is possible to apply some concrete understanding to an abstract concept. Likewise, although it might be possible to assess a product on its complexity, it may be a significant challenge to assess various product types equally and therefore allow for comparison between the two. How much more complex is a ballpoint pen to an office chair? By ensuring that the range or contributing elements apply to a diverse range of product types, a derived scoring system can be considered almost universal in its utility and thus enable a means of comparing complexity across product types.

4.4.f Analysis: Experimental Process - Estimation Fatigue

During both estimation workshops, it was clear that the participants found the task of estimating such a large number of experimental runs tiring. In informal discussions with participants, they commented on how mentally taxing they felt the activity was and that retaining the concept of a hypothetical project in their heads while making estimations was difficult. This fatigue is a result of the number of experimental runs (hypothetical projects) and the number of phases each experimental run has.

4.4.g Analysis: Experimental Process – Contributing Elements to Factors

When considering the other factors identified by the participants, "Project Scope", "Regulatory Complexity" and "Prior Knowledge", each of these factors could have a number (albeit not necessarily all the same number) of elements which contribute to their influence. Indeed, there is a potential for similar advantages to be gained from the detailed investigation of each factor, leading to an improved communal understanding, and providing context and definition to potentially abstract terms.

4.4.h Analysis: Experimental Process – Multi-Level Experimental Designs

As shown earlier in this section, the product complexity factor has a linear relationship with project length, or in some cases has a negligible curvature to the graph illustration of said relationship. Although it must be understood that the relationships described throughout the study only apply to DCA, their designers and their perceptions, the purpose of the method under investigation in this study is to model factor behaviour. Therefore, the benefit gained from a second round of estimations to investigate this relationship is outweighed by the additional time and effort to invest in the creation, execution and data analysis of a second estimation workshop.

4.4.h Analysis: Summary

The data collected in this case and how it was analysed has been summarised in Figure 26, which is based on the diagram presented in Chapter 3, but with the modifications to the research process that were made during the course of the case.

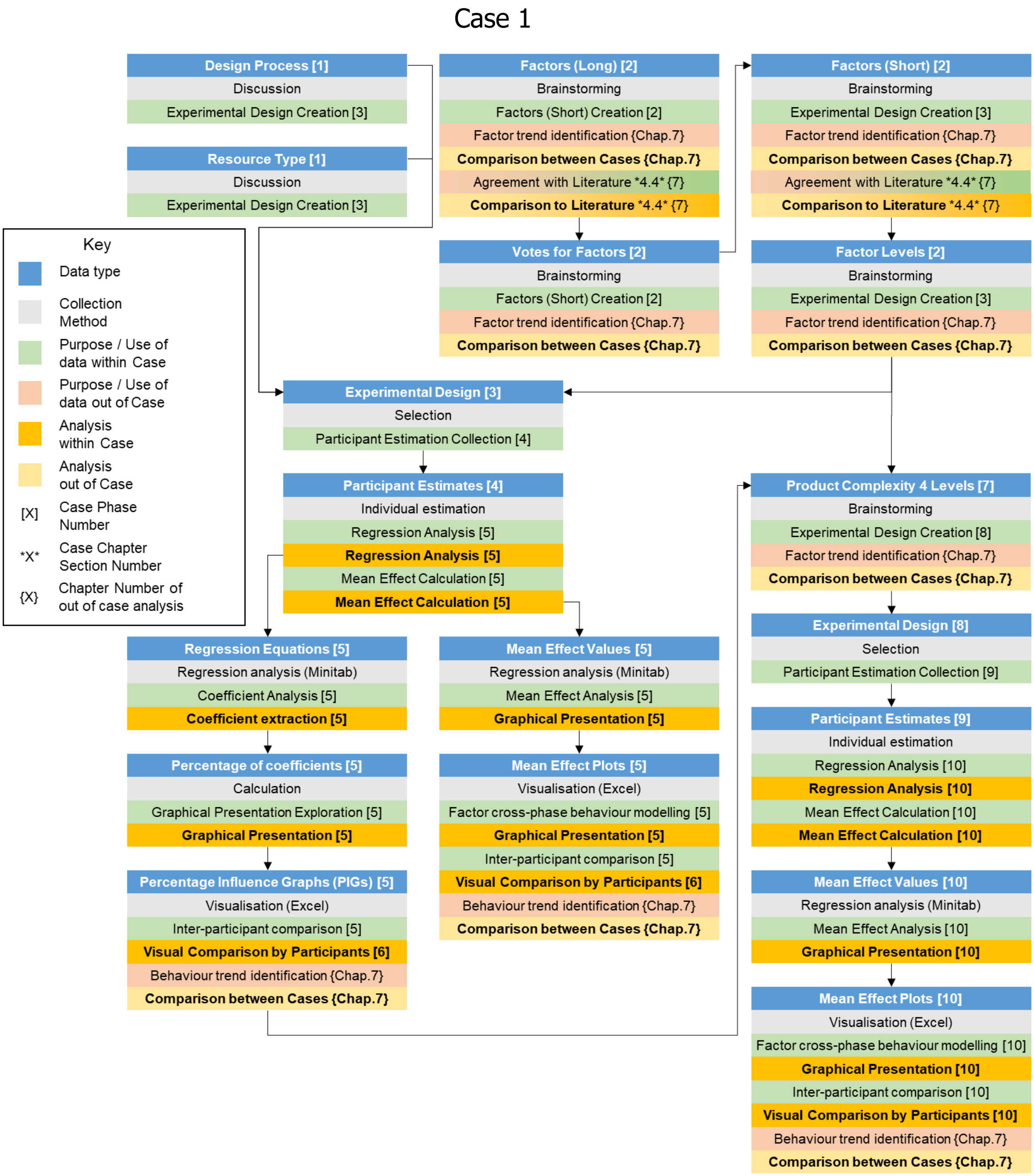


Figure 26 Case 1 Analysis Summary

4.5 Discussion

This section will discuss the major findings made by the researcher as a result of the actions, observations and results of Case 1. Of the findings presented, those that provide refinements to the experimental approach will be applied to future studies.

4.5.a Identifying Influential Factors

It is clear from this case that through the application of a DOE-based approach and working collaboratively with a product design company, it is possible to identify the most influential factors over design effort demands of product design projects. In the case of DCA, the most influential of these factors is product complexity. This has been demonstrated with the use of graphical modelling of the factor’s behaviour in the form of mean effect plots and its percentage of influence through the use of percentage influence graphs.

4.5.b Modelling Influential Factor Behaviour

This DOE-based process has produced a set of graphs (MEPs and PIGs) that model the behaviour of each influential factor over the duration of the project.

4.5.c Process Improvement: Factor Evaluation & Scoring Scheme (FEES)

Based on the assumption in found in the case analysis, formalising a procedure for participants to create sets of elements that contribute to each factor based on the grouping of factors (from the seventeen initial factors to seven grouped factors in the case of DCA). Developing a scoring system, like that adopted in Workshop 4, based in part on the levels of product complexity by Hubka & Eder (1988), will allow for participants to have a greater clarity on what each factor and each level might mean. Therefore, future cases will include a means to facilitate the creation of such scoring systems within their methodology.

4.5.d Addressing Estimation Fatigue

To reduce the likelihood of participant fatigue, the number of influential factors identified should be reduced from five to four. This would halve the number of experimental runs (hypothetical projects) each participant would have to estimate, from 16 to eight. Additionally, guiding future participants to define more generic project phases, would also reduce the number of estimates each participant would have to complete. This is evident in the Taguchi round of estimations, where the number of phases was halved from eight to four.

4.5.e Multi-level Experimental Runs

As there was found to be little value or insight offered using multi-level experimental runs, in particular in comparison to the estimation effort required of the participants, future studies should attempt to gather the relevant data from a single round of estimations, which will reduce the overall time a project requires to complete. This reduction in time will allow for further exploration of method features and benefits in future projects.

4.5.f Mean Effect Plots

To take advantage of the aforementioned advantages, future studies should include mean effect plots to facilitate the communication of factor influence. In future cases where a single participant’s estimates influence the legibility of the trend lines of other participants, these should be separated into other graphs.

4.5.g CoFIDE Method

The approach applied in Case 1 collects data and produces analysis that has value to PDCs. The identification of influential factors over design project resources and the graphical modelling of their behaviour may offer valuable insight for PDC teams and their members. The collaborative nature of this method makes it accessible to PDC teams, using techniques that are familiar to designers. With no significant issues encountered by the researcher or the participants during case 1, this approach can be adopted (in draft at this stage) to formulate a collaborative process for identifying design effort influencing factors, referred to as Collaborative Factor Identification for Design Effort (CoFIDE) method.

4.6 Conclusion

Through the adaptation and application of the Design of Experiments process in a product design company setting, an influential factor identification process has been created. The creation of Percentage Influence Graphs provide insight into which factors have the greatest percentage of overall influence per phase of a project, while the Mean Effect Plots depict how that influence relates to the presence, or absence of that factor. By adapting this experimental process, a collaborative method can be established which may, when refined, enable PDCs to identify and model the factors with the greatest influence over their design project resources. This method, referred to as the "Collaborative Factor Identification of Design Effort (CoFIDE), has been summarised in Figure 27, with changes to the proposed process mapped in Figure 28 and is described in detail in Table 33. From the findings of this case, various recommendations have been found to improve this process, adding to its viability and efficacy. These will be applied to the process used in Case 2.

4.7.a Role of the researcher in the case

In chapter 3, it was stated that the researcher would act as a facilitator when interacting with the participants in workshops and remained the case in this study. However, participants would ask questions that would require more interaction. Most queried the suitability of a potential factor, with the researcher responding by asking the participant if that factor was observable at the project's outset (a requirement of all suitable factors). During the estimation collection phase, participants would seek clarification around their approach to estimating resource demands, and whether there was one prescribed approach to be undertaken to complete the task. In these instances, the researcher stated that whichever approach was adopted by each participant was the correct one.

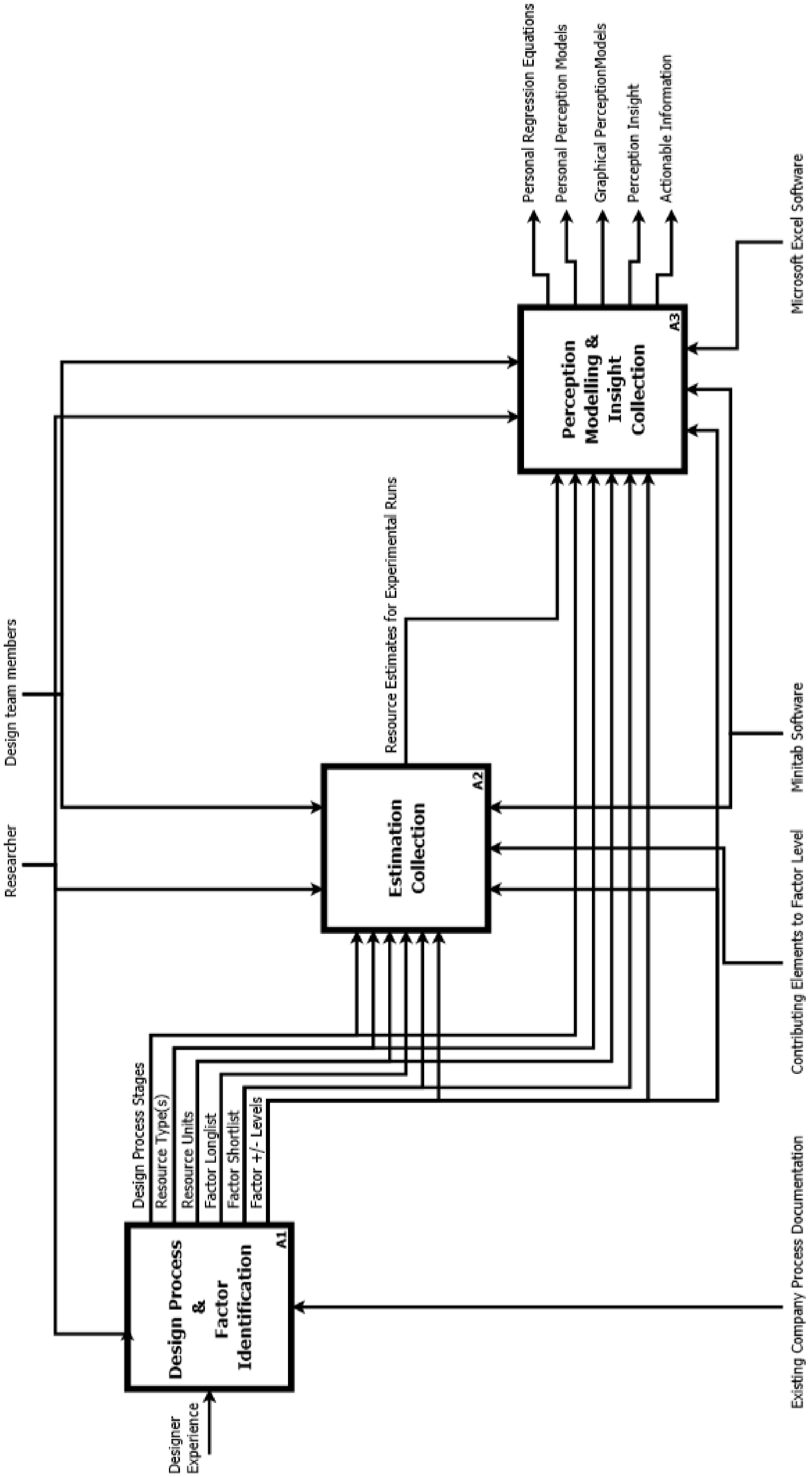


Figure 27 Case 1 Approach – IDEF0 Model of Adaptation of Design of Experiments for Tacit Knowledge and Experience Capture and Modelling in Product Design Company (CoFIDE)

The remaining questions were instances of participants seeking reassurance that the steps taken were the correct ones. There was no instance when the researcher had to intervene or make any meaningful alterations to the participants' actions during the case.

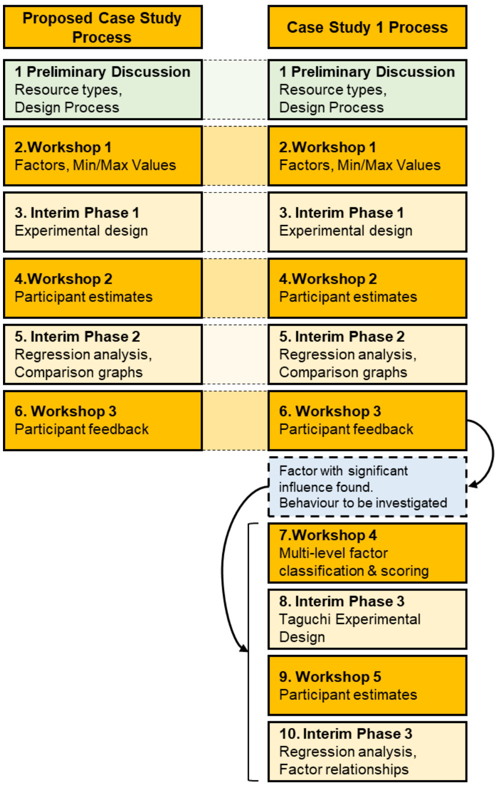


Figure 28 Changes to Experimental Process for CS1

4.7.b Answering Research Questions

This section will reiterate the research questions stated in the literature review and provide initial answers to each, based on the findings of Case 1.

RQ1

> *What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in literature?*

From the findings of Case 1, five factors were found to be most influential: "Product Complexity", "Project Scope", "Regulatory Complexity", "Prior Knowledge" and "Material Budget"; with the latter subsequently being eliminated for a second round of factor modelling for being shown not to have significant influence in graphical modelling. Taking this dataset on its own, it is not possible to derive any specific findings when comparing to the factors found in the literature, however, this will contribute to an analysis conducted in the cross-case analysis.

Case 1

Table 33 – Case 1 Approach – Case 1 Method

Case Study Phase	Purpose	People Required	Outcomes	Mapped DOE Stage
1. Preliminary Discussion	Identify key elements of product design projects at the participant company.	R / M	Suitable key resource(s) for future design projects. The design process is followed by the participant company.	*Describe*
2. Workshop 1	Identify key influential factors on project resource and their maximum / minimum values.	R / M / T	Key factors which influence resource(s) level Hypothetical viable max/min factor levels.	*Describe*
3. Interim Phase 1	Generate experimental design with identified factors and levels	R	Template experimental design	*Design*
4. Workshop 2	Collect experimental data (participant estimates) using the template	R / M / T	Participant estimates (1)	*Collect 1*
5. Interim Phase 2	Generate regression equations for participants Create regression models for each participant based on regression equations Build comparison graphs of regression models	R	Regression equations, Participant regression models, Comparison Graphs	*N/A*
6. Workshop 3	Gain insight into participant's views on comparison graphs	R / M / T	Feedback on process Feedback on comp. graphs	*Describe 2*
7. Workshop 4	Generate a multi-level factor classification scheme with a scoring system	R / M	Multi-level factor classification & scoring	*Describe 2*
8. Interim Phase 3	Generate Taguchi-base experimental design with identified factors and a greater number of levels	R	Template Taguchi experimental design	*Design 2*
9. Workshop 5	Collect experimental data (participant estimates) using the Taguchi template	R / M / T	Participant estimates (2)	*Collect 2*
10. Interim Phase 4	Evaluate factors, levels and resources to determine relationship types (i.e. linear, exponential, etc.)	R	Relationship between factors and resources	*Compare 2*
11. Workshop 6	Collect reflections and observations of participants considering the graphical representations of factor behaviour generated in Interim Phase 4.	R / M / T	Observations, reflections and comments from participants	*Compare 2*

Persons involved in study coded as: Researcher (R), Company Director & Office Manager (M), & Design Team (T)

RQ2

> *How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?*

As shown by the Percentage Influence Graphs (PIGs) and Mean Effect Plots (MEPs), the following behaviours can be identified:

Product complexity directly influences the resource demands of design projects, with a greater anticipated complexity of a product resulting in more resources being required. Its influence increases as the project progresses, with the manufacturing phase almost exclusively influenced by "product complexity".

Case 1

Project Scope has the greatest influence at the start of the project, diminishing as the project progresses, reflected in the PIGs in Appendix 4.10. Measured by how ambiguous the scope is, the more ambiguity, the greater the demand for resources.

Like its product counterpart, **Regulatory Complexity** has a direct correlation with resource demands, with more complexity leading to more resource needs. Unlike "product complexity", the influence of "regulatory complexity" increases towards the end of the project, specifically in phases relating to documentation, as shown in Appendix 4.10.

Prior Knowledge's influence remains consistent throughout the project (shown in Appendix 4.10), except for the manufacturing phase, where all other factors are dwarfed by the influence of "product complexity".

RQ3

> *How might PDC teams enhance their understanding of the project planning process and their teams through the collaborative capture and modelling of their understanding?*

The initial development of the CoFIDE method represents an opportunity for PDC teams to capture and model their understanding (their perceptions) of the factors that influence the resource demands of their projects. Through the creation of MEPs and PIGs, PDCs can interpret the lines and bars of each factor's influence visually, quickly identifying the behaviour of each factor.

5. Case 2

> *"Brainstorming, ironically, is a structured way of breaking out of structure. It takes practice."*
> *-- Tim Brown*

5.1 Introduction

5.1.a Background

The over-arching aims of Case 2 are to address the research questions stated in the literature review and consider the improvements to the CoFIDE method proposed in case 1. Case 2 was conducted between September 2017 and January 2018 with a Glasgow-based Product Design Company with experience in developing products in a diverse range of fields, referred to in this study as Design Company B (DCB). DCB has a team of six designers and a Studio Manager, all with varied levels of experience in the industry and with degrees in Product Design Engineering or Product Design. This study is comprised of four workshops, all of which were conducted in the offices of DCB. The number of participants included in each workshop was determined by the types of data gathered, with initial background information (design process, resource types, etc.) and estimation tool evaluation only requiring participation with the company director and office manager. A list of participants for each workshop is included in Table 34.

Table 34 Case 2: Workshop Participant Breakdown

Workshop	*Participants*
1	Company Director & Office Manager
2	All team members
3	All team members
4	Company Director & Office Manager

5.1.b Role of Researcher

The role of the researcher in this case remains as stated in Chapter 3, acting as a facilitator during workshops and collecting, collating and analysing the data generated from them. As some questions were asked during Case 1 about the process, the researcher adjusted the delivery of instruction to improve the clarity of the activities prescribed. A reflection on the researcher’s role is included in the conclusion of this chapter.

5.2 Changes to Experimental Approach

This section will discuss the changes made to the approach taken during this multiple round quasi-experimental case-based approach. These changes are based on the findings and outcomes of Case 1 and the process that will be applied to Case 2. The following sub-sections will outline each phase of the CoFIDE process based on the IDEF0 activities described in Figure

29 and expanded upon in Appendix 5.1 – 5.5. A phase-based breakdown of the experimental process is presented in Table 35. The sections will continue to follow the same step method outlined in the approach section of the Case 1 chapter. This section will only discuss the changes made to the approach and the differences between it and the Case 1 experimental approach.

1. Preliminary Discussion

The aim of this phase remains the same as that of the approach to Case 1. During the preliminary discussion, the capture of the participants' design project process has been updated to reflect the diagrammatic nature of its approach. The design process is now mapped, which enables the researcher to better capture this process information, but also allows the participants to have a visual context for the future activities in this study. The remaining steps of this phase remain the same as in Case 1.

2. Workshop 1

Workshop 1 concludes the remaining stages of the Design Process and Factor Identification (Figure 29). The workshop will be conducted with every member of the design consultancy in an informal brainstorming session. These steps remain the same as the Case 1 method, except for the factor selection activity. Based on observations made during Case 1, a public vote to decide which factors had the greatest influence lead to participants having their opinions influenced by others in the group. Furthermore, the sticky dot approach does not add any weighting to the votes. This was an issue during Case 1, where one of the junior members of the design team had to make a tie-breaking decision, which again could have been swayed by the other participants. Therefore the voting of influential factors is now a private activity, with participants asked to rank-vote the factors in order of believed influence.

3. Interim Phase 1

The activities of the first interim phase remain the same as in Case 1. However, based on observations of Case 1 participants, the number of influential factors to be examined was reduced from 5 to 4, this in turn reduced the number of experimental runs from 16 to 8 to reduce participant fatigue during Workshop 2.

7. Workshop 4

This phase seeks to develop a multi-level factor scoring system. This is done by recalling the elements that were used to develop the factors in workshop 1. From this, a range of elements are selected or synthesised that are observable and ideally measurable. Point spreads for each factor are calculated based on the number of elements and all factors and their corresponding elements are collated into a scoring system.

Case 2

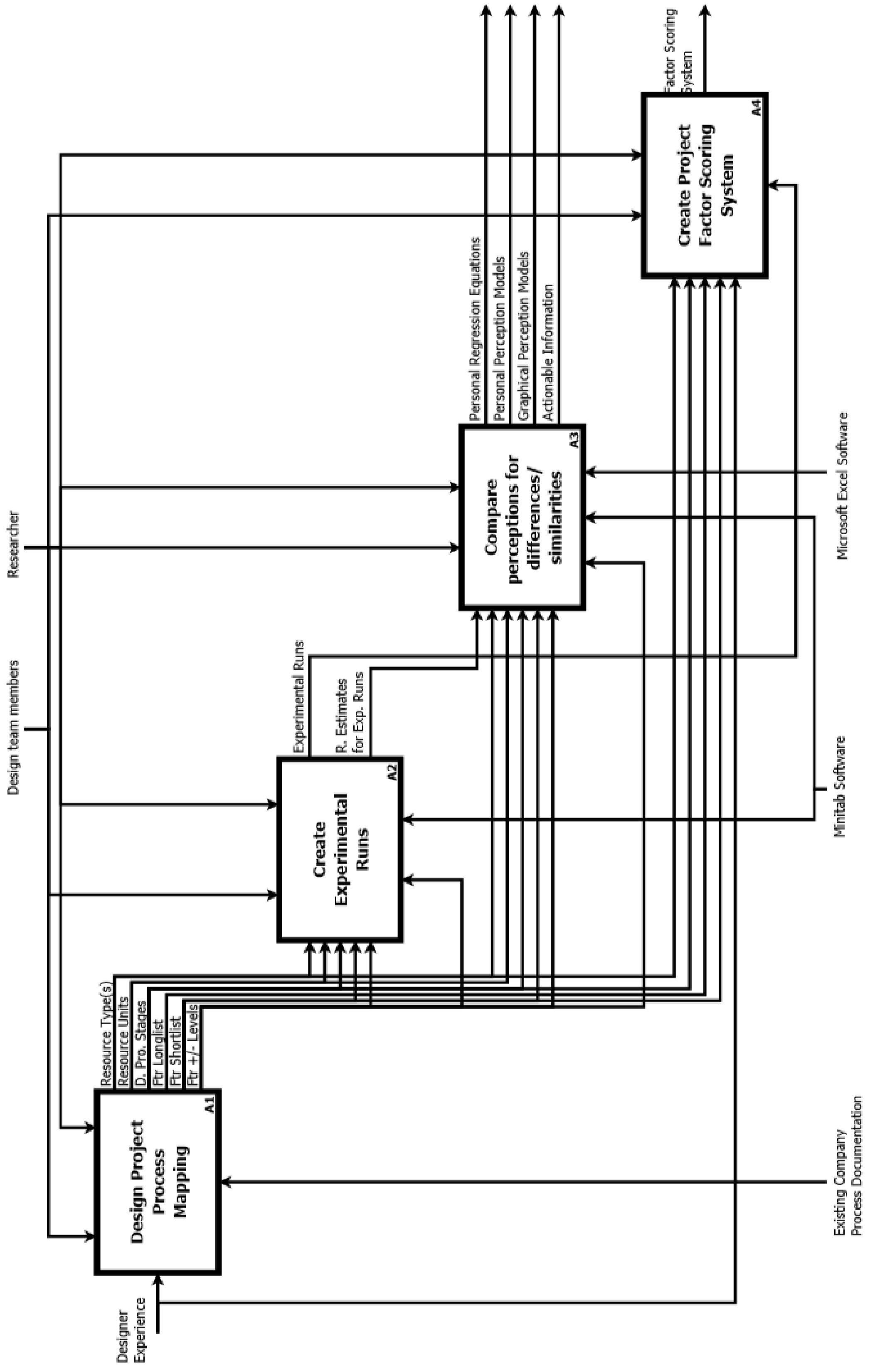


Figure 29 Case 2: Approach – IDEF0 Model

Table 35 – Case 2: Approach – Case 2 Method

Case Phase	Purpose (Identification, collection, etc.)	People Required	Outcomes	Mapped DOE Stage
1. Preliminary Discussion	Identify key elements of product design projects at participant company.	R / M	Suitable key resource(s) of future design projects. The design process followed by participant company.	*Describe*
2. Workshop 1	Identify key influential factors on project resource and their maximum / minimum values.	R / M / T	Key factors which influence resource(s) level Hypothetical viable max/min factor levels.	*Describe*
3. Interim Phase 1	Generate experimental design with identified factors and levels	R	Template experimental design	*Design*
4. Workshop 2	Collect experimental data (participant estimates) using template	R / M / T	Participant estimates (1)	*Collect*
5. Interim Phase 2	Generate regression equations for participants Create regression models for each participant based on regression equations Build comparison graphs of regression models	R	Regression equations, Participant regression models, Comparison Graphs	*N/A*
6. Workshop 3	Gain insight into participant's views on comparison graphs	R / M / T	Feedback on process Feedback on comp. graphs	*N/A*
7. Workshop 4	Create a multi-level factor scoring system based on the elements of the factors discussed in Workshop 1.	R / M / T	Factor Evaluation Scoring Scheme	*N/A*

R: Researcher, M: Management, T: Team

Workshop 4: Step 1

As a group, the participants were tasked with discussing and recording all possible features which could contribute towards a given factor through collaborative brainstorming. As an example, it was suggested to the participants that for the factor of Product Complexity, such features could be the number of parts, number of disciplines needed for development, etc.

There were three limitations placed upon this identification task.

- Any feature should be identifiable by the participants from the project's outset.
- All features should be ideally quantifiable, or at least objectively assessable so that anyone can evaluate a new project and get the same complexity scoring.
- These features should relate to the product being designed (product-centric), rather than the project itself (project-centric), i.e. for the Product Complexity factor, a need for a PCB, rather than, geographic locations of PCB manufacturers.

Workshop 4: Step 2

Participants were instructed to discuss which features have the greatest influence over Product Complexity. The output of this discussion should be a shortlist of the top four or five features.

Workshop 4: Step 3

Similar to that of Workshop 1, the participants were instructed to define four levels for each of the features through collaborative brainstorming. Guidance was given to the participants that this range of levels should be distinguished clearly and easily. These levels should fall into a table like the one below, where each level or range will have a corresponding score. Once defined, each factor and its features should be compiled into a table, an example of which is shown in Table 36.

Table 36 Case 2: Example of FESS Scoring Table

Feature	1	2	3	4
Feature 1	Level 1	Level 2	Level 3	Level 4
Feature 2	Level 1	Level 2	Level 3	Level 4
Feature 3	Level 1	Level 2	Level 3	Level 4
Feature 4	Level 1	Level 2	Level 3	Level 4

An overview of the changes made to the experimental process is shown in Figure 30. Additional changes are anticipated for Case 3, where the inclusion of the FESS development will be moved earlier in the process to coincide with the identification of the influential factors and their minimum and maximum levels.

5.3 Case Results

5.3.a Resources and Project Stages (Preliminary Discussion)

Preliminary discussions took the form of an informal semi-structured interview, held with the Studio Manager and the Company Director as they were responsible for the organisation of staff and the billing of clients. From which, it was determined that “person-hours” would be the most appropriate unit of measure for design effort as this matched the resource used when billing clients. The company director requested that this resource be split into two: Designer-Hours and Project Management-Hours to reflect the two types of work conducted during projects that may be conducted by different members of the design team. Furthermore, it was agreed that there are six main stages for each design project, each with its own assigned tasks, shown in Table 37.

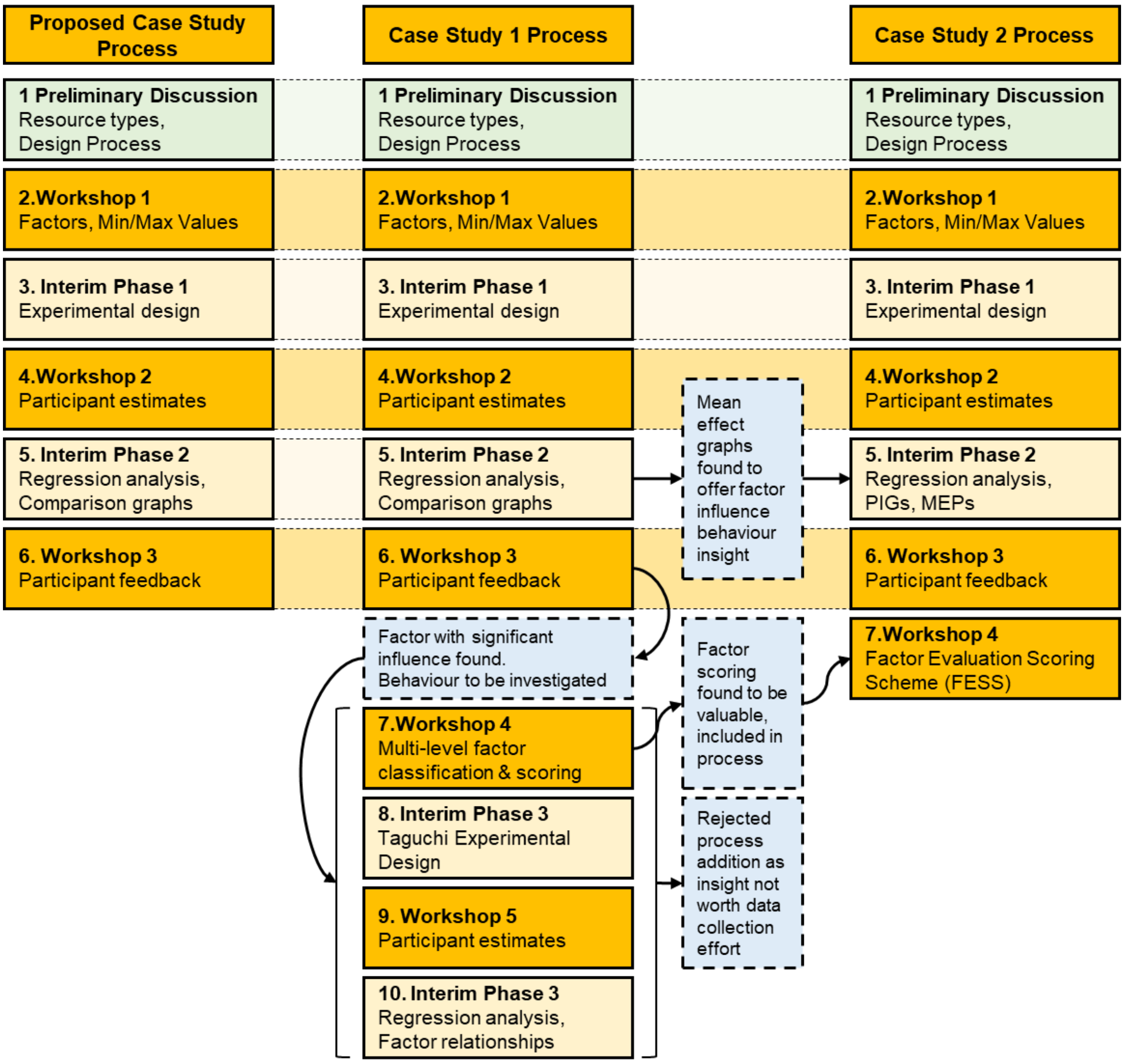


Figure 30 Case 2 - Changes to Experimental Process for CS2

Table 37 – Case 2: DCB Design Project Stages

Stage	***Example Tasks***
Pre-sign off	Client contact and meetings
Discover	Feasibility, user research, project direction
Define	Product specification and project planning
Design	Mood/Focus boards, Storyboards, Sketches, Concept presentation, CAD, coding boards, renders etc.
Detail	Detailed CAD, Renders, Animations, BOM, Prototype(s), Electronics creation and testing, Prototypes iteration Golden samples. Contact manufacturers.
Deliver	Working with manufacturers, handover, packaging design etc.

5.3.b Factors (Workshop 1)

During the collaborative semi-structured brainstorming activity, the factor identification task required participants to create an exhaustive list of every factor that may influence the number of person-hours a project would require for any or all phases of a design project. During the informal discussion and brainstorming session between all the participants, and unprompted by the researcher, the participants approached the task by addressing each design project phase, identifying those factors that influenced each respectively. Doing so created seven distinct categories, one for each stage, plus one for factors which affected more than one, or all of the stages. The DCB participants proposed forty different factors (shown in the right-hand column of Table 38) and then regrouped into ten (10) different categories, shown in the left-hand column of Table 38. This clustering process helped identify some similar terms which had been applied to separate stages of the design process and allowed for common themes to be established. The stage-by-stage process allowed the participants to formally define each of the clustered factors by the varied ranges of terms for similar factors. However, this process also allowed for some terms to be suggested that were activities/tasks, rather than factors, these have been placed in parenthesis in Table 38. Future cases will see this approach formalised within the tasks, with the researcher overseeing the process to edit any suggestions which are not factors.

To avoid the inter-participant influence observed during the key factor selection process in Case 1 participants were asked to independently and privately select what they considered to be the top four (4) most influential factors, shown in Table 39. The participants were further asked to rank these factors from most influential to least. These votes were then counted to not only capture what was collectively perceived to be the most influential, but also the perceived ranks of each subsequent factor, shown in Table 41. As *Delivery Output Complexity* and *Designer Experience* received the same number of votes, the participants decided that *Delivery Output Complexity* was more influential, concluding that the top four most influential factors were *Client "Gut Feeling", Definition Level Inputs, Product Complexity* and *Delivery Output Complexity*. was a more effective voting system, eliminating the potential influences of the "sticky dot" selection method and also capturing the ranked order of the factors per participant.

Participant Supplied Factor Definitions

Client "Gut Feeling" was defined by the DCB's participants as the intuition had of a client, their personality, and other client-centric issues. Definition Level Inputs was defined as the degree of clarity the initial information provided to DCB by the client, i.e. how detailed is the brief. Product complexity was defined as the perceived degree of complexity the product will likely have. Delivery Output Complexity was defined by the participants as being the level of complexity the project outcome was, i.e. the number and location manufacturers involved, the manufacturing processes involved, etc.

Table 38 – Case 2: Grouped Factors for Person-hour influence in Design Projects

Grouped Factor Name	Factors
Client "Gut Feeling"	Client experience Judge of character Scope alignment Client "hand holding" Willingness to compromise Scope Creep Client Expectations Client's motivation for product Laws of physics Decision making chain Client responsiveness Client management Curveballs and interruption University research project
Development Budget	Budget Knowing budget Funding
"Stuff" Happens	Hardware issues Distractions Personality Traits Holiday & Illness Bad day Team Efficiency Current resource of team
Definition Levels (Inputs)	How developed the brief is Key milestones Defined market Critical milestones
Regulatory Complexity	Regulatory Complexity
Geography	Supplier proximity Travel time/proximity Environmental parameters
Designer Experience	Designer Experience User research Sketch/Ideation CAD/Technical Project Management Fusion/Solidworks Motivation Presentation putting together New people Material Knowledge Manufacturing Knowledge
Product Complexity	No. of unique parts / Standard components Prototypeability IP Testing Novelty Complexity Rendering Functional requirements Build time Types of parts/mechanism
Delivery Output Complexity	Supplier risk factor Chinese New Year Supplier liaison Product Budget Volume of product Material diversity Process diversity
Communication complexity	Communication No. of stakeholders No. of subcontractors

Table 39 – Case 2: Factor Influence Voting (Round 1)

Group Factor	Votes
Client Gut Feeling	5
Product Complexity	5
Delivery Output Complexity	5
Definition Level Inputs	4
Designer Experience	4
Communication Complexity	3
Development Budget	1
"Stuff" Happens	0
Regulatory Complexity	0
Geography	0

Case 2

To build the experimental designs, high and low levels for each of the top factors were collaboratively established by the design team, shown in Table 40. The top initial constituent components of the *Client Gut Feeling* and *Definition Level (input)* factors were used to aid the construction of a four-point checklist, informing the characteristics of the different levels of each factor.

Table 40 Case 2: Factor Minimum and Maximum Levels

Factor	**Levels**	
	Low Level	**High Level**
Client "Gut Feeling"	1	4
Definition Level (Inputs)	1	4
Product Complexity	Simple	Complex
Delivery Output Complexity	Low	High

Table 41 – Case 2: Factor Influence Voting Scores (Round 2)

Grouped	**Votes**					**Score**					**Total Score**
Factor	**1**	**2**	**3**	**4**	**5**	**5**	**4**	**3**	**2**	**1**	
Client Gut Feeling	3	0	0	2	0	15	0	0	4	0	19
Product Complexity	0	3	1	0	2	0	12	3	0	2	17
Delivery Output Complexity	2	1	0	0	2	10	4	0	0	2	16
Definition Level Inputs	0	2	1	1	1	0	8	3	2	1	14
Designer Experience	1	0	1	3	0	5	0	3	6	0	14
Communication Complexity	0	0	2	0	1	0	0	6	0	1	7
Development Budget	0	0	1	0	0	0	0	3	0	0	3
"Stuff" Happens	0	0	0	0	0	0	0	0	0	0	0
Regulatory Complexity	0	0	0	0	0	0	0	0	0	0	0
Geography	0	0	0	0	0	0	0	0	0	0	0

Table 42 Case 2: Experimental Design

Run	**Client "Gut Feeling"**	**Definition Level (Inputs)**	**Product Complexity**	**Delivery Output Complexity**
1	-1	-1	-1	-1
2	1	-1	-1	1
3	-1	1	-1	1
4	1	1	-1	-1
5	-1	-1	1	1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	1

Adding the collated data collected in the previous activities, a half factorial experimental design was generated using the Design of Experiments tool within Minitab. This was combined with the six project phases identified in the preliminary work, to create the Estimation Sheet for Workshop 2 – Collect Phase, shown in Table 43.

Table 43 Case 2: Workshop 2 Estimation Sheet

Run	**Client "Gut Feeling"**	**Definition Level (Inputs)**	**Product Complexity**	**Delivery Output Complexity**		**Pre-sign off**	**Discover**	**Define**	**Design**	**Detail**	**Deliver**
1	1	1	Simple	Low	Management						
					Design						
2	4	1	Simple	High	Management						
					Design						
3	1	4	Simple	High	Management						
					Design						
4	4	4	Simple	Low	Management						
					Design						
5	1	1	Complex	High	Management						
					Design						
6	4	1	Complex	Low	Management						
					Design						
7	1	4	Complex	Low	Management						
					Design						
8	4	4	Complex	High	Management						
					Design						

5.3.d Participant Estimates (Workshop 2)

Each member of DCB's design team were gathered in the conference room of DCB's offices, each were given print outs of the estimation sheet for them to record their estimates by hand during a semi-structured workshop (Workshop 2). The recorded responses from five members of DCBs design team were input into a spreadsheet by the researcher and can be found in Appendix 5.6. The estimation activity took less than one hour to complete, with the quickest completion taking thirty-five minutes.

5.3.e Regression Equations (Interim Phase 2)

Each participant's estimation values (recorded by hand on their estimation sheets) were added to a spreadsheet and using the Design of Experiments regression analysis tool within the statistical analysis software Minitab to produce a set of sixty regression equations, 12 for each participant predicting each phase of the project for both design time and management time. As the experimental design is a half-factorial, not all inter-factor relationships can be modelled, those of *Definition Levels (inputs)* x *Product Complexity*, *Definition Levels (inputs)* x *Delivery Output Complexity*, and *Product Complexity* x *Delivery Output Complexity*. Each participant's regression equations are outlined in Appendix 5.6 and are translated into an equation using Equation 1 as a template, where "n" is the corresponding value in the table. The factors are labelled: A. *Client "Gut Feeling";* B. *Definition Level (Inputs);* C. *Product Complexity;* D. *Delivery Output Complexity*.

$$Output = \ Constant \ + n_A A + n_B B + n_C C + n_D D + n_{AB} AB + n_{AC} AC + n_{BC} BC + n_{BD} BD + n_{CD} CD$$

Equation 1

5.3.f Graphical Representation of Data (Interim Phase 2)

The graphs produced to represent the findings of the data analysis for this study take two forms. The first describes the percentage of influence each factor has over the regression equation of each participant, to compare factors. These graphs depict which factors have the greatest levels of influence over the phase length.

The second set of graphs shows the mean effect plots from each participant's regression equation, for each project phase, for each factor. These graphs allow for the identification of trends in influence, whether it is an increase or decrease in a given factor will positively or negatively influence the number of hours for each project phase. These graphs also allow for a consensus to be formed from these trends, the magnitude of influence, and the identification of participants who disagree with the consensus.

5.3.g Percentage Influence Graphs

For percentage influence graphs, the values for each of the regression equations was imported to a spreadsheet, separated by each project phase, and the coefficient values for each part of the equation were separated into columns. The coefficient values for each section of the equations were totalled, and then presented as a percentage of total influence per participant.

Case 2

This describes the percentage of influence each factor has over the regression equation of each participant, to compare factors. These graphs depict which factors have the greatest levels of influence over the phase length. The percentages shown in each graph are the percentage of influence each factor has over the output of the corresponding regression equation. It determines which factor has the most influence. It does not show the percentage of influence in comparison to the regression equation's coefficient, as this would not allow for comparison between two different regression equations (i.e. comparison between different participants). Percentage Influence Graphs in bar chart form are included in Appendix 5.7. The following graphs (Figure 31 - Figure 39) depict the changes in levels of influence throughout a product design project. This section includes graphs showing the changes in percentage influence (according to each participant's regression equations) as design projects progress. Each series in these graphs represents a participant, i.e. "Series 1" represents Participant 1.

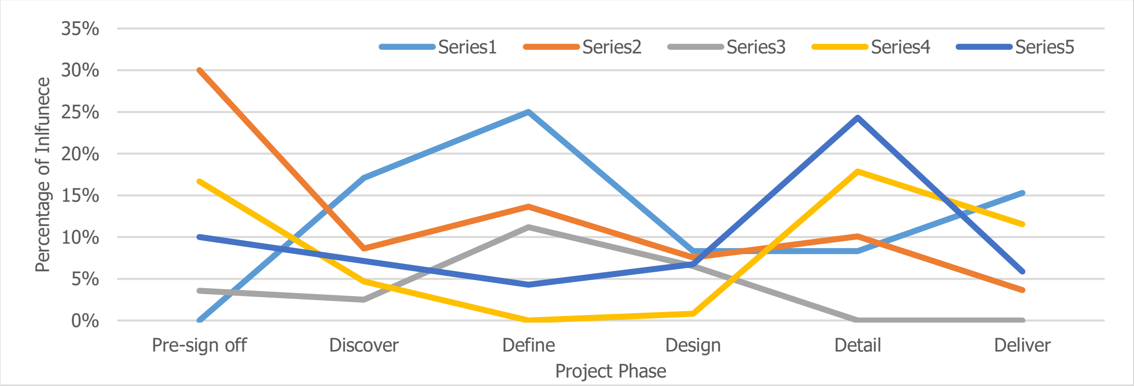


Figure 31 Case 2: Changes in Percentage Client Gut Feeling influence on Design Effort levels for Design activities

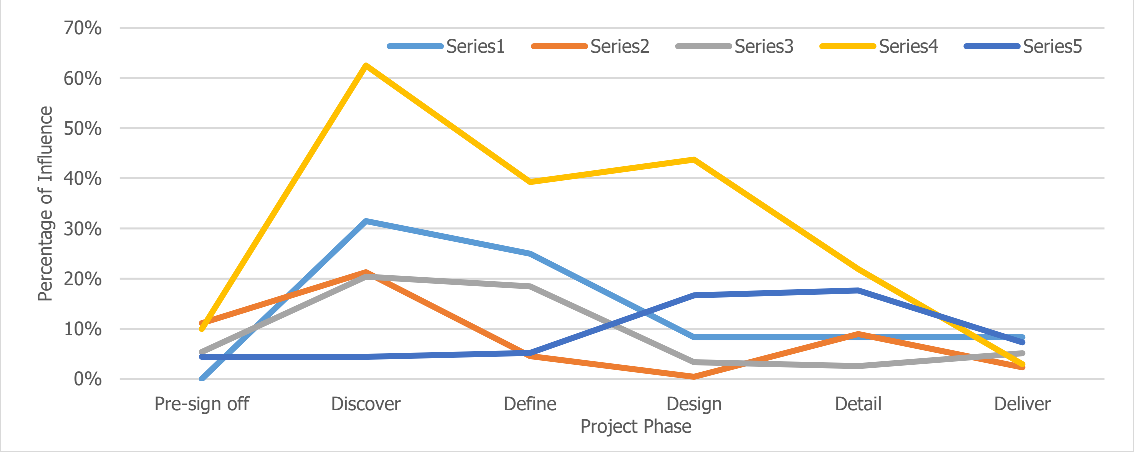


Figure 32 Case 2: Changes in Percentage Definition Levels influence on Management Activity Design Effort Levels

Case 2

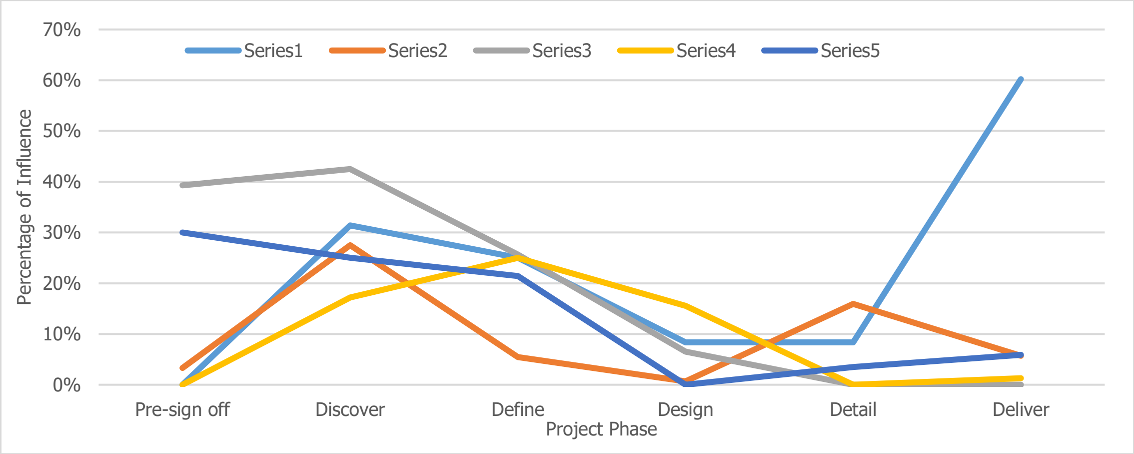


Figure 33 Case 2: Changes in Percentage ***Definition Levels*** *influence on Design Effort Levels of Design Activities*

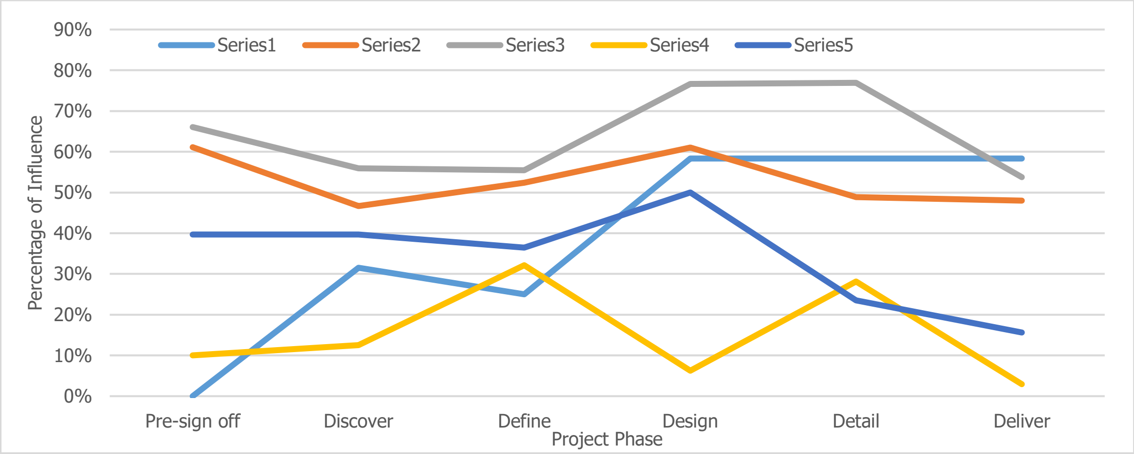


Figure 34 Case 2: Changes in Percentage ***Product Complexity*** *influence on Design Effort for Management Activities*

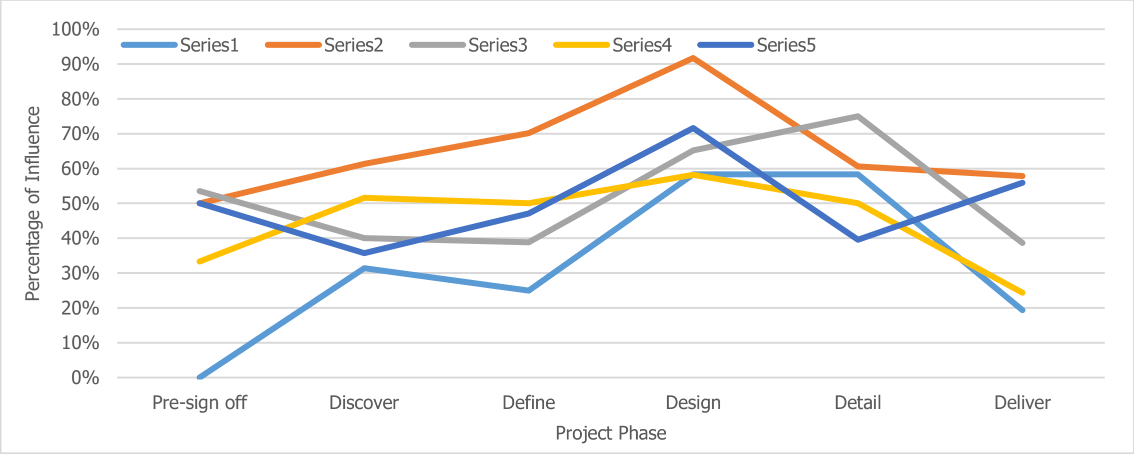


Figure 35 Case 2: Changes in Percentage ***Product Complexity*** *influence on Design Effort Levels for Design Activities*

Case 2

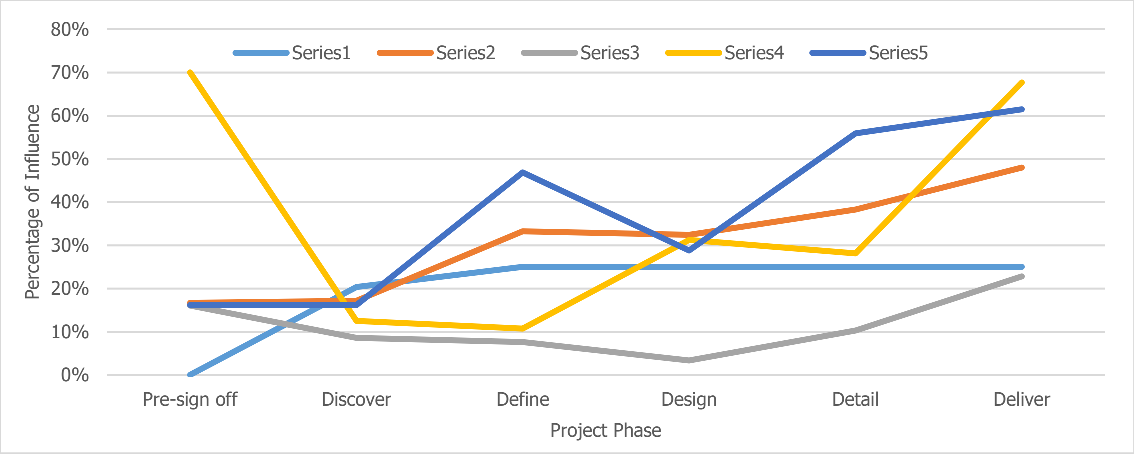


*Figure 36 Case 2: Changes in Percentage **Delivery Output Complexity** influence on Design Effort Levels for Management Activities*

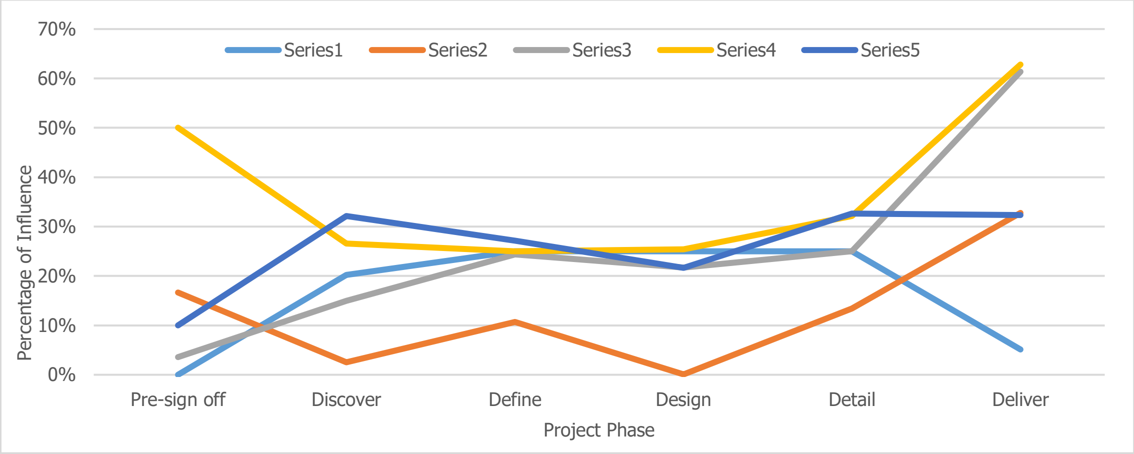


*Figure 37 Case 2: Changes in Percentage **Delivery Output Complexity** influence on Design Effort Levels for Design Activities*

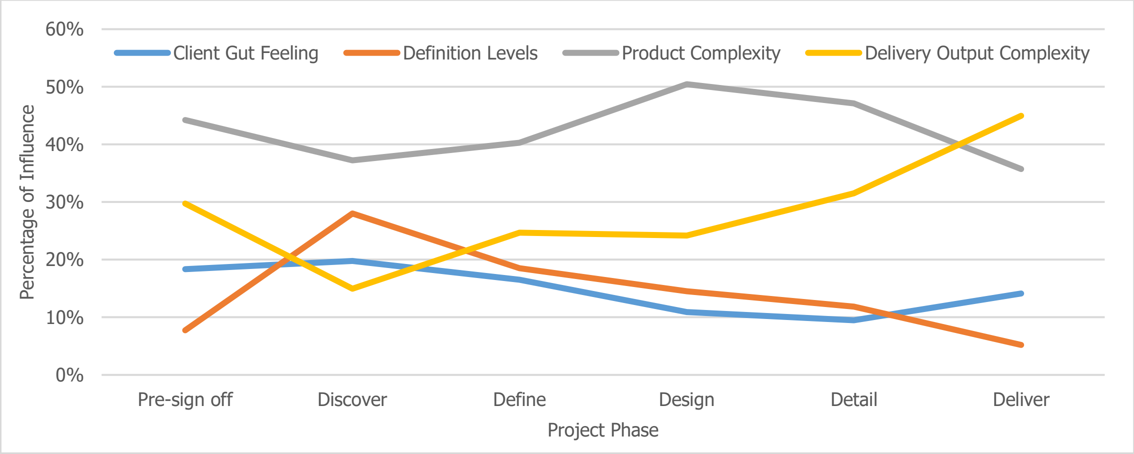


Figure 38 Case 2: Changes in Percentage of Factors' Influence on Design Effort Levels for Management Activities

Case 2

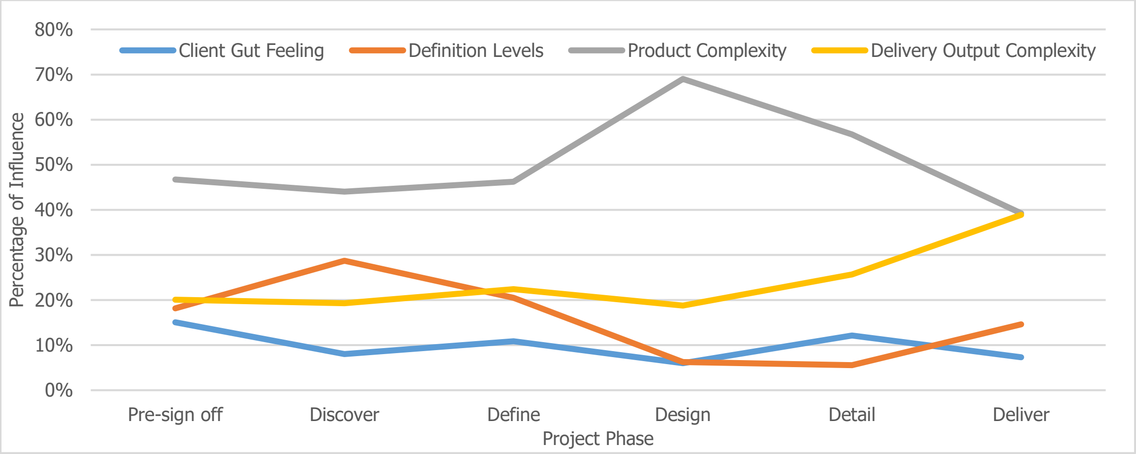


Figure 39 Case 2: Changes in Percentage of Factors' Influence on Design Effort Levels for Design Activities

5.3.h Mean Effects Plots

A mean effect plot illustrates the effect a single independent variable, in this case, a factor, has on the dependent variable, in this case, design effort levels and management resource needs, disregarding the effects of any other factor. The Mean effects values were calculated using the mean effect analysis tool in Minitab (Appendix 5.8), these were brought into a spreadsheet so that the Mean Effect Plots could be produced, shown in Appendix 5.9. These graphs illustrate the direction of influence each factor has on design effort levels, both management and design, where the gradient of the graph indicates both the correlation relationships of factors and design effort levels, but also the magnitude of said relationships. Each graph illustrates the mean effects of each participant for each factor and each project phase on design effort levels for both management and design activities.

5.3.i Participant Interviews & Reflections (Workshop 3)

A series of one-on-one interviews, each recorded with the permission of the corresponding participant, were held in the DCVB's offices. These interviews were semi-structured, allowing each participant to discuss their estimations and the insight offered by the graphs and diagrams. This section presents the findings from these discussions.

Estimation Task - Participant's Approach to the Task

A common approach to completing the estimation task was to take a single project - a single experimental run (typically the first run) and make estimations for the design and management requirements for each of the design phases, in order. This is considered to be a *project-centric approach*.

An alternative to the *project-centric approach* sees participants identify a baseline project, making estimations for each of both the design and management requirements for each of the design phases, in order. From which all other estimations are based, applying a positive or negative (i.e. better or worse) association with each project and estimating all requirements accordingly. This is considered to be a *baseline project-centric approach*.

Participant 2, a company director, is responsible for the new business development, the co-creation of project briefs and participates in the planning of all projects for the business also used a variant of the *project-centric approach*. By considering the overall billable value of a project, Participant 2 would assign a baseline budget for each project based on the "delivery output complexity" and would add, or subtract from that budget, based on the other factors. They suggested that if the project were to be perceived as difficult, then the cost of the project would be increased. For example, a £10k project would be "taxed" to £15k is considered to be difficult. The person-hours estimation would be calculated based on the project cost, at a ratio of 10% management, 90% design for simple projects, 20% management, and 80% design for complex projects. This is considered to be a *project cost-centric approach*.

Participant 3, a design director for the consultancy, is responsible for the planning and oversight of all design projects, also applied a variant on the *baseline project-centric approach*, whereby they identified the best and worst projects in the experimental design and selected past projects which would act as the exemplars for the estimation process. These were used as the maximum/minimum estimates from which all other estimations would be evaluated. Yet they also constrained all the experimental runs to a budget range of £10k to £80k, as projects under or over these prices would require a different approach to their planning. This combined approach is to be considered a *project parameter cost-centric approach*. [or a *bounded project cost-centric approach*].

Participants 3, 4 and 5 all used specific past projects and their experiences of each project, as examples for some of the experimental runs. This was to offer needed context to the estimation process. This context helped the participants who were unable to complete the estimation tasks based on the given information (the factors and their levels), due to the degree of abstraction.

Warm-ups

Many of the participants felt that they needed to complete a few projects (experimental runs) to "warm up", allowing for the remainder of the task to be completed faster. Participants stated that this allowed them to acquire a specific "frame of mind" to allow them to scrutinise each experimental run to the degree needed. It should be noted that the participants who self-identified as having less experience, were also the participants who believed that they needed to "warm up" during the task.

Completion Confidence

Participants were asked to evaluate their confidence in the estimations that they provided in the previous workshop. The levels of confidence of each participant varied. Most were confident with some parts of their estimations, while unsure, or less confident in others, as illustrated in Table 44. The term "Neutral opinion" means that the task was perceived as being neither easy nor difficult to complete.

Graphs Review

A note on estimation data processing

The sets of estimations completed by each participant were processed using the statistical-analysis software *Minitab 17.0* to produce a set of personal regression equations for each project phase and mean effect plots of each factor.

Table 44 Case 2: Estimation Task Confidence Levels

Participant	**Level of Perceived difficulty**	**Confidence Level**	**Caveat**
1	Unspecified	Confident	Should add an additional week to each estimation of the design phase
2	Neutral opinion	Unknown	N/A
3	Neutral opinion	Confident	Confident in relative values (the differences between each estimation), not confident in specific values.
4	Difficult	Confident	Possible consistent over-estimation. Task difficult due to lack of design experience.
5	Difficult	Unsure	N/A

Agreement with data presented in graphs

Each participant was asked to evaluate two sets of graphs, the percentage of influence on project phase length of each of the factor coefficients as shown in Appendix 5.7, and the mean effects plots of each participant's perception of each factor, are shown in Appendix 5.9.

Of the five participants interviewed, three participants (participants 1, 2 and 4) agree that the relationships between each factor and project phase length represented in the graphs accurately reflect their personal opinions, or perceptions, with the remaining two participants (3 and 5) having some reservation over particular factor-phase length relationships.

Participant 5 believed that the factor-phase length relationships depicted do correlate with their own beliefs, sharing the same general angle as those of their colleagues. However, Participant 5 also believed that their responses might be more "anomalous" as they considered the estimation task from Workshop 2 to be a particular challenge.

Observations on Definition Level (Inputs)

Several participants made specific observations of the *Definition Level (Inputs)* factor. Participant 2 did not agree that the *Definition Level (Inputs)* has as much influence over the latter phases of a project, as all possible issues (ambiguity of brief, etc.) would be resolved before said phases started. Participant 3 disagreed with the level of influence modelled of *Definition Level (Inputs)* on the management predictions for the Design Phase, suggesting that by that point in the project, any issues with the brief have been resolved.

Observations on other factors

Participant 2 believed that the Management time of the Pre-sign off phase reduces as *Delivery Output Complexity* increases. As the client has a better understanding of what they want from a project, this is reflected in the level of the *Delivery Output Complexity.* Yet less effort (time) is required in the project management to establish what the output requirements are, hence lower Pre-sign off phase length.

Participant 3 was further surprised by the lack of influence their perceptions of *Product Complexity* have over the Detail and Deliver phases.

Use of graphs in future

Each participant was asked about the utility of the graphs shown to them, whether they found, or could find, any use for the relationships and correlations between factor levels perceived by themselves and their colleagues.

Of the five participants, four believed that the graphs offered some insight into the way that they perceive the different factors.

Of the five participants, two (Participants 1 and 5) believed that the graphs provided some insight into their own perceptions, offering an understanding that they did not consciously have before. Both Participants 1 and 5, along with Participant 4 (3 of the 5 participants) make up the 60% of participants that stated that they gained insight into how other members of their team perceived project planning.

60% of participants believed that the information provided by the graphs could be used to aid in unspecified future managerial decision-making, with one participant (20%) stating that such information could help inform future team construction, qualifying that this would be of greater use when the designer team is larger. The findings of the participant reflection on these graphs is shown in Table 45.

5.3.k Factor Evaluation & Scoring Scheme Outcome (Workshop 4)

The level of each feature will correspond to a score (1 through 4) which dictates the lowest and highest possible score corresponding to the number of features. For example, if a factor has six features, the lowest score is 6 and the highest score is 24. With this example, this would result in a range of potential scores of 18. This range would be evenly divided up into four, which would give the participants score ranges for each of the four levels of a factor. Based on the previous example, this would result in a score spread, illustrated in Table 46.

Table 45 Case 2: Utility of personal perception graphs in future work

Participant	**1**	**2**	**3**	**4**	**5**	**Percentage**
Insight (personal)	x				x	40%
Insight (colleagues)	x			x	x	60%
Ability to identify another participant by their graphs	x	x		x		60%
Managerial decision-making (unspecified)		x	x		x	60%
Managerial decision-making (team creation)			x			20%

Table 46 Case 2: Example of Factor Score Ranges

Factor Level	**I**	**II**	**III**	**IV**
Factor Score Range	6 to 10	11 to 15	16 to 20	20 to 24

Definition Levels

The participants determined that there are six features which contribute to the Definition Levels factor, detailed in Table 47.

Knowledge of User/Market

Knowledge of User/Market refers to the level of understanding that the client has of the end user of the product and the market the product is intended for. The level of definition ranges from the client having a complete absence of knowledge to a complete understanding of the user and the target market. According to the participants, the lower the score of this feature, the more time is necessary to gather the relevant information on the end user and the target market.

Table 47 Case 2: Definition Levels Factor Scoring Table

Feature	**1**	**2**	**3**	**4**
Knowledge of User/Market	No Definition	Some defined	Mostly Defined	Fully Defined
Knowledge of Technology	No Definition	Some defined	Mostly Defined	Fully Defined
Knowledge of Commercials	No Definition	Some defined	Mostly Defined	Fully Defined
Knowledge of Regulation and IP	No Definition	Some defined	Mostly Defined	Fully Defined
Definition of required outputs	No Definition	Some defined	Mostly Defined	Fully Defined
Level of definition of timeline	No Timeline	Timeline but no milestones	Some milestones defined	All milestones defined
Definition Level Score	I	II	III	IV
Definition Level Range	6 to 10	11 to 15	16 to 20	20 to 24

Knowledge of Technology

Knowledge of Technology refers to the level of understanding that the client has of the technology (or technologies) required for the product, or the creation of the product. The level of definition ranges from the client having a complete absence of knowledge to a complete understanding of all relevant technologies. According to the participants, the lower the score of this feature, the more time is necessary to gather the relevant information on potential technologies.

Knowledge of Commercials

Knowledge of Commercials refers to the level of understanding that the client has of the commercial elements of the product, including product development and other parts of the product lifecycle. The level of definition ranges from the client having a complete absence of knowledge to a complete understanding of all commercial elements. According to the participants, the lower the score of this feature, the more time is necessary to gather the relevant information on commercial elements.

Knowledge of Regulation and IP

Knowledge of Regulation and IP refers to the level of understanding that the client has of the government legislation, governing body standards, etc. and the intellectual property, patents, etc. which may influence all elements of the product lifecycle. According to the participants, the level of definition ranges from the client having a complete absence of knowledge to a complete understanding of all regulations and IP. The lower the score of this feature, the more time is necessary to gather the relevant information on regulations and IP.

Definition of required outputs

Definition of required outputs refers to the level definition the client has specified the project to have from the project's outset. The level of definition ranges from a complete absence of definition to all necessary specifications fully. According to the participants, the lower the score of this feature, the more time is necessary to gather the relevant information on the end user and the target market. The lower the score of this feature, the more time is necessary to define the deliverables of the project.

Level of Definition of Timeline

Level of Definition of Timeline refers to the level of planning detail the client has specified in the brief. The level of definition ranges from no structured plan to a fully specified set of project milestones. According to the participants, the lower the score of this feature, the more time is necessary to define the timeline for the project.

Client "Gut Feeling"

The participants determined that there are five features which contribute to the Client "Gut Feeling" factor, detailed in Table 48.

Table 48 Case 2: Client "Gut Feeling" Levels Factor Scoring Table

Feature	**1**	**2**	**3**	**4**
Level of experience	No experience	On paper	In practice	Master
Team setup	Individual inventor	Start-up	SME	Corporate
Personality	Bad	More bad than good	More good than bad	Good guy
Funding Level for project	Seeking funding	Funds up to prototype or feasibility	Funds up to develop not launch	All funds available for develop and launch
Level of additional engagement required	2 - 3 engagements per week	1 engagement per week	1 engagement per month	End of Phase or set review point only
Definition Level Score	I	II	III	IV
Definition Level Range	5 to 8	9 to 12	13 to 16	17 to 20

Level of Experience

Level of experience refers to the level of experience the client has in developing projects. The measurement of experience ranges from no experience to a seasoned developer of products, with a high level of experience. According to the participants, the lower the score of this feature, the more time is necessary to explain the project phases, the tasks involved in product development, etc. to the client.

Team Setup

Team Setup refers to the composition of the client team. This ranges from a single person, or individual inventor, to a large-scale company. According to the participants, the lower the score of this feature, the more time is necessary to convince the client of decision-making. This is due to the level of "emotional investment" the client has for their project, where an individual inventor has a high level of "emotional investment".

Personality

Personality refers to how the client's character is perceived. According to the participants, although this is a subjective element, they believe that a poor personality can be easily identified. The participants stated that the worse the personality, the longer the project takes for several nuanced reasons.

Funding Level of Project

Funding Level of Project refers to the amount of money, or agreements for payment, that are in place from the project's outset. This ranges from the client still pursuing funding, to all funds being available from the project's outset. According to the participants, this feature can impact a project's overall length, as any deficits between available and required funding may cause delays and even halts project progress.

Level of Additional Engagement Required

Level of additional engagement required refers to how frequently the client wishes to conduct meetings to be informed of a project's success. This ranges from multiple times a week to only when a phase of the project has been completed. According to the participants, the lower the level of this feature, the more time has to be spent on bureaucratic project tasks, such as organising meetings, preparing briefing documents, etc.

Delivery Output Complexity

The participants determined that there are five features which contribute to the Delivery Output Complexity factor, detailed in Table 49.

Outsourced or in-house

Outsourced or in-house refers to the level of product development that needs to be done by third-party suppliers, such as specialist manufacturers, etc. This ranges from the project completion completely in-house to fully outsourced. According to the participants, the higher the score, the more time is spent identifying suitable third parties, communicating with them and waiting for files, samples, etc. to be sent to and from them.

Table 49 – Case 2: Delivery Output Complexity Levels Factor Scoring Table

Feature	**1**	**2**	**3**	**4**
Outsourced or in-house	Fully in-house	Mostly in-house	Mostly Outsourced	Fully Outsourced
No. Subcontractors/suppliers	0	1	2 or 3	3 +
No. Outputs/Deliverables	0	1	2 or 3	3+
No. Materials/Processes	0	1	2 or 3	3+
Tolerance Stack	Some parts - loose	Some parts – tight	Multiple parts - loose	Multiple parts - tight
Regulatory requirements	No regulation	Standard (CE)	Set Regulation in house testing	Set Regulation external test house
New or Prior Knowledge to Consultancy	Master	In practice	On paper	No experience
Definition Level Score	I	II	III	IV
Definition Level Range	7 to 12	13 to 17	18 to 22	23 to 28

No. Subcontractors / Suppliers

No. Subcontractors / Suppliers refer simply to the number of third parties that are involved, or likely to be involved, in product development. This can impact the project duration in similar ways to those stated in the outsourced or in-house feature.

No. Outputs / Deliverables

No. Outputs / Deliverables refers to the number of different outputs or deliverables the project has. According to the participants, as the number of outputs/deliverables increases, so too will the project length.

No. Materials / Processes

No. Materials / Processes refers to the number of different materials and the number of development and manufacturing processes required for the product's development and production. According to the participants, as the number of Materials / Processes increases, so too will the project length.

Tolerance Stack

Tolerance Stack refers to the level of tolerances required by the product. This ranges from a single part, with loose tolerances, to multiple parts with tight tolerances. According to the participants, the higher the level of required tolerances, the more time the project will require in order to maintain a strict level of tolerances.

Regulatory Requirements

Regulatory Requirements refer to the number of requirements and the severity or specificity of the requirements required for the development of the product. Ranging from no regulations to a high number of tight regulations that require external testing to determine conformity. According to the participants, the higher the level of regulatory requirements, the more time the project will require to fulfil all requirements mandated by the regulations.

New or Prior Knowledge to Consultancy

New or Prior Knowledge to Consultancy refers to the level of familiarity that DCB has with the types of specified outputs, the processes involved and the other contributing features to the *Delivery Output Complexity* factor. As an example, according to the participants, if a product has a high level of regulatory requirements, the impact that feature has on project length is modified by the level of experience the DCB staff has on achieving said requirements.

Product Complexity Levels

The participants determined that there are five features which contribute to the Product Complexity factor, detailed in Table 50.

Table 50 – Case 2: Product Complexity Levels Factor Scoring Table

Feature	**1**	**2**	**3**	**4**
Number of parts	1	Up to 5	Up to 30	30 +
Static of Dynamic	Fixed	Fixed with some moving parts	Fixed with lots of moving parts	Moving with lots of moving parts
Electronics to be developed	None	Yes, no UI/UX	Yes, UI/UX (buttons and screen)	Yes, UI/UX, sensors control etc.
Level of problem-solving	None	Basic	Medium	Complex
Standard VS Custom parts	All standard	Most standard	Most Custom	All Custom
Difficulty of CAD	1	2	3	4
Definition Level Score	I	II	III	IV
Definition Level Range	6 to 10	11 to 15	16 to 20	20 to 24

Static or Dynamic

Static or Dynamic refers to the anticipated level of motion a product will have. This ranges from a fixed, stationary product, to a moving product with moving parts. According to the participants, the greater the level of motion, the more time will be required to design the product.

Electronics to be developed

Electronics to be developed refers to whether the product will likely require any electronic components to be included. This ranges from a complete absence of any electronic part to one that has a user interface and user experience, with sensors, controllers, etc. According to the participants, the more electronics a product requires the more time it will take to develop the product.

Level of problem-solving

Level of problem-solving refers to the anticipated degree of mental challenges presented by the project. This can range from the inclusion of complex movements, power systems, etc. to overcoming a particular set of functional requirements that are not complimentary.

Standard vs. Custom Parts

Standard Vs. Custom Parts refer to the number of parts which require design effort to produce. This ranges from a product in which all parts are already available from suppliers to a product where the components have to be designed by DCB. According to the participants, the greater the number of parts to be designed, the more time will be required to design them.

Difficulty of CAD

Difficulty of CAD refers to the perceived difficulty involved in producing CAD drawings, files, etc. for the product. This will relate to several elements, including the complexity of the product's form, the number of parts, etc. According to the participants, the higher the perceived difficulty in producing CAD files for a product, the more time will be required to produce them.

5.4 Analysis

5.4.a Analysis: Influential Factors

Of the forty factors identified by DCB participants, ten grouped factors were created, of which four were voted as being most influential.

Categorising Factors

In Table 51, the ten grouped factors identified in this case are mapped to the factor categories developed in the literature review: *Team management, Product, Business Management, Information, Tools & Technology, Client, External Influences* and *Project*. The frequency of each category have been calculated to determine the spread. Under the assumption that more importance is placed on categories that are mentioned with greater frequency. Table 51 indicates that External Influences-based factors have the greatest significance, having been mentioned three times, while Information and Client-based factors are mentioned twice. One factor identified by DCB does not correspond to a category from literature, that of "Development Budget". It is unknown if this is an anomaly of this specific PDC or if this has some significance, which can only be determined through comparison of other case datasets. The definitions of each factor provided by the DCB participants is supported by the table of grouped factors, shown in Table 38.

Table 51 Case 2 Categorised Factors

	Team management	Product	Business management	Information	Tools & Technology	Client	Project	External Influences	Other
Client "Gut Feeling"						1			
Development Budget									**1**
"Stuff" Happens								1	
Definition Levels (Inputs)				1					
Regulatory Complexity								1	
Geography							1	1	
Designer Experience	1								
Product Complexity		1							
Delivery Output Complexity					1				
Communication complexity				1		1			
Instance	1	1	0	2	1	2	1	3	1
Case Percentage	8.33%	8.33%	0.00%	16.67%	8.33%	16.67%	8.33%	25.00%	8.33%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

Client "Gut Feeling"

The intuition the DCB team has of the client, referred to as the "Client "Gut Feeling"" factor, is clearly linked to other Client-based factors as identified in the literature review.

Case 2

Development Budget

Like "Materials Budget" in Case 1, there is no comparable category identified in the literature review for the "Development Budget" factor. As such this has been assigned to the "other" category for this analysis.

"Stuff" Happens

The use of the word "Stuff" was not the original term employed by the DCB design team for the ""Stuff" Happens" factor. This is indicative of the intention of what this factor relates to. As the popular term that was actually used relates to external issues or agents having influence over a project, it is clear that this factor falls under the External Influences-based factor category.

Definition Levels (Inputs)

The factor "Definition Levels (Inputs)" relates to the clarity of the information provided to the design team during the design project. This includes how well each element of the project is defined throughout the project. This is clearly an information-based factor.

Regulatory Complexity

Exactly like the factor identified in Case 1, the "Regulatory Complexity" factor refers to the volume and intricacies of the regulations and other legislation that the DCB design team will have to complete as part of the product development process. As these regulations (and similar) are mandated by external bodies, this is an "External Influence" factor.

Geography

The "Geography" factor is the first to have two independent categories assigned to it based on how it was defined by the DCB participants. Firstly, it is related to the Project category, as the travel times between critical project locations can have a notable influence on a project. This in itself is not a project category, however the DCB participants stated during their discussions that the selection, the mandated use of particular third parties, facilities, etc.. or some policy-based requirements made of DCB by their client (alluded to by the "environmental parameters" factor within the "Geography" factor grouping) make this a project-based factor. The "Geography" factor can also be categorised as an External Influences-based factor, as the term proximity is used in two of the factor terms: Supplier proximity and Travel time/proximity. These are determined by external factors, as suppliers, etc. will already have fixed locations from which they operate.

Case 2

Designer Experience

The "Designer Experience" factor, like that of the "Prior Knowledge" factor from Case 1, refers to the depth of relevant knowledge the DCB design team has that will be required for the completion of a project. As such, this knowledge is in part the result of effective team management. DCB management are responsible for the composition of their design team and therefore the skillsets and experience each member has. This mirrors the factors discussed in various sources within the literature review (Bashir and Thomson, 1999, 2004; Benedetto et al., 2018; Pollmanns et al., 2013; Salam et al., 2009).

Product Complexity

Identical to a factor found in Case 1, the "product complexity" factor is clearly a product-based factors having been specifically identified in various sources in the literature (Bashir and Thomson, 2001; Jacome and Lapinskii, 1997; Tatikonda and Rosenthal, 2000).

Delivery Output Complexity

The "Delivery Output Complexity" factor has been categorised as Tools & Technology based factor. This is due to the need for certain manufacturing processes as part of the production of the final product. Similarly, if there are specific tolerance requirements of the product, then the manufacturing technology employed will be more specialised and/or sophisticated.

Communication complexity

The "Communication complexity" factor has been categorised both as an Information-based factor, and a client-based factor. Information-based as the exchange of information is the foundation of communication, and client-based as the DCB participants stated that a high-degree of communication would be between them and the client.

When comparing the percentage of instances of the literature review and the case data, DCB's focus on External Influence-factors is significantly greater. Considering the datasets as a whole, the factors which are considered most significant are totally different. However, as highlighted in Case 1, the comparison of the literature review to a single dataset is in itself inconclusive, with more data collection needed for a robust comparison.

Considering the categorisation of the top voted factors, shown in Table 52, the distribution of factor categories further deviates from the distribution found in literature. No category received more than a single instance from the top voted factors, with only the Product, Information, Tools & Technology and Client categories being assigned. This clear difference between the distribution of categories from the literature review and the factors identified by DCB, indicating a level of disagreement on which factors play a significant role in influencing design project resources.

Case 2

Table 52 Case 2 Categorised Top Voted Factors

	Team management	Product	Business management	Information	Tools & Technology	Client	Project	External Influences	Other
Client "Gut Feeling"						1			
Definition Levels (Inputs)				1					
Product Complexity		1							
Delivery Output Complexity					1				
Instance	0	1	0	1	1	1	0	0	0
Case Percentage	0.00%	8.33%	0.00%	8.33%	8.33%	8.33%	0.00%	0.00%	0.00%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

5.4.b Analysis: Change in Percentage Influence Graphs

The graphs displaying the change in percentage of influence of each factor (Figure 31 - Figure 39) provide insight into the fluctuations of influence over the duration of a project and have been used as the basis of this factor influence analysis. However, when considering the PIGs in a side-by-side comparison, the same changes can be identified, while also allowing comparison between the influence of each factor. There is no additional value or insight to be gained from this type of depiction.

5.4.c Analysis: The Percentages of Factor Influence

The following section will discuss the Percentage Influence Graphs (found in Appendix 5.7) and the graphs depicting the change in percentage of influence (found in Figure 31 - Figure 39).

Percentage Influence Graphs: Client "Gut Feeling"

According to Figure 31 and the PIGs in found in Appendix 5.7, the influence of the *Client "Gut Feeling"* factor fluctuates over the duration of the project. There is an indication that its influence is greater at the Pre-sign off, Define and Detail phases. This may relate to the degree and frequency of interaction between DCB and the client during these phases.

Percentage Influence Graphs: Definition Level Inputs

According to Figure 32**,** Figure 33 and the PIGs in found in Appendix 5.7, the *Definition Level Inputs* factor has the greatest influence on the management and design times during the Discover phase and gradually reduces as the project progresses, with the least influence at the Deliver phase. From discussions with participants, this is likely due to any ambiguity in the project brief, reflected in the level of the factor, which would be resolved before the later stages of the project.

Percentage Influence Graphs: Product Complexity

According to Figure 35 and the PIGs in found in Appendix 5.7, the influence of the *Product Complexity* increases from the project start, peaking at the design phase, and maintaining a higher influence in the later project phases. Confirming what has been posited by authors such as Griffin (1997), the complexity of a product has a direct influence over project length, particularly during the design phase. Although Figure 34 suggests no particular trend of influence on management times, Figure 39 shows the average participant percentage, which indicates a sympathetic increase in management times towards the design phase of the project. This is likely due to a correlation between design phase length and the need for more management over the same phase.

Percentage Influence Graphs: Delivery Output Complexity

According to Figure 36**,** Figure 37 and the PIGs in found in Appendix 5.7, the influence of the *Delivery Output Complexity* factor increases throughout the project, with the greatest level of influence held over the Delivery phase of the project. This is the case for design effort levels for both management and design activities. This is more clearly shown in Figure 39**,** where the trend lines both steadily increase throughout the project. The participants confirmed that this was due to the factor representing the demands of the client and brief on what is expected as the output of the project, with a more detailed, long list of project deliverables causing an increase in its perceived complexity, and thus more time will be required.

5.4.c Analysis: Mean Effect Plots (MEPs)

This section will consider the Mean Effect Plots (found in Appendix 5.9) generated during Case 2 and what they indicate in their depiction.

Client "Gut Feeling"

The relationship between the *Client "Gut Feeling"* factor and both management and design activities and design effort levels has an inverse correlation, where the better score attributed to the client, the less time the project takes.

Definition Level Inputs

The relationship between the *Definition Level Inputs* factor and both management and design activities and design effort levels also has an inverse correlation, where the more defined the project brief is, the less time the project takes.

Product Complexity

As shown in the graphs of Appendix 5.9, there is a correlation between the *Product Complexity* factor and both management and design activity design effort levels.

Delivery Output Complexity

As shown in the graphs of Appendix 5.9, there is a correlation between the *Delivery Output Complexity* factor and both management and design activity design effort levels.

Mean Effect Plots Application

This application of Mean Effect Plots to communicate the interactions between factors and project resources has proven to be viable. Intuitive and comprehensible, they demonstrate the degree to which a factor influences resources, as the steeper the gradient, the greater the influence.

5.4.d Analysis: Modelling Factor Behaviour

When considered in combination, the Mean Effect Plots, Percentage Influence Graphs and the Change in Percentage of Influence graphs can be used to identify two key factor behaviours. The PIGs in Appendix 5.7 provide a per-phase perspective on which factor has the greatest influence. For example, the influence of the "Product Complexity" factor remains consistently dominant up until the deliver phase, when the influence of the "Delivery Output Complexity" factor increases drastically. As in Case 1, the MEPs for "Product Complexity" further illustrate the correlation between the complexity of the product and the level of resource demands made of the project.

For each of the four factors their behaviour can be determined:

Client "Gut Feeling"

The *Client "Gut Feeling"* factor has an inverse relationship with both management and design activities and their design effort requirements. This influence is at its greater at the Pre-sign off, Define and Detail phases.

Definition Level Inputs

The *Definition Level Inputs* factor has the greatest influence during the Discover phase of DCB's design process, having an inverse correlation between to both the management and design activity design effort needs.

Product Complexity

For both management and design activity design effort needs, the *Product Complexity* factor has a direct correlation, the higher the complexity, the greater the demand for design effort. Its influence is strong throughout DCB's design projects process, peaking during the design phase for Design activity resource needs. The same correlations cannot be made for management resources needs.

Delivery Output Complexity

As with *Product Complexity,* the *Delivery Output Complexity* factor has a direct correlation between its level and both management and design activity design effort requirements. As might be expected, its influence peaks during the later stages of DCB's process, with its greatest influence during the delivery phase.

5.4.e Analysis: Summary

Included in Figure 40 is a revised diagram of that presented in the Chapter 3, reflecting the actions and analysis taken in Case 2 and how this differs to those taken in Case 1.

5.5 Discussion

5.5.a Communicating Perceived Factor Influence Graphically

In the discussion of Case 1, the use of Mean Effect plots was suggested as a means of communicating the perceived behaviour or each factor held by participants. Mean Effect graphs were produced and shown to participants, with a detailed discussion included in the Workshop 3 section of this case. Of the five participants, four believed that the graphs offered some insight into the way that they perceive the different factors and three of the five were able to identify another participant, or other participants, based only on the graphs. As with Case 1, the mean effect plots were able to model and communicate the behaviour of each factor in relation to the design effort needs of a project. In further cases, the use of Mean Effect plots to convey perceptions of factor behaviour will be included in the method to refine the process and to potentially identify further uses for the information illustrated by them.

5.5.b Role of The Researcher In The Case

The role of the researcher during the case remained generally the same as that in Case 1. The facilitation of each workshop, the preparation of DOE experimental designs, and the analysis of collected data remained the same as before. The semi-structured interviews discussing and assessing the potential value of graphically modelled factors were the only formal addition to the experimental protocol.

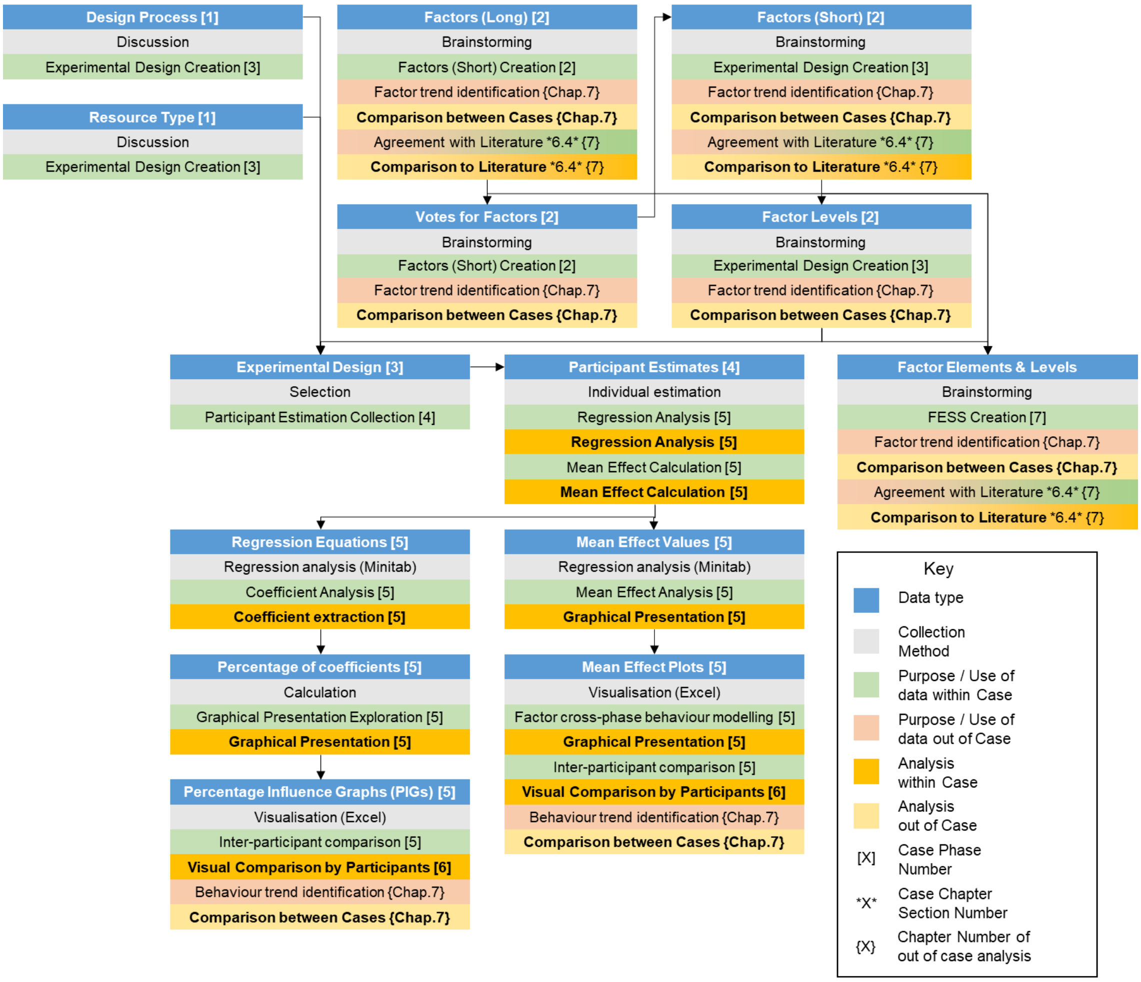


Figure 40 Case 2 Analysis Summary

5.5.c The Enthusiasm of Participants During Study

The company director and studio manager who participated in the preliminary discussions were highly enthusiastic during the study. They had several extra conversations with the researcher during the case, resulting in their active participation in the refinement of the experimental method for future cases. This included the clustering activity during the factor identification task in Workshop 1 and the management resource in the estimation activity in Workshop 2.

5.5.d Factor Evaluation & Scoring Scheme (FESS)

The inclusion of the Factor Evaluation & Scoring Scheme (FESS) into the method of this case provided some notable benefits in various areas. As suggested in Case 1, each factor had various numbers of elements contributing to their influence, which provided an improved communal understanding, context and definition to potentially abstract terms. Furthermore, by adopting a per-project phase approach when discussing factors, the elements of each factor were naturally discussed in the informal session of Workshop 1. The output of this activity significantly contributed to the ease of development of the FESS. Therefore, the method for future cases will include this per-project phase approach, to maximise the number of elements and factors identified at the outset.

5.5.e CoFIDE Method

Continuing on from the identified benefits of including a FESS creation process in workshop 1, this addition should also be applied to the proposed CoFIDE method.

5.6. Conclusion

Case 2 can be considered by all means as successful. The changes generated from the findings of Case 1 were implemented, including the development of a procedure to produce a Factor Evaluation and Scoring Scheme (FESS). Four factors were identified as being the most influential by the DCB participants: "Client "Gut Feel"", "Definition Levels (Inputs", "Product Complexity" and "Delivery Output Complexity". The MEPs and PIGs produced for each factor and project phase have clearly modelled the behaviour of the factors indicating, among other things, when the influence of a given factor is at its greatest and how it changes over time. From presenting these graphs to the DCB design team, participants were able in some instances to identify a fellow member of their team from their (anonymised) plots alone. This degree of insight has potential value to PDCs and should be explored further in future studies.

Based on the value identified by creating the FESS, this activity will me included in Workshop 1 in subsequent cases to provide better context for Subsequent changes can be made to the case procedure, which in turn will inform the proposed CoFIDE method from in Case 1.

5.6.a Answering Research Questions

This section will reiterate the research questions stated in the literature review and provide initial answers to each, based on the findings of Case 2. This multiple round quasi-experimental case-based approach aims to apply a DOE-based method for the identification and modelling of the most influential factors on design effort demands for product design projects conducted by product design companies. This aim will be achieved by completing the objectives previously stated. By addressing these aims, this case will answer this study's research questions:

RQ1

What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in literature?

From the results of Case 2, four factors were identified as being the most influential over design project resources: "Product Complexity", "Client "Gut Feeling"", "Definition Level Inputs", and "Delivery Output Complexity". These, along with the Factor Evaluation & Scoring Schemes for each, will contribute to this study's understanding of the factors influencing resources and how they compare to those found in the literature.

RQ2

How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?

The Percentage Influence Graphs (PIGs) and Mean Effect Plots (MEPs) developed during this case have modelled the behaviour of each of the four most influential factors.

The findings of Case 2 reiterate the behaviour of **Product Complexity** found in Case 1, directly influencing the resource needs; As "product complexity" increases, so too do resource demands. The magnitude of influence, shown in Appendix 5.7, is not as overwhelming as it was in Case 1, with influence from other factors remaining significant throughout a project. "Product Complexity's" influence increases throughout the project, and peaks during the detail phase. From the corresponding FESS, this factor can be evaluated to determine the strength of its influence, against the following measures: "Static or Dynamic", "Electronics to be developed", "Level of problem-solving", "Standard Vs Custom Parts", and "Difficulty of CAD".

There is an inverse relationship between the level of **Client "Gut Feeling"** assessed by DCB and the resource demands of the project, shown in Appendix 5.9. The higher (better) the feeling of the client, the fewer resources the project will require. However, Appendix 5.7 shows that this factor is not the most influential, but does have an almost constant influence during a design project, having a slightly increased influence at the "Pre-sign off" phase. The FESS created for "Client "Gut Feeling"" has five measures to assess this factor: "Level of experience", "Team Setup", "Personality", "Funding Level of Project", and "Level of Additional Engagement Required"

Definition Level Inputs is a factor whose influence is greatest at the project's outset. This is indicated in the PIGs shown in Appendix 5.7, where the factor's influence diminishes by the project mid-point. "Definition Level Inputs" is measured against five qualities, as defined by the corresponding FESS: "Knowledge of the User/Market", "Knowledge of Technology", "Knowledge of Commercials", "Knowledge of Regulation and IP", "Definition of Required Outputs", and "Level of Definition of Timeline". These relate to the amount of vital information present, with the greater the understanding and knowledge, the less resource is required. This also links to the "top-heavy" nature of the factor's influence, as knowledge and understanding of these measurable issues are gained as the project progresses.

As the name hints at, the influence of **Delivery Output Complexity** peaks at the "deliver" phase of DCB's design project. Like "Product Complexity", the greater the complexity, the greater the demand on project resources, which can be seen in the MEPs in Appendix 5.9. This factor is evaluated against five measures: "Outsourced or In-house", "Number of Subcontractors", "Number of Materials / Processes", "Regulatory Requirements", and "New or Prior Knowledge to Consultancy"; as shown in its FESS.

RQ3

> *How might PDC teams enhance their understanding of the project planning process and their teams through the collaborative capture and modelling of their understanding?*

From the adaptation and modification of the CoFIDE process, developed in Case 1, it has been possible to capture the perceptions held by a product design agency design team on the most influential factors of design effort levels. Through brainstorming activities, design teams can collaboratively identify influential factors and individually provide design effort estimate data which, once processed through some regression analysis, can be used to quantify the perceptions of each member of the design team. Modelled using Mean Effect Plots (MEPs) and Percentage Influence Graphs (PIGs), the behaviour of each factor can be assessed. Having evaluated these graphs, three of the five DCB participants agreed with the behaviour modelling shown, with the other two participants only disagreeing with specific factor-phase length relationships.

Additionally, presenting these models to the members of DCB, 80% of participants shown identified some value to the insight they offered, into how their colleagues considered design projects and the factors which influence them; possible aids in managerial decision-making, including the selection of project team members.

6. Case 3

"It is sometimes an appropriate response to reality to go insane" *-- Philip K. Dick, VALIS*

6.1 Introduction

The over-arching aims of Case 3 are to address the research questions proposed in the Literature Review, and to validate the CoFIDE method developed in the previous two cases. Case 3 was conducted between December 2018 to February 2019 with a Scotland-based Product Design Company with experience in developing and building small batch and bespoke products for a range of clients, working predominantly with natural materials, such as wood and leather. This consultancy will be referred to in this study as Design Company C (DCC). DCC has a team of two company directors (who act as the designers) and three manufacturing staff, all with varied levels of experience in the industry and with varying qualifications and experience in architecture, design and manufacture. This study is comprised of three workshops, all of which were conducted in the offices and workshops of DCC. The number of participants included in each workshop was determined by the types of data gathered, with initial background information (design process, resource types, etc.) and estimation tool evaluation only requiring participation with the company directors and office manager. A list of participants for each workshop is included in Table 53.

Table 53 Case 3: Workshop Participant Breakdown

Workshop	***Participants***
1	Company Director & Office Manager
2	All team members
3	All team members
4	Company Director & Office Manager

6.1.a Role of Researcher

The role of the researcher in this case remains as stated in Chapter 3, acting as a facilitator during workshops and collecting, collating and analysing the data generated from them. As some questions were asked during Case 1 about the process, the researcher adjusted the delivery of instruction to improve the clarity of the activities prescribed. A reflection on the researcher's role is included in the conclusion of this chapter.

6.2 Changes to Experimental Approach

This section will discuss the changes made to the approach taken during this multiple round quasi-experimental case-based investigation. These changes are based on the findings and outcomes of Case 2 and the process that will be applied to Case 3. The following sub-sections will outline each phase of the CoFIDE process based on the IDEF0 activities described in Figure 41, and expanded upon in Appendix 6.1 – 6.5. The sections will continue to follow the same step method outlined in the approach section of the Case 1 chapter. This section will only discuss the changes made to the approach and the differences between it and the Case 1 approach.

Table 54 Case 3: Approach Case 3 Method

Case Phase	Purpose (Identification, collection, etc.)	People Required	Outcomes	Mapped DOE Stage
1. Preliminary Discussion	Identify key elements of product design projects at participant company.	R / M	Suitable key resource(s) of future design projects. The design process followed by participant company.	*Describe*
2. Workshop 1	Identify key influential factors on project resource to produce a Factor Evaluation & Scoring Scheme (FESS)	R / M / T	Key factors and elements which influence resource(s) level A FESS for project evaluation	*Describe*
3. Interim Phase 1	Generate experimental design with identified factors and levels	R	Template experimental design	*Design*
4. Workshop 2	Collect experimental data (participant estimates) using template	R / M / T	Participant estimates (1)	*Collect 1*
5. Interim Phase 2	Generate regression equations for participants Create regression models for each participant based on regression equations Build comparison graphs of regression models	R	Regression equations, Participant regression models, Comparison Graphs	*N/A*
6. Workshop 3	Gain insight into participant's views on comparison graphs	R / M / T	Feedback on process Feedback on comp. graphs	*N/A*

Persons involved in study coded as: Researcher (R), Company Director & Office Manager (M), & Design Team (T)

Case 3

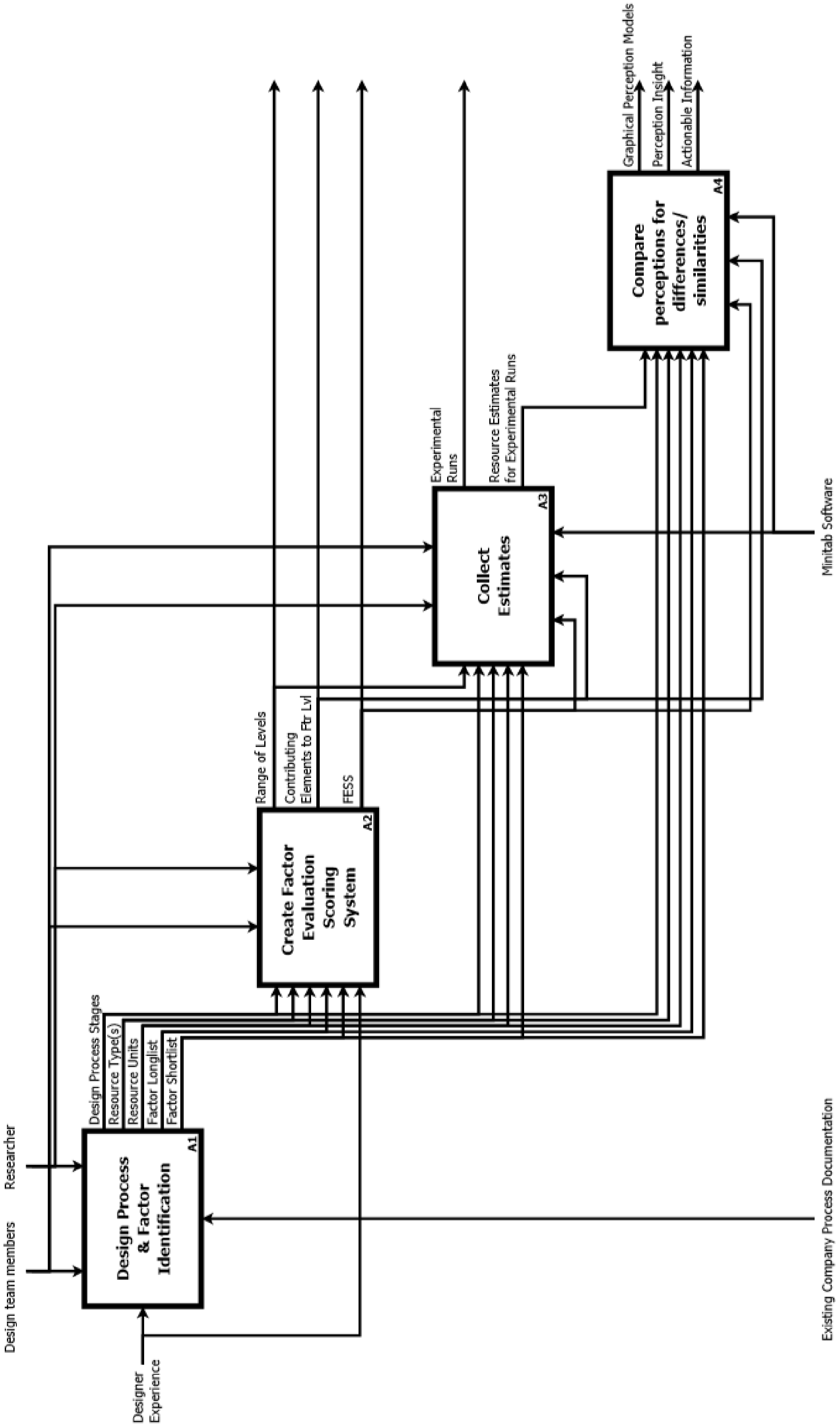


Figure 41 Case 3: Approach IDEF0 Model

6.2.c Workshop 1

This stage saw the only significant change from the approach of Case 2. The remaining steps were kept the same, but participants will take the factor longlist and shortlist and use them to produce a factor evaluation and scoring system (shown in Appendix 6.2), similar to that developed in Case 2, but in this case, before the estimation phase. The changes made to the experimental process for Case 3 are summarised in Figure 42.

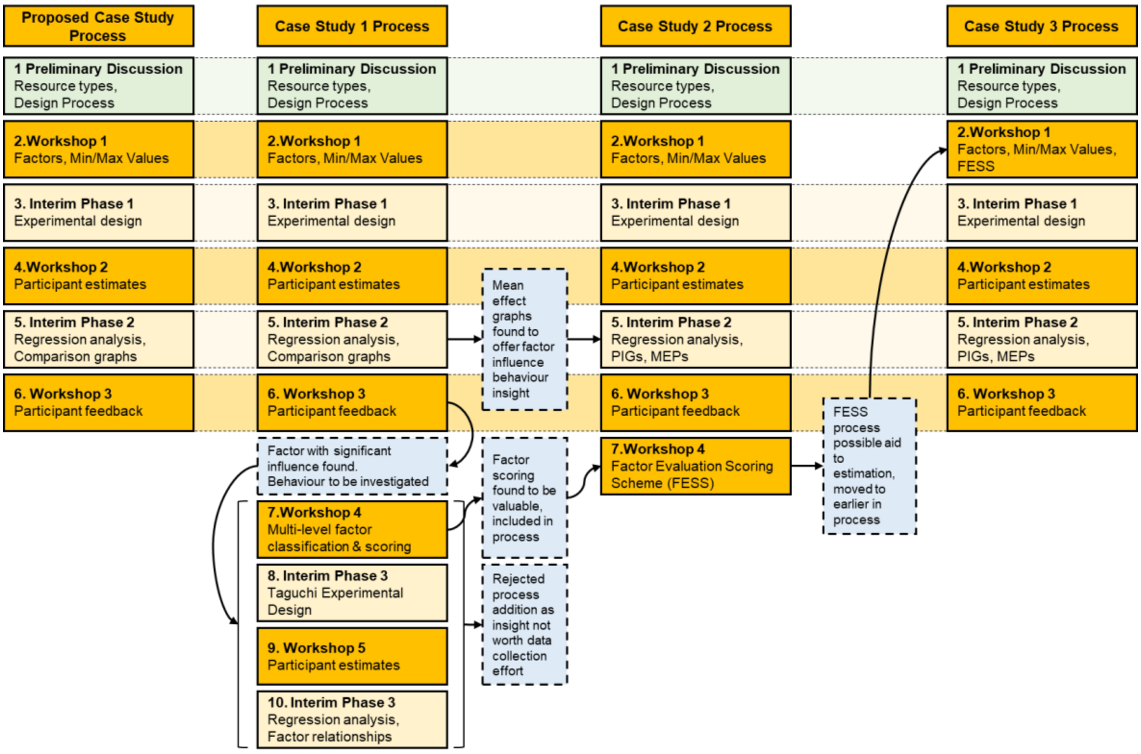


Figure 42 Case 3 - Experimental Process Changes for CS3

6.3 Case Results

6.3.a Discussions

The initial discussions were structured as a semi-formal interview in DCC's offices and were aimed to identify several key elements of any product design project to develop an experimental design to be applied in a subsequent workshop:

1. The key resource, or resources, required for any future design project and a suitable unit of measurement.
2. The stages are universal to any design project.

Resources and Project Stages

Preliminary discussions were held with company directors as they were responsible for the organisation of staff and the billing of clients. During these discussions, it was agreed that the best resource for the case would be "person-hours" as this matched the resource used when billing clients. Furthermore, it was agreed that there are five main stages for each design project, each with its own assigned tasks, shown in Table 55.

6.3.b Workshop 1

Workshop 1 was conducted within the offices of DCC and was structured as a collaborative brainstorming session with the research acting as facilitator. During Workshop 1, the most influential factors on design effort levels for a product design project at DCC were identified. However, due to the limited availability of the DCC design team and staff, the tasks to accomplish these aims were spread over two workshops: Workshop 1a and Workshop 1b.

Table 55 – Case 3: DCC Design Project Stages

Stage	**Example Tasks**
Pre-sign off	Client contact and meetings, Stakeholder identification, etc.
Concept Design	Concept ideation, Brainstorming, etc.
Technical Draft	CAD modelling, CAD drawing, BOM creation, etc.
Prototyping	Prototype building, Test rig build, Jig building, etc.
Final Build	Material sourcing, Final build, Finishing, Painting/spraying, etc.

Workshop 1a: Factors

During Workshop 1a, participants were assigned the task to create an exhaustive list of every factor that may influence the number of person-hours a project would require for any or all phases of a design project. During the informal discussion and brainstorming session between all the participants, and unprompted by the researcher, the participants approached the task by addressing each design project phase, identifying those factors that influenced each respectively. The participants recorded their own suggestions using sticky notes. Due to time limitations, the participants were only able to generate a list of seventy-six different factors, shown in Table 56.

Workshop 1b: Factor Refinement

During Workshop 1b, participants were assigned the task of collating each of the factors identified in Workshop 1a into categories based on the types, or meanings of factors. Doing so created seven distinct categories, one for each stage, plus one for factors which affected more than one, or all of the stages. Sixty-three (63) different factors were suggested, shown in the right column of Table 56 and were then regrouped into ten (10) different categories, shown in the left-hand column of Table 57. This clustering process helped identify some similar terms which had been applied to separate stages of the design process and allowed for common themes to be established. The stage-by-stage process allowed the participants to formally define each of the clustered factors by the varied ranges of terms for similar factors. Once these categories were identified, the participants privately rank-voted those factors they felt were the most influential on design effort levels, these votes and scores are shown in Table 58. The results show that Client / Brief Clarity, Time, Budget and Product Complexity factors were found to be the most influential by the participants.

Table 56 – Case 3: Factor Longlist by Project Phase

Project Phase	Factors
Pre Sign Off	Is there a budget? Y/N, Does a design exist?, Concept definition, Deadline?, Specific materials, Site visit required?, How solid foundations?, Red tape hell, Electronics required?, Fragile maintenance, Private vs. Corporate, Indecision level, Final destination, Scheduling clashes, Our visibility, Separate development budget?, Middleperson or decision maker?, Why us? Are they trouble?, How desperate are we for the business?,
Concept Design	Is it a novel design?, Potential misuse, Life span, Number of functions, Delivery restrictions, IP issues, New techniques, Tricky materials, New tooling, How custom, Samples?, Pre-existing infrastructure, Previous experience, Health and safety, Durability Brand language / limitations, New subcontractors required, How many subcontractors, Contents available, Quantity
Technical Draft	Client sign-off on CAD, Desired complexity vs Manufacturing efficiency, Tolerances, Material restrictions, Does it have wheels Amount of info to communicate, Amount of polish / finishing needed
Prototyping	Working vs mock up, New aspect time, Time, Budget, How many rounds, Subcontracted prototypes, Scale, Client expectation, Subcontractor consistency, Volume Is the decision finalised, Confirmation delays, The right budget
Final Build	How many unknowns left, Room for error, Certification External quality control, Site complexity, Tooling, Time for difficult solutions, Scheduling clashes, Final packaging, Final cleaning / inspection, Seasonal delays, Material consistency, Site completion,

Factor Evaluation & Scoring Scheme

Based on the findings of Case 2 – Workshop 4, the participants created a factor evaluation and scoring scheme (FESS) for each of the top four factors. This was completed during

Workshop 1b under the supervision of the researcher. The following sections will discuss each of these factors and the elements used to make up their corresponding FESS.

NB:- The terms classified as "factors" in Table 57 will be referred to as "elements" in this section.

Table 57 – Case 3: Grouped Factors for design effort influence product design projects

Grouped Factor Name	Elements
Client (POC)	Private vs. Corporate, Middleperson or decision maker, Why us?, Are they trouble, Indecision level, IP issues, Expectations of presentation, Client sign-off of CAD, Samples?, Client expectation
Product Requirements	Health and safety, Contents available, Volume, Working vs Mock-up, Quantity
Product Complexity	Future Maintenance, Potential Misuse, Life span, Material Type, Tricky Materials, Durability, Does it have wheels, Material restrictions, Scale
Our Experience	Does a design exist, Previous experience, New techniques, Our Visibility How desperate are we for the business?, Amount of info to communicate
Brief Clarity	Brief Clarity, How many unknowns left?, Material Consistency, Red tape hell, Brand language / limitations, How solid foundations?, Deadline Is the decision finalised, Number of functions, Room for error, Concept definition, Separate development budget, External quality control, What is the concept for?,
Budget	Budget, Is there a budget? Y/N, The right budget
Making / Fabrication	Is it a novel design?, How custom, Pre-existing infrastructure , Electronics required, Amount of polish / finishing needed, Tolerances New tooling, Specific materials, Desired complexity vs. Manufacturing efficiency, New aspect time (additional details)
Time	How many rounds, Time for difficult solutions, Time, Confirmation delays, Scheduling clashes, Seasonal Delays
Subcontractors	Subcontracted prototypes, How many subcontractors, Subcontractor consistency, New subcontractors required?
Logistics	Site completion, Site visit required, Site complexity, Final packaging, Final destination, Certification, Delivery restrictions

Client / Brief Clarity FESS

The elements of the Client / Brief Clarity factor were synthesised from those collated in Table 57. Table 59 collates the definitions for each of these elements, provided and collected through the discussions held during the workshop. Using these definitions, the participants collated these elements to synthesise the features shown in Figure 43. These features were then given four levels, shown in Time FESS

Case 3

Table 58 – Case 3: Factor Influence Voting Scores

Grouped Factor	**Votes** **1**	**2**	**3**	**4**	**5**	**Score** **5**	**4**	**3**	**2**	**1**	**Total Score**
Time	2	1	0	0	0	10	4	0	0	0	**14**
Brief Clarity	1	0	3	0	0	5	0	9	0	0	**14**
Budget	1	2	0	0	0	5	8	0	0	0	**13**
Product Complexity	0	2	0	1	0	0	8	0	2	0	**10**
Client POC	1	0	1	0	0	5	0	3	0	0	8
Fabrication	0	0	0	3	1	0	0	0	6	1	7
Subcontractors	0	0	1	1	0	0	0	3	2	0	5
Logistics	0	0	0	0	2	0	0	0	0	2	2
Our Experience	0	0	0	0	2	0	0	0	0	2	2
Product Requirements	0	0	0	0	0	0	0	0	0	0	0

Table 59 Case 3: Client / Brief Clarity Element Definitions

Element	**Definition**
Material Consistency	How consistent is the reference material supplied by the client?
Brand language/limitations	How restrictive are the client's branding guidelines
How solid are foundations?	How clear and robust are the client's requirements
Is the decision finalised	Have all client-based approvals been made?
Number of functions	How many discrete functions should the product have
Room for error	How tight are the tolerances for the product
Concept definition	How well-defined is the concept description
Red tape hell	How many bureaucratic "hoops" will the design team have to "jump through", specifically around shipping?
Separate development budget	Is there a discrete budget for the development of the product, separate to the building of the product(s).
External quality control	Does the product need to be checked/approved by a third party?
What is the concept for?	What is the intended use of the product?
How many unknowns left?	How many issues are yet to have clear answers?
Deadline	How strict is the deadline for the project

Case 3

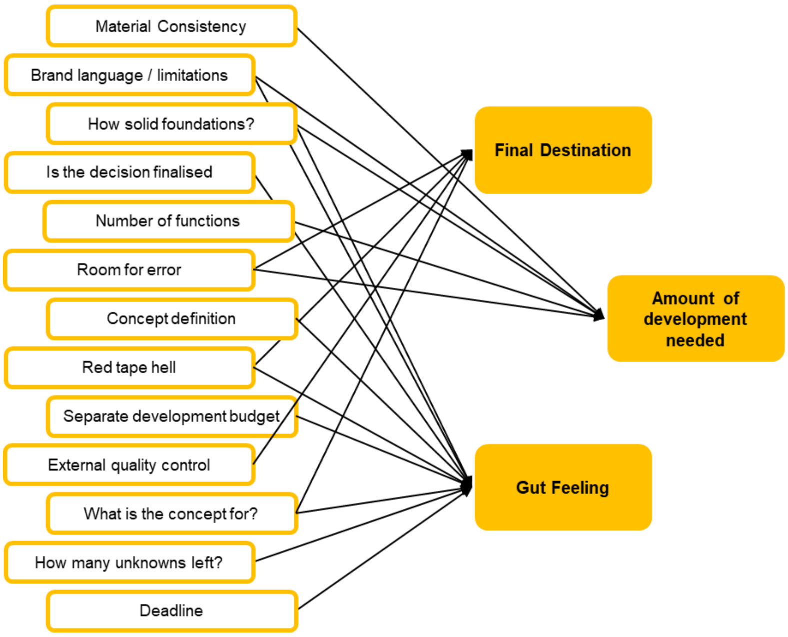


Figure 43 Case 3: Client / Brief Clarity factor element synthesis

Time Available FESS

The Time Available factor elements identified earlier in this workshop (Table 57) were given definitions, shown in Table 61. Using these definitions, the participants' synthesised factor features, shown in Figure 44 and were given a 4-level range, shown in Table 62. Two of the features of this facto had binary yes/no options: *Client's Timetable* (reasonable or unrealistic), which is a judgement call based on the client's expectations of DCC's capabilities and capacity; and *Established Deadline* (yes or no), which reflects whether the client has a fixed deadline for the end of the project. Participants commented that if the deadline were ambiguous, then projects would likely take longer.

Table 60 Case 3: Factor evaluation & scoring scheme (FESS) for Client / Brief Clarity Factor

Feature	**1**	**2**	**3**	**4**
Final Destination	Local & Private	UK Shipped	High Red Tape Location	Foreign - International
Amount of development needed	Low	Medium	High	Extreme / Total
Gut Feeling	Feels so good	No-read	Troubling	Sruli!!!
Good to Bad	+			-
Definition Level Score	1	2	3	4
Definition Level Range	3 to 5	6 to 7	8 to 9	10 to 12

Case 3

Table 61 Case 3: Time Element Definitions

Element	**Definition**
How many rounds	How many client concept reviews have been planned?
Time	What is the expected timescale for this project?
Time for difficult solutions	Do the client's time expectations allow for complex solutions?
Confirmation delays	How long does it take for the client to respond to requests for information, etc?
Scheduling clashes	What other projects in-process with the company
Seasonal Delays	Will public holidays (Christmas, Chinese New Year, etc.) delay the project?

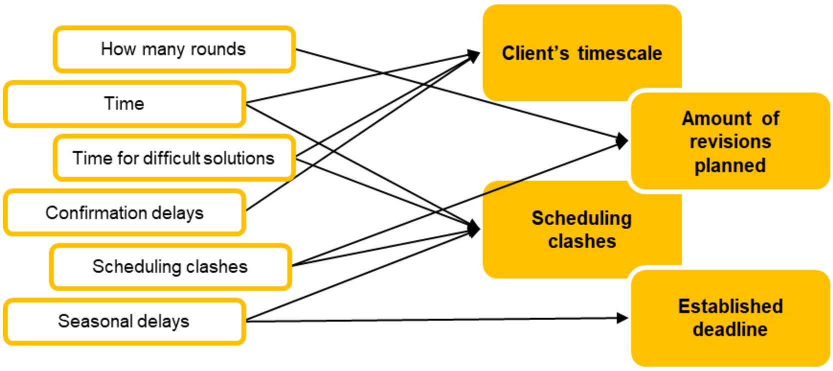


Figure 44 Case 3: Time factor element synthesis

Budget FESS

The elements of the *Budget* factor were synthesised from those collated in Table 63, using their definitions (Table 63) to create two-factor features (Figure 45). The *Right Budget* feature was given a 4-level range by participants, shown in Table 64, whereas the *Disclosed Budget* feature was given the binary yes or no option.

Table 62 Case 3: Factor evaluation & scoring scheme (FESS) for Time Available Factor

Feature	**1**	**2**	**3**	**4**
Client's timescale	Reasonable	X	X	Unrealistic
Amount of revisions planned	1	2	3	4+
Scheduling clashes	Free Time	Manageable Squeeze	Overtime required	Subcontractors / help needed
Established deadline	Y	X	X	N
Good to Bad	**+**			**-**
Definition Level Score	1	2	3	4
Definition Level Range	4 to 7	8 to 10	11 to 13	14 to 16

Table 63 Case 3: Budget Element Definitions

Element	Definition
Budget	How generous is the budget based on the requirements?
Is there a budget? Y/N	Is there a disclosed budget for the desired project?
The right budget	Is the budget sufficient for the intended project output?

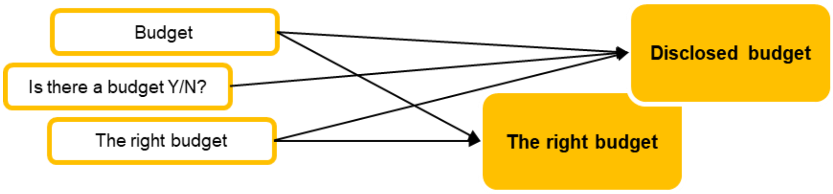


Figure 45 Case 3: Budget factor element synthesis

Table 64 Case 3: Factor evaluation & scoring scheme (FESS) for Budget Factor

Feature	1	2	3	4
The right budget	Healthy	Sufficient	Restrictive	Insufficient
Disclosed budget	Y	X	X	N
Good to Bad	+			-
Definition Level Score	1	2	3	4
Definition Level Range	2 to 3	4 to 5	6 to 7	8

Product Complexity FESS

Each element of the Product Complexity factor (synthesised from those collated in (Table 57) was given definitions, shown in Table 65. Using these definitions, the participants produced a range of factor features Figure 46, each provided with their own 4-level range, shown in Table 66.

Table 65 Case 3: Product Complexity Element Definitions

Element	Definition
Future Maintenance	How much maintenance would be expected of the agency after the product has been delivered
Potential Misuse	The likeliness of the product being used incorrectly
Life span	The expected time the product would remain functional
Material Type	The types and quantities of materials needed for the final product
Durability	How hard wearing the product is be expected to be

Case 3

Tricky Materials	Do the materials specified need special equipment or skill to use?
Does it have wheels	A summary term for portability and the likelihood that it would be moved during its use
Material restrictions	Are there limits to the uses of the material, either functionally or otherwise?
Scale	What is the anticipated size of the final product?

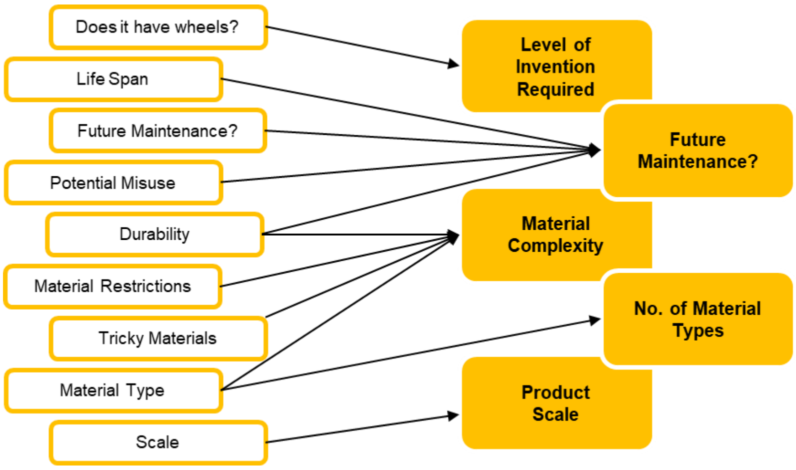


Figure 46 Case 3: Product Complexity factor element synthesis

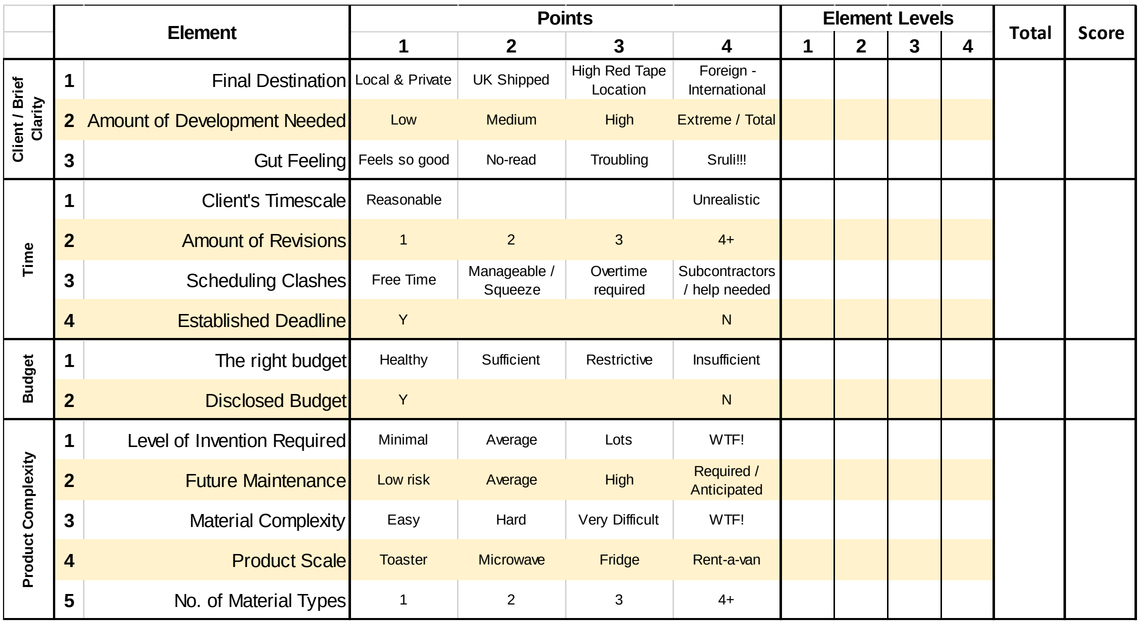
Table 66 Case 3: Factor evaluation & scoring scheme (FESS) for Product Complexity Factor

Feature	**1**	**2**	**3**	**4**
Level of invention required	Minimal	Average	Lots	WTF!
Future maintenance	Low risk	Average	High	Required / Anticipated
Material complexity	Easy	Hard	Very Difficult	WTF!
Product scale	Toaster	Microwave	Fridge	Rent-a-van
No. of material types	1	2	3	4+
Good to Bad	**+**			**-**
Definition Level Score	1	2	3	4
Definition Level Range	5 to 8	9 to 12	13 to 16	17 to 20

Workshop 1c: Scorecard

A scorecard that can be used to assess future projects is created by collating the FESS of each of the influential factors, shown in Figure 47. The FESS Scorecard will also act as the basis for the estimation tool. For the following section, this scorecard was used as a prompt, to aid the participants to visualise the types of projects described by the experimental design.

Case 3



		Element	Points				Element Levels				Total	Score
			1	2	3	4	1	2	3	4		
Client / Brief Clarity	1	Final Destination	Local & Private	UK Shipped	High Red Tape Location	Foreign - International						
	2	Amount of Development Needed	Low	Medium	High	Extreme / Total						
	3	Gut Feeling	Feels so good	No-read	Troubling	Sruli!!!						
Time	1	Client's Timescale	Reasonable			Unrealistic						
	2	Amount of Revisions	1	2	3	4+						
	3	Scheduling Clashes	Free Time	Manageable / Squeeze	Overtime required	Subcontractors / help needed						
	4	Established Deadline	Y			N						
Budget	1	The right budget	Healthy	Sufficient	Restrictive	Insufficient						
	2	Disclosed Budget	Y			N						
Product Complexity	1	Level of Invention Required	Minimal	Average	Lots	WTF!						
	2	Future Maintenance	Low risk	Average	High	Required / Anticipated						
	3	Material Complexity	Easy	Hard	Very Difficult	WTF!						
	4	Product Scale	Toaster	Microwave	Fridge	Rent-a-van						
	5	No. of Material Types	1	2	3	4+						

Figure 47 Case 3: FEES Scorecard

6.3.c Creating the Estimation Sheet (Interim Phase 1)

A data collection sheet was created by the researcher by developing a four factor, two level half factorial experimental design using the Design of Experiments tools within Minitab, with the data collected in Workshop 1, shown in Table 67. As with the considerations in Case 2, the experimental runs in this table were not randomised, based on the estimation behaviour of the participants in previous studies. The experimental plan was combined with the five project phases identified in the preliminary work, to create the Estimation Sheet for Workshop 2 – Collect Phase, shown in Table 67.

Table 67 Case 3: Experimental Design

Run	Client / Brief Clarity	Time	Budget	Product Complexity
1	-1	-1	-1	-1
2	1	-1	-1	1
3	-1	1	-1	1
4	1	1	-1	-1
5	-1	-1	1	1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	1

6.3.d Participant Estimates (Workshop 2)

All DCC participants gathered in their offices to complete the resource estimation task. Each participant was presented with a print out of the estimation sheet (Table 68) to record their estimates. Resource estimates of DCC participants were collected using an estimation sheet, shown in. Participant estimates can be found in Appendix 6.5.

Case 3

Table 68 Case 3: Workshop 2 Estimation Sheet

Run	Client / Brief Clarity	Time	Budget	Product Complexity	Pre Sign Off	Concept Design	Technical Draft	Prototyping	Final Build
1	4	4	4	4					
2	4	1	1	4					
3	4	1	4	1					
4	1	1	4	4					
5	1	4	4	1					
6	4	4	1	1					
7	1	4	1	4					
8	1	1	1	1					

6.3.e Regression Equations (Interim Phase 2)

Each participant's estimation values (recorded by hand on their estimation sheets) were added to a spreadsheet and using the Design of Experiments regression analysis tool within the statistical analysis software Minitab to produce twenty (20) regression equations in total, 5 for each participant predicting each phase of the project for design effort. As the experimental design is a half-factorial, not all inter-factor relationships can be modelled, those of *B. Time Available x C. Budget, B. Time Available x D. Product Complexity, C. Budget x D. Product Complexity*. Each participant's regression equation values can be found in Appendix 6.6 and are translated into an equation using Equation 1 as a template, where "n" is the corresponding value in the table. The factors are labelled: A. Client / Brief Clarity; B. Time Available; C. Budget; and D. Product Complexity

$$Output = Cft. + n_A A + n_B B + n_C C + n_D D + n_{AB} AB + n_{AC} AC + n_{BC} BC + n_{BD} BD + n_{CD} CD$$

Equation 1

6.3.d Graphical Representation of Data

Following the findings of Case 2, the graphs produced from the data analysis take two forms: the percentage of influence graphs each factor has over the regression equation of each participant (for factors comparison) and the mean effect plots (for the identification of trends in influence).

Percentage Influence Graphs

Continuing the same graph creation process as found in Case 2, the values for each of the regression equations was imported to a spreadsheet, separated by each project phase, and the coefficient values for each part of the equation were separated into columns. The coefficient values for each section of the equations were totalled, and then presented as a percentage of total influence per participant. This describes the percentage of influence each factor has over the regression equation of each participant, to compare factors. These graphs depict which factors have the greatest levels of influence over the phase length. Following the same format as those created in Case 2, these graphs do not show the percentage of influence in comparison to the regression equation's coefficient, as this would not allow for comparison between two different regression equations (i.e. comparison between different participants). These graphs also depict the changes in levels of influence throughout a product design project. Appendix 6.7 presents all the PIGs for Case 3.

Mean Effects Plots

The mean effect values (shown in Appendix 6.8) were calculated using the mean effect analysis tool in Minitab, these were brought into a spreadsheet so that the Mean Effect Plots could be produced. These graphs (shown in the following sections) illustrate the direction of influence each factor has on design effort levels with the gradient of the graph indicating both the correlation relationships of factors and design effort levels, but also the magnitude of said relationships. Each graph illustrates the mean effects of each participant for each factor and each project phase on design effort levels for design activities.

6.4 Analysis

This section an analysis of the results of Case 3.

6.4.a Analysis: Influential Factors

The design team of DCC developed a list of sixty three factors, which were collated by the participants into ten groupings. Each were defined by the group, based in part on the constiuant groupings. These factors have been categorised using thes categorisation approach adopted in the literature review and the previous cases.

Client (POC)

The "Client (POC)" factor is comprised of twelve elements, shown in Table 57. Many of these consider the personality traits of the client themselves. Terms such as "Are they trouble" and "Indecision level" address issues that cannot be practically addressed, e.g. replace a sub-standard material with a higher performing one. This can clearly be categorised as Client-based factor.

Product Requirements

The specific needs for what the product should have and be capable of doing, as stated by the client; the "Product Requirements" can clearly be categorised as a Product-based factor.

Case 3

Product Complexity

Unlike the other definisions of the "Product Complexity" factor, the DCC participants draw a distinction between some functionality (attributed to the "Product Requirements" factor) and attributes that contribute to a product's complexity. However, as with the uses of the term, the "Product Complexity" factor can be categorised as a Product-based factor.

Our Experience

"Our Experience" shares its definition with the Case 2 factor "Designer Experience", relating to the degree of knowledge and past experience of subjects specific to a particular project. Therefore the same justification can be applied to this when assigning it as a Team management-based factor.

Brief Clarity

"Brief Clarity" shares a similar definition to "Definition Levels (Inputs)" from Case 2 being considered the degree of specificity and the lack of ambiguity of a brief. This is about the transfer of information (requirements, etc.) from the client to DCC and as such, is an Information-based factor.

Budget

As with "Materials Budget" from Case 1, and "Development Budget" from Case 2, the "Budget" factor has no comparable category identified in the literature review. As such this has been assigned to the "other" category for this analysis.

Making / Fabrication

The "Making / Fabrication" factor can be categorised as a Tools & Technology-based factor. From the grouped factors shown in Table 57, this factor considers various equipment required to produce their products, as well as other technologies to be encorproated within the products themselves.

Time Available

"Time Avaiable" can be categorised with two factor types: Team management and Business Management-based factors. Team management, because of terms such as "Scheduling clashes" as part of the grouping (shown in Table 57) which relates to the distribution of other work within the design team. Business Management-based factor as issues such as "How many rounds" relates to how the business decides to operate that specific project.

Subcontractors

In the context of DCC and how they operate, the "Subcontractors" factor can be categorised as both a Tools & Technology and External Influences-based factor. As DCC builds many of their designs in-house, the "subcontractors" factor is a Tools & Technology-based factor as it prompts the consideration of internal production capability (equipment available) and therefore whether the production of a product part needs to be outsourced. Which leds to the External Influences category, as any third party brought onto a project are external to the organisation.

Table 69 Case 3 Categorised Factors

	Team management	Product	Busienss management	Information	Tools & Technology	Client	Project	External Influences	Other
Client (POC)						1			
Product Requirements		1							
Product Complexity		1							
Our Experience	1								
Brief Clarity				1					
Budget									**1**
Making / Fabrication					1				
Time Available	1		1						
Subcontractors					1			1	
Logistics								1	
Instance	2	2	1	1	2	1	0	2	1
Case Percentage	16.67%	16.67%	8.33%	8.33%	16.67%	8.33%	0.00%	16.67%	8.33%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

Logistics

The "Logistics" factor refers to the movement of supplies and the final product(s). This is therefore an External Influence-based factor as DCC's logistics are delt with by third parties.

Considering these factor categorisations (shown in Table 69) there is an emphasis on the Team management, Product, Tools & Technology and External Influence based factors. Although no factor category received greater than two instances, which is a limitation of analysing a small dataset. When comparing the categorisation of the factors identified by the DCC participants to the spread of factors found in the literature review (Table 69) there is some agreement between the datasets, both sharing that emphasis on Team management and Prodcut-based factors, however the other two significant factor categories from DCC do not agree with the literature review findings.

Considering just the top-voted factors, including DCC's decision to combine the "Client (POC)" and "Brief Clarity" factors, this distribution of categories remains largely the same (Table 70). No factor category has more than one instance, with only Team management, Product, Information, Client and Other categories being included. Although mentioned twice in the grouped factors, the Tools & Technology and External Influence based factors categories are not included within the top factors. This may be an indication that such factors are more frequent in occurrence, and therefore do have influence for DCC design projects, but are not as acute as others. Significant in this instance is that the "Budget" factor, an outlier from the categorisation, is included in the top factors. There is a clear difference between the distribution of categories from the literature review and the factors identified by DCC. This indicates a level of disagreement on which factors play a significant role in influencing design project resources.

6.4.b Analysis: The Percentages of Factor Influence

The Percentage Influence Graphs (PIGs) for Case 3 can be found in Appendix 6.7. This section will consider the PIGs and how they depict the behavior of the most influential factors for DCC's design project resource demands.

Client/ Brief Clarity

The PIGs in Appendix 6.7 indicated that the influence of the "Client/ Brief Clarity" factor remains consistent throughout the duration of a project, with a sight increase during the prototyping phase.

Time Avaiable

The influence of the "Time Available" factor (modelled by the PIGs shown in Appendix 6.7) remains constant throughout the design process. Shown in grey, the "Time Available" factor holds between 20%-30% of the overall influence during any given project phase, with few execptions for specific phases and participants (e.g. Participant 2 considers only "Client / Brief Clarity" and "Budget" factors have influence during the prototyping phase.)

Budget

The "Budget" factor's influence is portrayed as being greatest overall throughout the DCC's design projects. Shown in yellow, the PIGs indicate that "budget" controls a large percentage of influence of design effort requirements for all but the prototyping phase, and this is only due to two of the four participants placing less emphasis on it, with the remaining two still considering it to be significantly influential.

Case 3

Table 70 Case 3 Categorised Top Voted Factors

	Team management	Product	Busienss management	Information	Tools & Technology	Client	Project	External Influences	Other
Client / Brief Clarity	1					1			
Product Complexity		1							
Time Available	1		1						
Budget									**1**
Instance	2	1	1	0	0	1	0	0	1
Case Percentage	33.33%	16.67%	16.67%	0.00%	0.00%	16.67%	0.00%	0.00%	16.67%
Literature Review Percentage	24.00%	21.00%	13.00%	11.00%	8.00%	7.00%	4.00%	5.00%	7.00%

Product Complexity

The PIGs in Appendix 6.7 indicated that the influence of the "Product Complexity" (shown in blue) peaks at the Prototyping phase of a DCC design project, with it having little comparitative influence during all other phases. Although sharing a peak in similar phases of their respective project processes, this is in stark contrast to the behaviour of the "product complexity" factors from Cases 1 and 2.

Percentage Influence Graphs Application

As only four members of the DCC design team participated in the estimation activity, only four bars are included in the PIGs, one for each participant. This is the least number of graph sets of any case in this study. Using the "Client / Brief Clarity" factor as an example, in the PIGs for the Pre Sign Off, Technical Build and Final Build phases two participants give significantly more emphaisis on this factor than the other two. In the case of the Technical Draft phase, Participants 1 and 2 attribute less than 10% of the total influence to "Client / Brief Clarity", whereas Participants 3 and 4 attribute more than 25%. This level of disagreement between participants is not uncommon, however when there are such few participant datasets, such disagreements leave a wider margin for what degree of influence a factor might have.

6.4.c Analysis: Mean Effect Plots (MEPs)

This section will consider the Mean Effect Plots (found in Appendix 6.9) generated during Case 3 and what they indicate in their depiction.

Client / Brief Clarity

The "Client/ Brief Clarity" factor remains consistent throughout the duration of a project, with a direct correlation between the level of the factor and the amound of design effort required for the project.

Time Available

The relationship between the *Time Available* factor and design effort levels is shown in Appendix 6.9. These plots illustrate that as the factor level increases (i.e. when it gets worse) the design effort levels needed increase.

Budget

As shown in the graphs of Appendix 6.9, there is an inverse correlation between the *Budget* factor and design activity design effort levels. The higher the factor level (i.e. the larger the budget), the less the demand for design effort.

Product Complexity

Similar to what has been shown in previous plots shown in other cases, the mean effect plots shown in Appendix 6.9 indicates a correlation between the *Product Complexity* factor and design effort levels. This indicates that as the product becomes more complex (its score increases), as does the demand for design effort

Mean Effect Plots Application

This application of Mean Effect Plots to communicate the interactions between factors and project resources has proven to be viable. Intuitive and comprehensible, they demonstrate the degree to which a factor influences resources, as the steeper the gradient, the greater the influence.

6.4.d Analysis: Modelling Factor Behaviour

Combining the information provided by the Mean Effect Plots and Percentage Influence Graphs, two factor behaviours can be identified. The PIGs indicate which factor each participant considers to be most influential, or if any of the chosen factors are influential at all, at a per-phase perspective. For example, the PIGs in Appendix 6.7 indicate that the "Product Complexity" factor has greatest influence during the prototyping phase. The MEPs indicate the correlation between the amount of design effort resource needed and the given level of a factor. The MEPs of "Product Complexity" at the Prototyping phase (shown in

Appendix 6.9) indicate that as the complexity of the product increases, as too does the anticipated amount of design effort needed for the project phase. This combination of MEPs and PIGS for every factor and every project phase provides a holistic view of how each factor's influence changes throughout the duration of the project.

For each of the four factors their behaviour can be determined:

Client / Brief Clarity

From the plots shown in Appendix 6.9, it is possible to identify that the relationship between the *Client / Brief Clarity* factor and design effort levels has a direct correlation, where the higher the score attributed to the client and brief, the greater the design effort required for the project.

Time Available

The influence of the "Time Available" factor is constant throughout the design process and that as the factor level increases the design effort levels needed increase.

Budget

The "Budget" factor is the most influential throughout the DCC's design projects, having an inverse correlation design activity design effort levels. The higher the factor level (i.e. the larger the budget), the less the demand for design effort.

Product Complexity

The "Product Complexity" factor only has significant influence during the Prototyping phase of DCC design projects, at which point, the greater the complexity, the greater the demand on project resources.

Although untested with the DCC participants, the Mean Effect plots were suitable visual representations to easily identify and understand the perceived behaviour of influence over design effort levels Appendix 6.9 clearly illustrates the behaviours shown of each factor, as perceived by each participant. Furthermore, they enable the identification of participants that do not share the same perceptions of these factors as their team members. This clear and simple identification provides opportunities for discussion with these graphs as the focal point.

Percentage Influence graphs further provide valuable insight into these influential factors. Appendix 6.7 illustrates how the influence of each factor changes during a design project and which factors offer the greatest influence for each phase.

In future applications of this method, both Mean Effect plots and Percentage Influence graphs should be used to communicate their respective depictions of factors' influence.

6.4.e Analysis: Experimental Process – Factor Evaluation & Scoring Scheme (FESS)

The development of the FESS before the estimation collection enabled the participants to have a clear reference guide to the types of projects that the experimental design is describing. This is a clear improvement in the overall process and should be continued in future applications of this method.

Similarly, by introducing a per-phase approach to identifying potentially-influencing factors, there were natural points of focus for the discussions to talk around. Furthermore, by using the project phases as a framing device for these discussions, participants were able to "backtrack" to previous stages if potential factors for one phase influenced another.

During the development of the FESS in Case 3, some features were set with binary yes/no levels. This presents a challenge to split the points range evenly for these factors when developing a scoring system. Although not a major issue per se, it is possible that future instances of FESS development may result in complex, uneven point splits that will need to be resolved in the logic of the scoring system spreadsheet.

6.4.f Analysis: Summary

Below (FIG) is a version of the analysis diagram first shown in Chapter 3, which has been amended to reflect the actions and analysis undertaken during, and presented in, Case 3.

6.5 Discussion

6.5.a Communicating Perceived Factor Influence Graphically

By testing the use of Mean Effect Plots and Percentage Influence Graphs as a means of graphically modelling the behaviour of the most influential factors in design projects,

6.5.b Budget as a Top-Voted Factor

Unlike any other case, "Budget" was one of the top-voted factors in Case 3. Moreover, it has been shown to be the most influential factor for DCC's design projects. This is significant as nowhere in literature is there mention of budget, in particular with this degree of influence. This finding must act as a prompt for further investigation to determine if DCC is unique among PDCs, or if this is a significant, yet under represented, influential factor.

6.5.c Numbner of Participants For Robust Comparison

During the analysis of the PIGs, it was challenging to make a comparison between two subgroups of participants whose percentages represented within the PIGs were starkly difference in some instances. This was a limitation based on the size of DCC's design team (all non-director team members were involved in the study with only one of the company directors unavailable to participate. In future cases, where possible, the number of participants should be maximised.

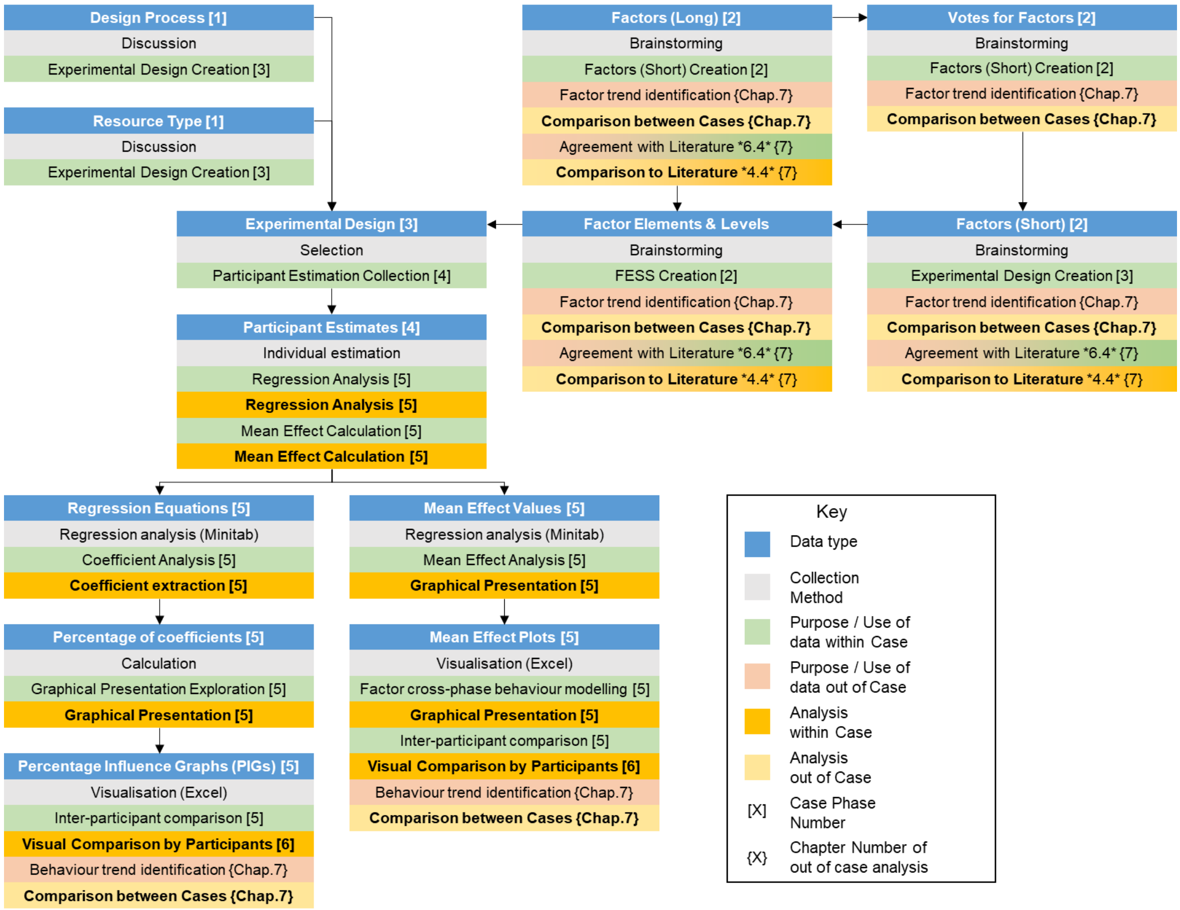


Figure 48 Case 3 Analysis Summary

6.6 Conclusion

Case 3 can be considered a partial success. The CoFIDE method has been verified, with the changes identified in the previous cases being employed and tested. The production of PIGs and MEPs work to model factor behaviour and the creation of the FESS during the early stages of the process worked well. However, as the DCC withdrew their support, citing workload issues, therefore an investigation into how each participant regarded the findings of the CoFIDE method could not be assessed. Likewise, the value in the modelling of factor behaviours could not be determined.

6.6.a Experimental Reflection

This section will collate some additional observations and reflections of the case and discuss what impacts, if any, result from them.

Role of the researcher in the case

The role of the researcher during the case remained generally the same as that in Case 2. The facilitation of each workshop, the preparation of DOE experimental designs, and the analysis of collected data remained the same as before.

6.6.b Answering Research Questions

This section will reiterate the research questions stated in the literature review and provide initial answers to each, based on the findings of Case 3. This multiple round quasi-experimental case-based investigation aims to develop a DOE-based method for the identification and modelling of the most influential factors on design effort demands for product design projects conducted by product design companies. This aim will be achieved by completing the objectives previously stated.

RQ1

> *What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in literature?*

From the results of Case 3, four factors were identified as being the most influential over design project resources: "Product Complexity", "Time Available", "Budget", and "Client/Brief Clarity". These, along with the Factor Evaluation & Scoring Schemes for each, will contribute to this study's understanding of the factors influencing resources and how they compare to those found in the literature.

RQ2

> *How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?*

The Percentage Influence Graphs (PIGs) and Mean Effect Plots (MEPs) developed during this case have modelled the behaviour of each of the four most influential factors.

The findings of Case 3 reiterate the behaviour of **Product Complexity** found in Cases 1 and 2, having direct influence over resource needs; As "product complexity" increases, so too do resource demands. The magnitude of influence, shown in the PIGs in Appendix 6.9, reflects the perceptions of DCB's participants in Case 2, with "product complexity" not having an overwhelming influence over project resources. Taking one further showing that its influence decreases throughout the project. Had the opportunity to interview the participants been available, this question could be explored further.

Case 3

There is a direct relationship between the level of **Client/Brief Clarity** assessed by DCC and the resource demands of the project, shown in Appendix 6.9. The higher (worse) the feeling of the client and brief, the more resources the project will require. The PIGs in Appendix 6.7 also show that this factor has a consistent pervasive influence over project resources, only diminishing towards the end of the project.

Time Available is another factor with consistent influence over project resources. The FESS created for "Time Available" assesses projects against the measures of "Client's timescale", "Amount of revisions planned", "Scheduling clashes", and "Established deadline", as this factor increases in magnitude, as does the anticipated demand for project resources.

The **Budget** factor has some of the most significant influence of any of the factors identified by DCC. As the budget factor improves, the anticipated resource demand is reduced, as shown by the MEPs in Appendix 6.9. "Budget" influences the project and in many instances is the most influential over resource demands.

RQ3

> *How might PDC teams enhance their understanding of the project planning process and their teams through the collaborative capture and modelling of their understanding?*

Case 3 saw the verification of this CoFIDE method, from which Percentage Influence Graphs and Mean Effect Plots were produced. These graphical forms are capable of modelling the behaviour of influential factors to determine what factors exert what influence at what points of a design project. Although discussion with participants was limited and infeasible, it is clear that modelling this behaviour can offer PDCs insight into how these factors influence their projects. From this, viable uses for this insight can be identified and capitalised upon.

PART 3

Part 3 Introduction

"If you spend too much time thinking about a thing, you'll never get it done." – Bruce Lee

Introduction

This part of the thesis starts with a presentation of the results and an analysis of the multiple round quasi-experimental case-based investigation, through a cross-case analysis. This analysis will address the first two research questions of this study (RQ1 & RQ2) by identifying influential factors common to all cases and the identification of a novel influential factor, not found in literature.

The subsequent chapter addresses the third research question (RQ3) by presenting the Collaborative Factor Identification for Design Effort (CoFIDE) method, a method to identify and model the behaviour of the factors which have the greatest influence over design effort levels of product design projects.

The final chapter of Part 3 is the conclusion to this thesis. The conclusion will present the contributions to knowledge that this research has found and will discuss the research impact for industry and within an academic context. The quality of the research and its limitations will also be discussed, with future work also suggested.

7. Cross-Case Analysis

"If facts don't fit the theory, change the facts." –– Albert Einstein

7.1 Introduction

This cross-case analysis presents the collation and analysis of the multiple round quasi-experimental case-based investigation findings and the resulting contributions to knowledge. As the focus of this research is in the investigation of influential factors and attempting to understand their behaviour, this analysis will follow an *analytic induction* approach to identify what Bryman (2012) refers to as universal explanations of phenomena. This chapter will also include a secondary analysis of each of the cases and their findings.

7.1.a Aims

This chapter aims to identify findings from the presented analysis with the aim of answering the stated research questions. Doing so by achieving the following aims:

1. To identify the factors which have the greatest influence over PDC project resources.
2. To determine the behaviour of the influential factors, modelling the changes in behaviour over time.
3. To identify similarities and difference between those factors considered influential in both literature and by PDC designers.
4. To identify suitable graphical modelling approaches to depict the behaviour of influential factors on PDC project resources.
5. To synthesise an output from this analysis that can offer practical value to PDCs.

7.1.b Analysis Structure

This chapter has six sections, the first three present an analysis on the data collected during each case. The remaining three sections consider the techniques adopted within the case and evaluate their value if applied in a PDC context both within and outside of research.

Section 7.2 presents an analysis of the collated influential factors found in each case, drawing comparisons and identifying correlations between each data set, and presents a synthesised list of most influential factors for design effort needs in product design projects.

Section 7.3 presents an analysis of the Product Complexity factor and its dimensions identified within each case. As the only factor common to each case, it calls for additional discussion and analysis. As a contribution to knowledge, this section presents a synthesised list of dimensions of product complexity derived from this analysis.

Section 7.4 presents an analysis of the collated influential factors based on the categorisation developed in the literature review and compares the results of this analysis with the findings of the literature review. A contribution to knowledge is presented showing the differences found between the findings of this analysis and the literature review findings on factor categorisation.

Section 7.5 considers the research approach findings of each case and presents the Factor Evaluation & Scoring Scheme (FESS). FESS is a method developed throughout the cases to define a set of dimensions and scales for assessing the most influential factors of product design project design effort demands.

Section 7.6 presents an analysis of various approaches to graphically model the influence of factors on design effort demands in product design projects. From the presented analysis, two graphical approaches were identified to be the most successful in modelling such factors behaviours, the Percentage Influence Graph (PIG) and the Mean Effect Plot (MEP).

Section 7.7 introduces the subsequent sections as both offer start-to-finish methods which can be applied by design teams, or similar.

7.2 An Analysis of the Influential Factors

Conducting three cases with different organisations provides an opportunity for those factors identified during each study to be compared, to determine which factors are generally seen to be the most influential by practising PDCs. Therefore, this section will discuss the factors gathered during each of the cases and will analyse any commonalities, agreements or disagreements between each of the cases. This section expands upon the work presented in "Planning Product Design & Development: Resource-Influencing Factors Based on Experience" by Holliman, Hird and Thomson, 2018 to include the findings of Case 3.

7.2.a A Comparison of Case Top Factors

This section will consider the top factors found in each case (shown in Table 71) and draw comparisons between them. An initial comparison will exclusively consider the term given to each factor and their voted rank to calculate their importance, shown in Table 72. Consideration will then be given to the scales (or dimensions) of each factor defined within their corresponding case to identify further similarities, with the results of this analysis presented in Table 71 presents the top factors identified in each case, in their voted-for order. From this, some factors are mentioned by each participating group, notably "Product Complexity".

Table 71 presents the top factors from each case, including their rank of importance based of the votes received during each case, with each rank receiving a score (rank 1 = 5 points, 2 =

4, etc.). To facilitate comparisons between datasets, enabling identification of commonalities and agreements, these factors have been categorised using the same scheme developed in the literature review. From which, the significance of each factor can be determined by assessing the cumulative score attributed to each category and their frequency of across the cases. From this, it is clear that "Product Complexity" is by far the most significant factor in this analysis too, accruing the highest score based on vote rank.

Table 71 Cross Case Analysis: Top Factors from Cases Ranked

Rank	Case 1	Case 2	Case 3
1	Project Scope	Client Gut Feeling	Time
2	Product Complexity	Product Complexity	Brief Clarity
3	Regulatory Complexity	Delivery Output Complexity	Budget
4	Prior Knowledge	Definition Level Inputs	Product Complexity
5	Material Budget	(Designer Experience)	-

However, this analysis does not consider the commonalities between different terms. The comparison shown in Table 74 considers the specific text used for each factor, rather than their sentiment.

Therefore, the following subsections will present an analysis of the PDC designers' sentiment for each of the terms identified in the cases. Like the method applied in the literature review, by scrutinising the PDC designers' intent when using each term, an improved basis for comparison can be created. Discussion of each factor identified by their corresponding case participant groups is contained within the discussion of each case chapter, so this section will examine potential commonalities between case factor datasets and the top factors identified within them. Additionally, this section will also consider the behaviour of each of these factors, examining the percentage influence graphs (PIGs) and mean effect plots (MEPs) of each to determine specifically how these factors influence design effort needs of PDC projects. A more detailed discussion on the behaviour of each factor, modelled by the PIGs and MEPs shown in the appendices, has been included within each case chapter, therefore this section will cover the assumed behaviour of each factor identified through this cross-case analysis. Note this section will not include the "management" data from Case 2, as no other PDC considered this resource type.

Table 72 Cross Case Analysis: Case Factor Ranks Analysis

Literature Review Factor Categories																
Time											5				5	1
Regulatory Complexity			3												3	1
Project Scope	5														5	1
Product Complexity		4					4							2	**10**	3
Prior Knowledge				3											3	**1**
Material Budget					1										1	1
Designer Experience										2					2	1
Delivery Output Complexity								3							3	1
Definition Level Inputs									2						2	1
Client Gut Feeling						6									5	1
Budget													3		3	1
Brief Clarity												5			5	1
Factor	Project Scope	Product Complexity	Regulatory Complexity	Prior Knowledge	Material Budget	Client Gut Feeling	Product Complexity	Delivery Output Complexity	Definition Level Inputs	Designer Experience	Time	Brief Clarity	Budget	Product Complexity	**Total Score**	**Instance**
Rank	1	2	3	3	5	1	2	3	4	4	1	1	3	4		
Cas	1	1	1	1	1	2	2	2	2	2	3	3	3	3		

Brief Clarity

“Project Scope”, “Definition Levels (Inputs)” and “Brief Clarity” are terms within each case relating to the brief and how clearly it has been written. Measured on a scale between “Ambiguous” and “Defined” (Case 1); other cases have a more detailed scale. For example, in Case 2 the term “Definition Levels (Input)” is coupled dimensions that include “Scope definition" (is the scope of the project has been established?); "Budget" (is there a clear established budget for the project?); "Background Research" (has the client provided their own research, supplementing the brief?); and "Milestones" (has the client defined specific timeframes that the project should be completed within?). With clear links between them, these factors can all be defined under the term "Brief Clarity", shown in Table 73, measured on a scale of "ambiguous" to "Defined".

The PIGs representing these factors across the cases share some commonalities. Particularly when considering "Project Scope" (Orange in Figure 49) and "Definition Level (Inputs)" (Orange in Figure 50), their influence is significantly top-heavy, with the greatest influence had at the project outset, reducing in influence with every successive phase. The MEPs for these factors indicate that the greater the clarity, the less design effort is required, and conversely the more ambiguous, the more design effort is required. Therefore the proposed factor of "Brief Clarity" is considered highly influential during the early phases of a project, with an inverse correlation between the clarity and the design effort required.

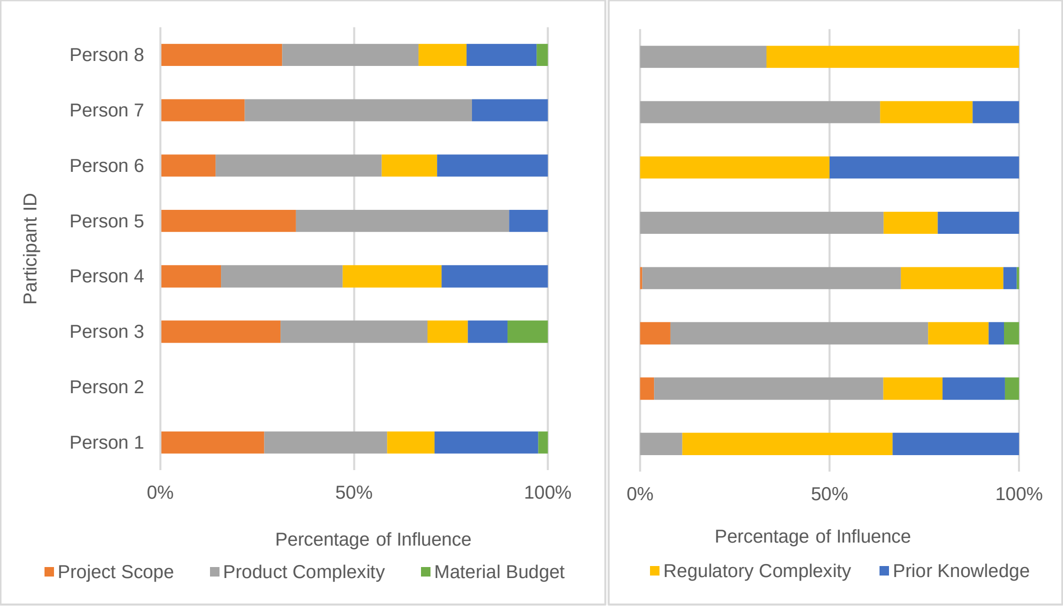


Figure 49 Cross Case Analysis: Case 2 PIG for Gather Phase (left) and Documentation 2 Phase (right)

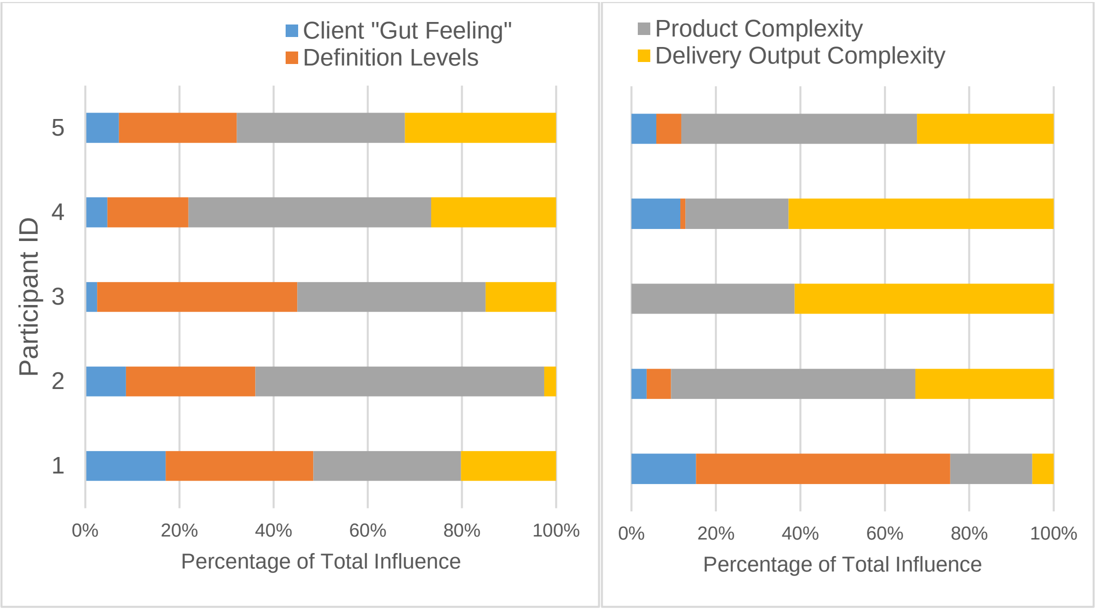


Figure 50 Cross Case Analysis: Case 2 PIG for Discover Phase (left) and Deliver Phase (right)

Designer Knowledge and Experience

The terms "Prior Knowledge" and "Designer Experience" are clearly related, as one of the foundations of knowledge is experience. The Case 1 participants defined the measurement scale of Prior Knowledge as being between "no knowledge" and "expert"; Case 2 participants did not specifically define a scale for Designer Experience, however, the terms used to define the factor include multiple instances of the term "knowledge". The measurement of knowledge and experience is a particular challenge and is inherently subjective, yet experience is key to the modelling and planning of design processes (Eckert and Clarkson, 2010) and therefore must be considered the same factor. This factor shall be measured on a scale between "novice" and "expert".

Considering the PIGs of "Prior Knowledge" in Appendix 5.7, the influence of this factor remains even throughout the project. Mean Effect Plots for "Prior Knowledge" indicate (unsurprisingly) that the more experience or knowledge that a designer, or design team, have, the less design effort is required. Model data is not available for "Designer Experience", however, it can be assumed that there will be an agreement between the participants . Therefore, the factor of Designer Experience would have an even level of influence throughout a project and would have an inverse correlation between experience and the design effort required.

Regulatory Complexity

The term Regulatory Complexity occurs in both Case 1 and 2 explicitly, yet only the Case 1 participants regarded it as a key influential factor, assigning a scale range between "simple" and "complex". Case 2 participants gave no further terms to apply to this phrase, yet both teams discussed legislation and international standards as contributing elements to the term. Both teams further agreed that the bureaucratic tasks required to adhere to said standards would require significantly more time to accomplish. These can be combined with the "Delivery Output Complexity" factor identified in Case 2.

Considering the PIGs from Case 1, the influence of "Regulatory Complexity" peaks at the project outset and (in the case of DCA) phases relating to documentation. It can be assumed that these "documentation" phases include activities around testing and accreditation and the initial phases will include research into what regulations may influence the development of a product. The MEPs from Case 1 further indicate that the more regulation that a project will include, the greater the demand for design effort. Therefore the "Regulatory Complexity" factor will have the greatest influence at the project outset and whenever documentation, testing, etc. activities are included within a design process.

Designer's Intuition of the Client

The Gut feeling of the client is a generalised term for a tacit intuition that the management of Case 2 has on their client. It is informed by the contributing elements, Client experience, Judge of character, Scope alignment, Client "hand holding", Willingness to compromise, Scope Creep, Client Expectations, Client's motivation for the product, Laws of physics (a client's ability to rationally understand what can, and cannot be done), Decision-making chain, Client responsiveness, Client management, Curveballs and interruption, and University research project. Other than University research project¸ (a simple binary categorisation) none of these elements can be fully assessed objectively. When the researcher asked for further information on how the participants would measure these traits, the participants synthesised a four-entry checklist in which clients could be objectively measured against (Technical Experience, Business Experience, Personality and Competency), based on their interactions with the design team and the information they provided. One can draw a partial link between these categorisations and the discussions of personality (Bryson and Delbecq, 1979). Yet Bryson and Delbecq's discussion of personality relates to that of the design team, not that of the client, and does not refer to the designer's perceptions and intuition of the client. Remarks in other literature entries refer to priorities which may have similar links, yet do not expand beyond the factor name. Case 3 participants did highlight the issue of client gut feeling as a measure of their "Client / Brief Clarity" factor, which can therefore be matched together. This is a challenging factor for the author to define a scale for, therefore a suggested scale of "bad" to "good" is proposed, although, for any practical applications within a PDC, more concrete terms should be determined by the design team.

Considering the Case 2 PIGs in Appendix 5.7, the influence of "Client Gut Feeling" is consistent throughout a design project. Likely this is due to the constant interaction needed with a client therefore if there is a poor "gut feeling" with the client, then there will likely be one or more issues that will require more time (and therefore design effort) spent on the project. The MEPs for "Client Gut Feeling" indicate that the better the feeling of the client (i.e. the higher the score), the less design effort will be needed for the project. The overlap that Case 3's "Brief/Client Clarity" factor has, confirms this behaviour. Therefore, the factor "Designer's Intuition of the Client" will influence a design project and has an inverse correlation between the score of the client (the designer's opinion of the client) and the requirement for additional design effort.

7.2.b Ranking Factor Influence

Adopting the clarification and categorisation suggested in the previous section, the factors can be re-evaluated for comparison using the same approach as shown in Table 73. As before, with their ranked votes are used to indicate the participants' weight of significance to them. Table 73 shows this and highlights some notable changes to the overall scoring, presenting the same structure as Table 72, but considers the sentiment of each factor just discussed. Table 73 saw "Product Complexity" as having the highest score (of 10). Yet now "Brief Clarity" has superseded this factor, and "Client Gut Feeling" equalling its score with "Product Complexity". Within this study, "product complexity" has been placed in second place, as it is mentioned explicitly in all three cases.

From this analysis, it can be determined that the factors of "Brief Clarity", "Product Complexity", "Client Gut Feeling" and "Delivery Output Complexity" are considered the most influential of design effort needs in PDC design projects. There are limitations to this conclusion, naturally one cannot make a sweeping generalisation about the entire PDC industry based on the data collected from three PDCs, however, this is indeed indicative of the perceptions of industry as a whole.

Delivery Output Complexity

With a name taken from the factor found in Case 2, "Delivery Output Complexity" encompasses the issues found in the "Regulatory Complexity" factor discussed previously, expanded to include issues relating to manufacturing and similar. The associated MEPs indicate that as the anticipated complexity of deliverables increases, so too does the expected amount of design effort required.

Product Complexity

There is one further factor which has yet to be addressed within this analysis, "Product Complexity". Due to the significance of this factor and the quantity of data collected on it, this will be addressed in a separate section.

Table 73 Cross Case Analysis: Collated Case Factor Ranks Analysis

Cas	1	1	1	1	1	2	2	2	2	2	3	3	3	3		
Rank	1	2	3	3	5	1	2	3	4	4	1	1	3	4		
Factor	Project Scope	Product Complexity	Regulatory Complexity	Prior Knowledge	Material Budget	Client Gut Feeling	Product Complexity	Delivery Output Complexity	Definition Level Inputs	Designer Experience	Time	Brief Clarity	Budget	Product Complexity		
Collated Factor Categories (Re-categorised)																
Budget													3		1 3	**Instance** **Total Score**
Client Gut Feeling						5						5			1 5	**Instance** **Total Score**
Delivery Output Complexity			3					3							2 6	**Instance** **Total Score**
Designer Experience				3						2					2 5	**Instance** **Total Score**
Material Budget					1										1 1	**Instance** **Total Score**
Product Complexity		4					4							2	3 **10**	**Instance** **Total Score**
Time											5				1 5	**Instance** **Total Score**
Brief Clarity	5								2			5			3 12	**Instance** **Total Score**

7.2.c Research Output - Factor Influence Summary

This section has discussed the factors found to be most influential of design effort needs of PDC projects, as considered by the participants of three cases. Within this discussion, four factors have been derived from the differences between case data and behaviours for each factor have been established through the examination of the mean effect plots (MEPs) and percentage influence graphs (PIGs) produced during their corresponding case. The results from this analysis have been summarised in Table 74

The *Designer Experience* factor considers the knowledge and skill members of a design team have on the specific areas required for any given project, measured on a scale between novice (no experience) to expert (highly competent with subject area). From this analysis, it has been shown that as a designer's experience increases, the demand for design effort decreases. This factor has been shown to have an even distribution of influence over the duration of a project.

The *Brief Clarity* factor considers the specificity and precision of a client's brief. Given a scale between ambiguous and defined, this analysis has shown that as the clarity of a brief increases, the demand for design effort decreases. This phenomenon is most clearly observed at the project outset, with its influence reducing over the duration of a project.

The *Designer Experience* factor considers the knowledge and skill members of a design team have on the specific areas required for any given project, measured on a scale between novice (no experience) to expert (highly competent with subject area). From this analysis, it has been shown that as a designer's experience increases, the demand for design effort decreases. This factor has been shown to have an even distribution of influence over the duration of a project.

Table 74 Cross Case Analysis: Factor Influence Behaviour

Factor	Behaviour	Correlation	Scale
Brief Clarity	Top-heavy, reducing over the project duration	Increased clarity, decreased design effort	Ambiguous – Defined
Designer Experience	Even	Increased experience, decreased design effort	Novice – Expert
Designer's Intuition of the Client	Even	Increased opinion, decreased design effort	Bad – Good
Delivery Output Complexity	Bottom-heavy (*Documentation & Testing Phases)	Increased complexity, increased design effort	Simple - Complex

The *Designer's Intuition of the Client* factor considers how a designer (or design team) regards their client, and is measured on a general bad to good scale, with an increase in (positive) opinion of a client resulting a decrease in design effort demands.

The *Delivery Output Complexity* factor considers the ultimate deliverables of a project; the quantity and types of deliverables, measured from simple to complex. From this analysis, it has been shown that as the delivery output complexity of a project increases, as too does the design effort demands. The behaviour of this factor has been categorised as bottom-heavy, as the latter phases of a design project are most greatly influenced by this factor.

These factors can be considered as the most influential of design effort needs in PDC design projects, except for Product Complexity, which will be discussed in the following section. This research output offers value to PDCs by providing insight into these factors which can be used for design project planning. This can take the form of understanding when to add contingency resources (design effort) within a project plan to compensate for each factor's influence, and to take steps to mitigate the negative impacts that these factors may have through training (in the case of "Designer's Experience") and educating the client (in the case of "Designer's Intuition of the Client").

7.3 Defining and Measuring Product Complexity

As discussed in the previous section, "product complexity" is a significant factor found in the case data. Unlike any other factor, it features in all three PDCs' most influential factor lists. Not only that, but each case also includes a participant-generated range of dimensions to assess product complexity and therefore a comparison between these dimensions can be made. Furthermore, a comparison to dimensions found in the literature can be made, from which some findings and recommendations can be made.

This section will start with a discussion of the behaviour of product complexity, followed by the definitions of product complexity found in the sources identified in the literature, followed by a discussion of the dimensions identified in the cases, contextualising the definitions developed from the literature.

7.3.a The Behaviour of Product Complexity's Influence

The assumption that one might make is that as the anticipated complexity of a product increases, so too does the anticipated amount of design effort. This is underscored by the MEPs and PIGs from each of the cases. The results form Case 2 show that the influence that "Product Complexity" peaks at the "design" phase. That is the concept generation and development phase of the project. In contrast, the PIGs of Case 3 indicate that not only does Product Complexity not have the greatest influence during the concept development phase, instead further on in the project during prototyping; but that it is not the most influential in comparison to the other three factors. Case 1 data tends to agree with the findings of Case 2, being the most influential overall, but its influence being ever-present, but peaking in the concept generation and development phases, from the Imagine phase, through to Documentation 2.

7.3.b Dimensions of Product Complexity in Literature

By defining the characteristics of product complexity, attention can be given to the measurement of them as a means of measuring product complexity itself. If measures of complexity are agreed upon, then it would be possible for designers to identify risks to project cost, risks to project scope and risks and project schedule; as well as select alternative structures to avoid unnecessary complexity (Ameri et al., 2008; Hölttä and Otto, 2005; Phukan et al., 2005; Summers and Shah, 2003). Fundamentally, it is possible to minimise the design efforts of a team if a measure of complexity can be defined and used (El-Haik and Yang, 1999).

There are many measures of product complexity found in literature. Table 75 provides sample of such dimensions and presents a categorisation of these dimensions, with the categories identified from the definitions provided by the authors of each source. By categorising these measures, it is possible to draw comparisons between different terms by examining their commonalities. Once collated, any differences between datasets can be identified. Likewise, with similarities, from which conclusions can be drawn. Table 75 also considers the significance of each category through totalling total number of sources found and presenting the percentage of this total each category has. Hubka and Eder (1988) define four levels of complexity for a technical system (the output of design activity). Ultimately, this is a single-dimension measure of complexity, based on the number of parts and subassemblies within a system, but many other sources consider many more. Simon (1996) and Moran and Carrol (1996) consider the number of these parts and the interconnectivity between them, whereas the number of parts becomes one contributing element to the dimension of size and coupling, as discussed by Ameri et al. (2008). In her doctoral thesis on the measurement of complexity in product development, Xiao Qi Zhang (2017) proposes a knowledge-based scale to measure complexity to evaluate the complexity of individual functions and integration tasks, where the intensity and diversity of knowledge requirements are incorporated.

These sources were found using the multi-source search engine Scopus to identify peer-reviewed papers with "product complexity" in the title. These sources were analysed to identify such dimensions, which in turn, can be measured and act as a quasi-measure for product complexity. One challenge found when reviewing these sources is the blur between dimensions that are explicitly product-related (those that describe a characteristic, feature, etc. of the intended product to be designed) and those which are organisational, environmental, or similar. Discussion of specific stakeholders involved in a project within the literature (Hobday, 1998; Lloyd, 2001; Moulianitis et al., 2004; Shah and Runger, 2013; Summers and Shah, 2003; Weber, 2005; Zhang and Luo, 2007) is broad and clearly influential over design projects. Yet these are also clearly project-centric issues. There are, however, dimensions that are not as clear cut. The creativity required to solve a design problem is well-regarded within the literature, (Ahmadinejad and Afshar, 2011; Barbalho et al., 2019; Bolaños and Barbalho, 2021; Frenken, 2006; Maurer, 2017; Novak and Eppinger, 2001; Pugh, 1991; Wang et al., 2021; Weber, 2005) and relates directly to the features of the intended design. However, this is viewed in the context of the abilities of design teams. Is this a true dimension

Table 75 Cross Case Analysis: Dimensions of Product Complexity in Product Design in Literature

Measure	Example of text	Source	Instances	Sources	Percentage of Measures
Functionality	Function, technology involved, integrated software, etc.	Bashir and Thomson (1999), Bashir and Thomson (2004), Bolañosa and Barbalhob (2021), Danilovic and Browning (2007), Danilovic and Browning (2007), Gonzalez et al. (2020), Griffin (1997), Hobday (1998), Hobday (1998), Hubka and Eder (2012), Kannapan (1995), Kota and Ward (1990), Kusiak and Szczerbicki (1992), Lindemann et al. (2009), Mauer (2017), Maurer & Lindemann (2007), Meyer and Utterback (1995), Pugh (1991), Shafiee et al. (2019), Shah and Runger (2013) , Shou et al. (2017), Shou et al. (2017), Tatikonda and Rosenthal (2000), Wang et al. (2021), Weber (2005), Xu and Yan (2006), Yoon et al. (2022), Zirger and Hartley (1994),	33	27	43.5%
Components	Type of, Number of, Interactions/Interdependencies between, etc.	Bashir and Thomson (1999), Bashir and Thomson (2004), Bolañosa and Barbalhob (2021), Danilovic and Browning (2007), Gonzalez et al. (2020), Griffin (1997), Hobday (1998), Hubka and Eder (2012), Kannapan (1995), Kota and Ward (1990), Kusiak and Szczerbicki (1992), Lindemann et al. (2009), Mauer (2017), Meyer and Utterback (1995), Pugh (1991), Shafiee et al. (2019), Shah and Runger (2013) , Shou et al. (2017), Ssah and Runger (2013), Tatikonda and Rosenthal (2000), Wang et al. (2021), Weber (2005), Weber (2005), Xu and Yan (2006), Yoon et al. (2022), Zirger and Hartley (1994),	24	13	21.0%
Creativity*	Skills required, Effort to design, Disciplines used, etc.	Ahmadinejad and Afshar (2011), Barbalho et al. (2019), Bolañosa and Barbalhob (2021), Frenken (2006), Mauer (2017), Novak and Eppinger (2001), Pugh (1991), Pugh (1991), Shah and Runger (2013), Wang et al. (2021), Weber (2005)	7	7	11.3%
Form	Size, Shape, Structure, Architecture, etc.	Henning et al (2022), Hobday (1998), Xu and Yan (2006)	6	3	4.8%
Regulation	Regulatory intensity, Quality requirements	Hobday (1998), Mauer (2017)	4	3	4.8%
Manuf. & Assembly	Assembly complexity, Manufacturing difficulty, etc.	Alkan (2019), Hobday (1998), Shou et al. (2017), Ssah and Runger (2013)	5	5	8.1%
Financial	Unit cost, financial scale	Hobday (1998), Ssah and Runger (2013)	3	3	4.8%
Materials	Number of materials	Shou et al. (2017)	1	1	1.6%
			83	62	

of product complexity? These dimensions have been included in Table 75, although whether they belong on the list is still subject to debate.

What is shown in this literature, is that although there is some agreement between studies, as to the measure of product complexity, there is clearly still a high degree of disagreement as to what dimensions contribute to product complexity, as reflected in the right-hand columns Table 75. This review posits a further question, how does one measure these dimensions of product complexity? Many of the sources' reviews had their suggestions, including a simple numerical count, or scaled levels, like those shown in Hubka and Eder (1988).

The following section will provide definitions for each of the factors identified in the cases, comparing them to terms found in literature and attributes a category (or categories) to each.

Case 1 - "Number of Disciplines"

The anticipated number of engineering disciplines expected to be involved in the development of a product. In all the case PDCs, there were members of the design team with specialist expertise, from patents and regulatory issues to electronics and software development. This was covered by Weber (2005) with their term "number of disciplines involved in creating the product/system".

Case 1 - "Functional Diversity"

The anticipated number of operational functions the product will have is ubiquitous across the literature (Bashir and Thomson, 1999a; Bolaños and Barbalho, 2021; Griffin, 1997; Hobday, 1998; Hubka and Eder, 2012; Kannapan, 1995; Kusiak and Szczerbicki, 1992; Lindemann et al., 2009; Pugh, 1991; Shafiee et al., 2019; Wang et al., 2021; Zirger and Hartley, 1994).

Case 1 - "Frequency of Interaction"

The anticipated frequency with which the product will be in use. Measured on a scale of "None" to "Constant" defined in Case 1, this aligns with the factor suggested by Hobday (1998) of "Intensity of user involvement".

Case 1 and 2 - "Number of Parts"

The anticipated number of parts the product will have. This ranges from a single part to over 30. Case 2 participants stated that as the number of parts increased, the anticipated degree of complexity the product would have. This shares clear links with the "components" dimension, with many sources found in the literature that agree with the inclusion of this dimension.

Case 2 - "Static or Dynamic"

The anticipated level of motion a product will have. This ranges from a fixed, stationary product, to a moving product with moving parts. According to Case 2 participants, the greater the level of motion, the more time will be required to design the product. This broadly aligns with the dimensions of "type of dynamics" and "Amount of possible states" defined by Mauer (2017), which are included within the "functionality" dimension.

Case 2 - Electronics to be developed

Whether the product will likely require any electronic components to be included. This ranges from a complete absence of any electronic part to one that has a user interface and user experience, with sensors, controllers, etc. According to Case 2 participants, the more electronics a product requires the more time it will take to develop the product. Electronics fall under the broader term of technology of which there have been many inclusions within the "Functionality" dimension in Table 75 (Danilovic and Browning, 2007; Lindemann et al., 2009; Maurer and Lindemann, 2007; Meyer and Utterback, 1995; Tatikonda and Rosenthal, 2000; Yoon et al., 2022).

Case 2 - Level of problem-solving

The anticipated degree of mental challenges presented by the project. This can range from the inclusion of complex movements, power systems, etc. to overcoming a particular set of functional requirements that are not complimentary. Problem-solving is a variety of "creativity", with Summers and Shah (2003) and Lloyd (2001) stating problem-solving as a dimension.

Case 2 - Standard vs. Custom Parts

The number of parts which require design effort to produce. This ranges from a product in which all parts are already available from suppliers to a product where the components must be designed by Case 2. According to the participants , the greater the number of parts to be designed, the more time will be required to design them. Within the literature reviewed and shown in Table 75. Yet no specific source considers a ratio between standard and custom parts, yet with 24 separate dimensions from 13 sources discussing components or parts, this can clearly be categorized as a "Components" dimension.

Case 2 - Difficulty of CAD

The perceived difficulty involved in producing CAD drawings, files, etc. for the product. This will relate to various elements, including the complexity of the product’s form, the number of parts, etc. According to the participants , the higher the perceived difficulty in producing CAD files for a product, the more time will be required to produce them. This relates to the "product shape" dimension defined by Xu and Yan (2006), which falls under the "Form" categorisation. Yet this can also be considered a "creativity" dimension, as a more challenging form will require more effort to design (Shah and Runger, 2013) for the CAD operator.

Case 3 - Level of invention required

Considers how much development would be required to create mechanisms, etc. as part of the overall product. Case 3 participants stated that the higher the level of invention required, the more complex the product would be. This, like "Level of problem-solving" has clear links to the "Creativity" dimension.

Case 3 - Future maintenance

The lifespan of the product and the likelihood that Case 3 would have to perform care or other maintenance steps after the product was deployed. One of the likely triggers for maintenance would be its use and the location in which it was used, which can increase wear and tear. Case 3 participants suggested that, although product complexity can be seen to influence maintenance requirements, they stated that more time would be spent in the development of the product if there was an anticipated increase in maintenance needs. Based on the definition provided by the Case 3 participants, this dimension may fall under "Functionality" or "Manufacturing" categories, with no specific dimension found in the literature.

Case 3 - Material Complexity

The complexity of handling the material. This includes its fragility, as well as the difficulty of its use. Case 3 participants suggested that as material complexity increases, so too does product complexity. This is a clear dimension which would fall under the "Materials" dimension categorisation.

Case 3 - Product Scale

The size of the product was regarded by the Case 3 participants as influential over product complexity, increasing with size. The dimensions of "size" were identified by Xu and Yan (2007) and Henning et al. (2021) and included as part of the "Form" dimension.

Case 3 - Number of Material Types

The anticipated number of different materials likely to be used in the final product. This ranges from a single material to over 4. Case 3 participants stated that as the number of materials to be used increased, so too would the anticipated degree of product complexity, falling into the "Materials" dimension.

7.3.b Collation of Case Dimensions for Product Complexity

There is an unusual dichotomy shown in the results from Case 3 in comparison to the other results. Unlike Case 2, The PDC of Case 3 produce their prototypes and manufactures many of their designs in-house, with members of their design team acting as makers also. This may suggest the greater focus on manufacturing and materials-related dimensions ("material complexity" and "number of materials"), as shown in Figure 51. These are practical issues which they must face. This contrasts with the more whimsical or colloquial nature of the levels they assigned to their scale, which seem less practical, in comparison to those of Cases 1 and 2. Case 1 and 2’s dimensions have a closer alignment to those found in the literature. Although Case 1’s results only consider three categories total, they are the same three as the most significant found in the literature. Similarly, Case 2’s dimensions have a greater focus on parts and functionality, issues that are generally considered at earlier stages of the design process.

Having applied the same categorisations to the most influential factors found in each of the cases, there are several instances where a factor identified in a case falls into multiple categories. Totalling the number of categorisations and instances for each factor and case, Figure 51 presents a comparison the percentage of category instances to illustrate the difference in focus between the literature review findings and the findings of the cases.

Figure 51 Cross Case Analysis: Dimensions of Product Complexity Comparison of Individual Case Results (Percentage)

However, drawing a comparison between a collection of analysed literature and case data at an individual level is not a robust approach. Figure 52 presents the combined percentages of the case data, presenting a more balanced, fair comparison. However, even this cannot compare the differences in attitudes between the literature on Product Complexity and those held by the PDC industry. A much broader study would need to be conducted to assess this.

When considering Figure 52, it is clear that the dimensions of "functionality", "Components" and "Creativity" hold the greatest significance over the assessment of product complexity, and that both the literature (totalling 75.81%) and the case data (totalling 72.23%) reflect an agreement. That said, the significance that "functionality" has over product complexity, as perceived by the PDC design team members is notably less, with a more even distribution between the top three dimensions.

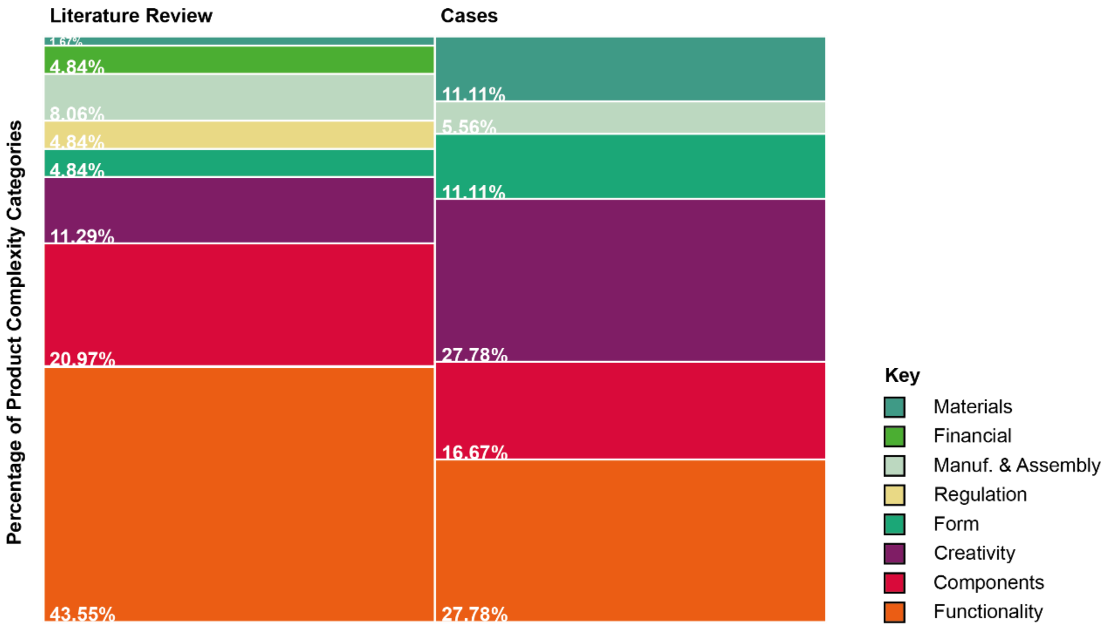


Figure 52 Cross Case Analysis: Dimensions of Product Complexity Comparison of Combined Case Results (Percentage)

As a dimension, the significance of the anticipated number of components within a product remains similar between datasets, indicating agreement between the literature sources and the participants . However, the same agreements cannot be said of the "Creativity" dimension. Considering issues such as what skills are required of the design team, the perceived effort needed to design the product and the number of disciplines, the "Creativity" dimension has more than twice the significance within the case dataset (27.78% to the literature's 11.29%). This may be the result of the differences in organisation types the data was derived from. As mentioned in Chapter 1, PDCs are SMEs with small teams and some degree of speciality. For example, one member of the team may have a background in electrical engineering. Whereas, certainly several of the studies contained within the literature review (chapter 2, rather than the additional one included within this section), gathered data from large businesses which will have specific teams from different disciplines (electrical, etc.), and have specific use cases for the resource estimation tools, and therefore will likely have experience with the technical areas a project will demand. Conversely, as emphasised in Chapter 1, PDCs have such a diverse range of potential project types, while comprising a small number of designers, that there is an increased likelihood that the specialist areas associated with a new project could be unfamiliar. This would lead to a greater significance being placed on this familiarity within the context of "product complexity".

Additionally, considering the dimension of "regulation", this is a measure that, in literature, is associated with product complexity. However, when exclusively considering Figure 52, one would assume that PDCs do not need to assess the regulations when developing a new product. However, from the findings of the cases, regulations, and the complexity they present to design teams, has such influence and significance, that PDC teams have made it their own distinct factor. The same can be said for the "financial" measure (the specific terms found in literature being "Unit cost" and "financial scale"), but this measure will be covered in detail in a later section of this chapter.

7.3.c Synthesising the Dimensions of Product Complexity

From this analysis of literature and case data, several dimensions of product complexity can be derived. Specifically, those that hold a strong agreement between data sources, those of "number of components", "functionality" and "creativity". As huge significance is placed upon these three dimensions (assessed by the number of mentions within literature/case data) is so great (totalling over 70%), these are used as the dimensions, and therefore the de facto measures of "product complexity".

From the case data, it is possible to further define these dimensions, by deriving units of measure for each dimension can be measured. As all cases include a 4-point scale for these dimensions, this section will synthesise a unit of measure derived from these 4-point scales.

Number of components

The units of measure used within the scales for "number of parts" in Case 1 and Case 2, shown in Table 76, are both simply numbers, therefore little is need to deviate from this. This analysis did include a qualitative measure for the ratio between the number of standard (i.e. of the shelf) parts and the number of parts to be designed as part of the project. Therefore, an additional measure can be derived that follows on from the "number of parts", as a percentage, i.e. what percentage of the anticipated number of parts are anticipated to be custom designed.

Table 76 Cross Case Analysis: Scales for Product Complexity Dimension "Number of Parts" from Cases

Case	Characteristic	I (1)	II (2)	III (3)	IV (4)
1	**Number of Parts**	1 – 5	6 – 30	30 – 99	100 +

2	**Number of parts**	1	Up to 5	Up to 30	30 +
2	**Standard VS Custom parts**	All standard	Most standard	Most Custom	All Custom

Functionality

The scales of "Functionality" from each of the cases are qualitative, providing indicative qualities/values to assess a potential product by. The anticipated number of functions the product will have, shown as "Functional Diversity" from Case 1 (Table 77), can be re-defined to be numerical, i.e. "Anticipated Number of Functions". As a dimension, "Static or Dynamic" can also be redefined numerically if it is recontextualised to refer to the anticipated degrees of freedom the product will have, with zero used to represent a fixed, static object; adding 1 for each axis of movement (*x,y,z*) and rotation (pitch, roll, yaw). In effect, this would be a 7-point scale. This is further emphasised by considering the source of Case 3's "level of invention required" measure. From Chapter 7, it is shown that this dimension was derived by the participants from the factor "does it have wheels?", alluding to the mobility of the product as a cause of complexity.

Table 77 Cross Case Analysis: Scales for Product Complexity Dimension "Functionality" from Cases

Case	Characteristic	I (1)	II (2)	III (3)	IV (4)
1	**Functional Diversity**	Single	Few	Many	Infinite
2	**Static of Dynamic**	Fixed	Fixed with some moving parts	Fixed with lots of moving parts	Moving with lots of moving parts
2	**Electronics to be developed**	None	Yes, no UI/UX	Yes, UI/UX (buttons and screen)	Yes, UI/UX, sensors control etc.
3	**Level of invention required**	Minimal	Average	Lots	WTF!

The need for "electronics to be developed" refers to the functionality of the product. The more electronics-enabled functionality the product has, the higher among of electronics to be developed and the greater the need for electronics outright. Therefore, a second measure of "Functionality" should refer to the electronics needed in a product. However, as will be discussed in the next subsection, more specialisms might be required in a product, such as pneumatics, hydraulics, chemistry, etc. etc. Remaining within the scope of functionality, an additional measure added to the "number of anticipated functions" of a product, should be "anticipated number of function-facilitating technologies required". Again, this can purely be counted.

Creativity

As discussed in the analysis of the literature for this section, the creativity dimension is more diverse in its definition, although sharing the key theme of creativity. From the literature, the number of disciplines was a key feature, therefore this anticipated number of disciplines will remain a countable measure of creativity within this context. This measure is a simple count, like that shown in Table 78. This is echoed by the "electronics to be developed" from Case 2. As mentioned in the previous discussion of "functionality", this is purely one of several specialisms to be considered.

Table 78 Cross Case Analysis: Scales for Product Complexity Dimension "Creativity" from Cases

Case	Characteristic	I (1)	II (2)	III (3)	IV (4)
1	**Number of Disciplines**	1	2	3	4 +
2	**Electronics to be developed**	None	Yes, no UI/UX	Yes, UI/UX (buttons and screen)	Yes, UI/UX, sensors control etc.
2	**Level of problem-solving**	None	Basic	Medium	Complex
2	**Difficulty of CAD**	1	2	3	4
3	**Level of invention required**	Minimal	Average	Lots	WTF!

The "level of problem-solving" (CS2) and "Level of invention required" (CS3) relate to the anticipated degree of challenge faced by the designers. Measured qualitatively (shown in Table 78), it is difficult to generate a quantitative measure from this scale alone, There are two distinct approaches which could be adopted.

A percentage of confidence could be applied as a measure, reflecting how confident the design team are with the challenges presented by the product. As with all percentage evaluations where direct measurement cannot be done, this is abstract, subjective, and potentially inaccurate. However, it can be indicative and therefore potentially valuable. Alternatively, this whole dimension could be an addition to the "functionality" measure. Viewed from this perspective, a measure can be added to the "number of function-facilitating technologies". This can take one of two forms. Either an overall evaluation of the design team and whether or not they have experience with the function-facilitating technologies counted, and therefore a single measure; Or a per function-facilitating technology (i.e. a further scale depicting the level of in-house understanding of each technology required).

7.3.d Research Output – Dimensions of Product Complexity

It can be determined that the most suitable dimensions for product complexity that are viable for PDCs are "Number of Parts", "Functionality", and "Creativity", with their scales shown in Table 79. The synthesis of this can be considered a contribution of this study. There is value to be had for PDCs by understanding how "product complexity" influences design effort demands. From where within a design project it has the greatest influence, to how it can be measured. The presented dimensions of "product complexity" enable PDC design teams to assess their projects, with a standardised, replicable list, providing context and insight to aid their project planning.

Table 79 Cross Case Analysis: Dimensions and Scales of Product Complexity

Dimension	Scale	Units
Number of Parts	Number of Parts	-
	Percentage of Parts to be Custom Designed	Percentage
Functionality	Number of Functions	-
	Degrees of Freedom	0-7
	Number of function-facilitating technologies	-
Creativity	[EITHER] Percentage Confidence of Design Team Abilities [OR] Percentage of understanding of function-facilitation technologies identified	Percentage

7.4 Factor Categorisations: Case Data Analysis

7.4.a Factor Categorisations

In itself, the categorisations of design effort influencing factors on design projects can be regarded as a contribution of this thesis. However, there are further refinements to this categorisation that need to be considered. This section will discuss the factor categorisations defined in the literature review, categorises the factors collected from each of the cases and compares them to the literature review findings. From the literature review, nine categorisations of factors were synthesised, excluding those that were not practically valuable in the context of this study. These factor categorisations were, in order of frequency of occurrence: Team management, Product, Business Management, Information, Tools & Technology, Client, External Influences and Project. Definitions for each of these categories are stated in the literature review. During each case, a range of factors were identified by participants, these were collated into over-arching factors. These have been mapped to the categorisations synthesised in the literature review and are shown in Table 80.

Table 80 Cross Case Analysis - Case Factor Categorisations

		Team mgmt.	Product	Bus. mgmt.	Information	Tools & Tech.	Client	Project	Extl Inf.	Other
Case 1	Product Complexity		●							
	Project Scope							●		
	Regulatory complexity								●	
	Prior Knowledge	●								
	Materials Budget									●
	Geographic Accessibility of key stkhldrs						●			
	Availability of staff	●								
	Instance	2	1	0	0	0	1	1	1	1
	Percentage	28.57	14.29	0	0	0	14.29	14.29	14.29	14.29
Case 2	Client "Gut Feeling"						●			
	Development Budget									●
	"Stuff" Happens								●	
	Definition Levels (Inputs)				●					
	Regulatory Complexity								●	
	Geography							●	●	
	Designer Experience	●								
	Product Complexity		●							
	Delivery Output Complexity					●				
	Communication complexity				●		●			
	Instance	1	1	0	2	1	2	1	3	1
	Percentage	8.33	8.33	0	16.67	8.33	16.67	8.33	25.00	8.33
Case 3	Client (POC)						●			
	Product Requirements		●							
	Product Complexity		●							
	Our Experience	●								
	Brief Clarity				●					
	Budget									●
	Making / Fabrication					●				
	Time	●		●						
	Subcontractors					●			●	
	Logistics								●	
	Instance	2	2	1	1	2	1	0	2	1
	Percentage	16.67	16.67	8.33	8.33	16.67	8.33	0	16.67	8.33

7.4.b A novel factor identified

When considering the categorisation of the factors presented in each of the cases, one-factor categorisation stands out, being unmentioned in the literature, yet appeared in all three cases. Taking each case as a discrete source of data, collecting their categorisations, shown in Table 80. In itself, the categorisations of design effort influencing factors on design projects can be regarded as a contribution of this thesis. However, there are further refinements to this categorisation that need to be considered. This section will discuss the factor categorisations defined in the literature review, categorises the factors collected from each of the cases and compares them to the literature review findings. From the literature review, nine categorisations of factors were synthesised, excluding those that were not practically valuable in the context of this study. These factor categorisations were, in order of frequency of occurrence: Team management, Product, Business Management, Information, Tools & Technology, Client, External Influences and Project. Definitions for each of these categories are stated in the literature review. During each case, a range of factors were identified by participants, these were collated into over-arching factors. These have been mapped to the categorisations synthesised in the literature review and are shown in Table 80, and initially exclusively categorising the factors based on those synthesised in the literature review, the percentage distribution of each set of factor categorisations can be compared, shown in Table 81. Further examination of the terms found in the case data identified a commonality between each of the cases. A term relating to budget occurred in every case, in some cases more than once. In Case 1, the term "materials budget" was identified; in Case 2, the term "development budget"; and in Case 3, the term "budget" was included as a factor. Due to the project phase-based approach introduced into the process for each study, the factors of Cases 2 and 3 were synthesised from a broader range of factors generated by their participants.

Table 81 Cross Case Analysis - Factor Categorisation Comparison

	Case Total	Case Percentage	Literature Review Percentage
Team management	5	16.13%	24%
Product	4	12.90%	21%
Business management	1	3.23%	13%
Information	3	9.68%	11%
Tools & Technology	3	9.68%	8%
Client	4	12.90%	7%
Project	2	6.45%	4%
External Influences	6	19.35%	5%
Other	3	9.68%	7%

When considering budget as its own category and reviewing the categorisations of the factors identified in the cases, it (budget) becomes the joint third more frequent factor category in the cases, shown in Table 82. Furthermore, when comparing them to those found in the case to those found in literature, it is clear that this is a factor not currently considered in the peer-reviewed literature for product design projects.

Table 82 Cross Case Analysis - Factor Categorisation Comparison with Budget Category

	Case Total	Case Percentage	Literature Review Percentage
Team management	5	16.13%	24%
Product	4	12.90%	21%
Business management	1	3.23%	13%
Information	3	9.68%	11%
Tools & Technology	3	9.68%	8%
Client	4	12.90%	7%
Project	2	6.45%	4%
External Influences	6	19.35%	5%
Budget	3	9.68%	0%
Other	0	9.68%	7%

7.4.c Defining Budget from Case Findings

In Case 2, the participants joined "Budget", "Knowing the Budget" and "Funding" into the "Development Budget" factor, shown in Table 84. During the voting for which factors were most influential, the participants did not select budget as one of their factors, yet within the FESS for "Client Gut Feel", shown in Table 83, one measure was "Funding Level for Project". This emphasises the possible influence that budget can have over the resource needs of a project. Considering the levels set within this FESS, the measures relate to the availability of funds for the project. Furthermore, within the same grouping activity, the participants of Case 2 also included "Product Budget" within their "Delivery Output Complexity" Factor, shown in Table 85, although this term was not included in the FESS for Delivery Output Complexity later in the case.

Table 83 Case 2: Client "Gut Feeling" Levels Factor Scoring Table

Feature	**1**	**2**	**3**	**4**
Level of experience	No experience	On paper	In practice	Master
Team setup	Individual inventor	Start-up	SME	Corporate
Personality	Bad	More bad than good	More good than bad	Good guy
Funding Level for project	Seeking funding	Funds up to prototype or feasibility	Funds up to develop not launch	All funds available for develop and launch
Level of additional engagement required	2 - 3 engagements per week	1 engagement per week	1 engagement per month	End of Phase or set review point only
Definition Level Score	I	II	III	IV
Definition Level Range	5 to 8	9 to 12	13 to 16	17 to 20

In Case 3, the participants created the group factor term “budget” from the factors listed in Table 86. During the voting phase, the participants included this factor within its most influential, further emphasising its importance and significance in relation to design project resourcing. Creating the terms for the Budget FESS, the participants grouped the three terms together into two, shown in Figure 53, and defined measures for this factor within the Budget FESS, shown in Table 88.

Table 84 Case 2: Grouped Factors for Person-hour influence in Design Projects (Development Budget)

Grouped Factor Name	**Factors**
Development Budget	Budget Knowing budget Funding

Table 85 Case 2: Grouped Factors for Person-hour influence in Design Projects (Delivery Output Complexity)

Grouped Factor Name	**Factors**
Delivery Output Complexity	Supplier risk factor Chinese New Year Supplier liaison *Product Budget* Volume of product Material diversity Process diversity

From the findings of these cases, it can be assumed that “Budget” is a factor categorisation which influences the design effort requirements of a design project. However, it is acknowledged that the definitions of a budget factor category cannot exclusively be derived from the findings of three cases, each with its own level of clarity and specificity in describing budget-related factors. That said, from these findings, general guidance and indication of a definition of this category can be synthesised. The size of funding available and its availability to the design team are key elements of this budget factor category, along with its intended purpose (i.e. for development or prototyping expenses) can also play into its definition.

Table 86 Case 3: Grouped Factors for design effort influence in product design projects (budget)

Grouped Factor Name	**Factors**
Budget	Budget, Is there a budget? Y/N, The right budget

Table 87 - Case 3: Budget Element Definitions

Element	**Definition**
Budget	How generous is the budget based on the requirements?
Is there a budget? Y/N	Is there a disclosed budget for the desired project?
The right budget	Is the budget sufficient for the intended project output?

Figure 53 - Case 3: Budget factor element synthesis

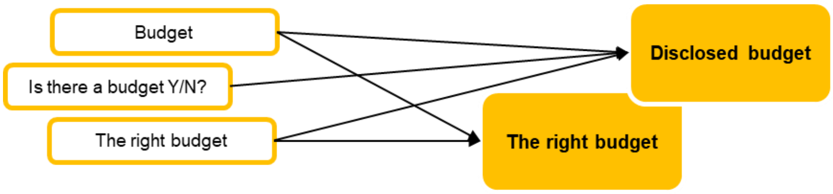


Table 88 - Case 3: Factor evaluation & scoring scheme (FESS) for Budget Factor

Feature	**1**	**2**	**3**	**4**
The right budget	Healthy	Sufficient	Restrictive	Insufficient
Disclosed budget	Y	X	X	N
Good to Bad	**+**			**-**
Definition Level Score	1	2	3	4
Definition Level Range	2 to 3	4 to 5	6 to 7	8

7.4.d Why might budget not be in the literature?

It must be acknowledged that there are possible reasons why a category like "budget", or similar, was not produced during the analysis of the literature. There are three potential reasons for this, none of which are mutually exclusive: the source of the data (i.e. the organisations involved), the use case of the methods being developed; and the scope of the literature review itself. Each will be addressed in the following section.

Source of data in studies.

Many of the studies identified in the literature review were in collaboration with large businesses, like Bashir & Thomson (2004) working with GE, and Salam & Bhuiyan (2016) with Pratt & Whitney. In these instances, it can be assumed that budgetary issues may not be a factor based on the size of the organisations involved in the study. These large organisations can perhaps offer sufficient funding for a project so that issues highlighted from the case findings, that of the client applying for funding, etc. would not even factor.

In some cases the studies do not disclose their sources, either to protect the secrets of the organisation, i,e, Hellenbrand et al. (2010), or are simply unstated, such as Pollmanns et al (2013) and Shang & Yan, (2016). Naturally, one cannot speculate on these businesses, but there must indeed be a possibility that they too may be larger and therefore have sufficient funding for a project.

The scope of the tools and methods developed within the literature

Many papers do not address the broader challenge of design projects, while being applicable for the literature review, they address a more specific type of project. The aforementioned Pratt & Whitney (Salam and Bhuiyan, 2016) and GE projects (Bashir and Thomson, 2004) were for specific use cases. Much like the studies conducted with larger organisations, the specificity of these studies may limit the scope of what may be considered an influential factor. This may lead to factors, such as budget, being overlooked or disregarded entirely.

Scope of Literature Search

A key issue discussed at length in the literature review is the lack of peer-reviewed publications discussing design effort estimation, specifically in product design (and similar). This has resulted in the dataset used to synthesise the factor categorisations coming from a much broader range of industries than the PDCs used within the cases presented. There may be a degree of comparing "apples to oranges" with this. However, it can be assumed that the issues faced in design engineering projects and all the other fields included within the search terms covered in the literature review are indeed similar as the general tasks, and objectives of a design project within these contexts remain similar too. If a broader range of data sources from PDCs were available, a more robust comparison could be made.

Additionally, when one further broadens the scope of the search to include other project management sources (textbooks, etc.) indeed budget does become an issue, but only in the context of estimation and management (Lock, 2013; Maylor, 2010), where it is the duration of the project which influences the project cost, rather than cost, budget, etc. being a factor which influences the duration of the project. Additionally, these sources do not address the specific issues faced by PDCs (or similar) as outlined in the literature review.

7.4.e Budget is a Design Effort-Influencing Factor Category

Despite the limitations previously stated, there remains a clear need to include "budget" as a category for design effort influencing factors in PDC projects. It was mentioned to some degree in all three cases, with one identifying it as one of the top four most influential. What further emphasises this is the significance that is shown when representing the percentage data graphically, Figure 54 emphasises the significance of budget as a factor categorisation within the context of PDCs and their design projects. Sharing equal standing as "Tools & Technology", Budget has been included. Therefore, "Budget" must be considered a design effort-influencing factor category for PDCs.

7.4.f Client Qualities

Client is a factor category identified in the literature review, with seven instances found, shown in Table 89. Although each instance relates to clients, there are differences in the specific issues they address. From the definitions, also shown in Table 89, the majority of the terms found in literature refer to the expectations of the client, or the ease with which their expectations can be met.

Table 89 - Cross Case Analysis: Client Factors From Literature

Source	**Term In Literature**	**Definition / (Categorisation)**
Griffin (1993)	Strategic driver development	• Motivation for project (Motivation)
Bashir & Thomson (1999b)	Technical difficulty	• Ease in meeting expectations (Expectations)
Bashir & Thomson (2001a)	Severity of Requirements	• Ease in meeting expectations (Expectations)
Griffin (1993)	Process	• Client expectations/ requirements (Expectations / Requirements)
Bryson and Bromiley (1993)	Process	• Communication with client (Communication) • Disagreement resolution (Disagreement)
Christensen (1985)	Clarity of goals	• Communication (Communication) • Client expectations (Expectations)
Bashir & Thomson (2004)	Type of drawings submitted to the customer	• Client expectations/ requirements (Expectations / Requirements)

The participants in all three cases discussed the client and suggested factors that were client related. Table 90 presents each term identified by the participants and their corresponding client factor categories (Expectation, Experience, Personality, Organisation, Motivation, Communication, Requirements, Disagreement and Proximity) in conjunction with the terms found in literature. From this analysis and comparison to the literature review findings, there is a broader range of categories beyond those found in literature (Motivation, Expectations, Requirements, Communication and Disagreement). Most significantly of which are the categories of Client Experience and Client Personality.

Client Experience

Similar to the "Designer Experience" factor discussed previously, "Client Experience" refers to the degree of familiarity the client has with the business, technical, design-centric and other relevant subject areas that are relevant to the project. DCB participants suggest several key points that are of particular note:

Table 90 - Cross Case Analysis: Client Factor Analysis

Source	Factor	Term	Category	Expect.	Exper.	Persona.	Org	Motiv.	Comms.	Reqs.	Disag.	Proximity
Literature	n/a	Strategic driver development (Griffin, 1993)	Motivation for project					●				
		Technical difficulty (Bashir & Thomson, 1999b)	Expectations	●								
		Severity of Requirements (Bashir & Thomson, 2001a)	Expectations	●								
		Process (Griffin, 1993)	Expectations / Requirements	●						●		
		Process (Bryson and Bromiley, 1993)	Communication / Disagreement						●		●	
		Clarity of goals (Christensen, 1985)	Expectations / Communication	●					●			
		Type of drawings submitted to the customer (Bashir & Thomson, 2004)	Expectations / Requirements	●						●		
CS1	n/a	Accessibility of client (geographically)	PDC's proximity to client									●
		Accessibility of client (availability and willingness)	Personality / Experience		●	●						
		Personality & Relationship with clients	Personality			●						
CS2	Client " Gut Feeling"	Client experience	Experience		●							
		Judge of character	Personality			●						
		Scope alignment	Expectations	●								
		Client "hand holding"	Personality / Experience		●	●						
		Willingness to compromise	Disagreement resolution								●	
		Scope Creep	Expectations	●								
		Client Expectations	Expectations	●								
		Client's motivation for product	Motivation for project					●				
		Laws of physics	Expectations / Experience	●	●							
		Decision making chain	Organisation				●					
		Client responsiveness	Communication						●			
		Client management	Expectations / Experience	●	●							
		Curveballs and interruption	Personality / Expectations / Experience	●	●	●						
		University research project	Organisation				●					
CS3	Client (POC)	Private vs. Corporate	Organisation				●					
		Middleperson or decision maker	Organisation				●					
		Why us?	Motivation for project					●				
		Are they trouble?	Personality			●						
		Indecision level	Personality / Expectations / Experience	●	●	●						
		IP issues	Expectations / Experience	●	●							
		Samples? Expectations of presentation	Expectations / Requirements	●								
		Client sign-off of CAD	Expectations	●								
		Client expectation	Expectations	●								
				16 34.0%	8 17.0%	7 14.9%	4 8.5%	3 6.4%	3 6.4%	3 6.4%	2 4.3%	1 2.1%

The amount of "hand holding", i.e. how much close guidance the client may need throughout the project indicates that this additional contact would provide a greater resource burden for the PDC. This was defined in DCB's FEES for Client "Gut Feeling" as "Level of additional engagement required" (shown in Table 91) and is measured from 2-3 engagements a week as worse, and at end of phase or set review points only at best. Clearly DCB anticipate that every project will be required to interact with the client with some frequency, hence their use of "additional" in the element name in the FEES.

Table 91 - Cross Case Analysis: Client "Gut Feeling" Levels Factor Scoring Table (Case 2)

Feature	**1**	**2**	**3**	**4**
Level of experience	No experience	On paper	In practice	Master
Team setup	Individual inventor	Start-up	SME	Corporate
Personality	Bad	More bad than good	More good than bad	Good guy
Funding Level for project	Seeking funding	Funds up to prototype or feasibility	Funds up to develop not launch	All funds available for develop and launch
Level of additional engagement required	2 - 3 engagements per week	1 engagement per week	1 engagement per month	End of Phase, or set review point only
Definition Level Score	I	II	III	IV
Definition Level Range	5 to 8	9 to 12	13 to 16	17 to 20

Four points from Table 90 that are not brought into the FEES: The client's understanding and acceptance of practicalities around the project (referred to as "Laws of physics") is not mentioned within the Client "Gut Feeling" FEES (Table 91), but this alludes to the clients naivete, if nothing else. The client's focus on the agreed goals, or their deviation from them, referred to as "Curveballs and interruption" by DCB participants. DCC participants also identified that a client's experience will have a bearing on their ability to made decisions ("Indecision level") and their understanding of issues related to intellectual property (referred to as "IP issues").

Client Personality

Client Personality is an equally interesting and significant client-based factor issue, having been discussed by participants from all three cases, yet unmentioned in the literature. An efficient working relationship with a client is clearly key to PDC project success and the personality of the client can have significant impact on that success. This is emphasised by the inclusion of it as a term within DCB's "Client "Gut Feeling"" FEES (Table 91) where the design team must make a straight judgement call on the client's personality, from "Good Guy" to "Bad Guy", with "Bad Guy" a replacement for the unpublishable term defined by the DCB participants. DCC's participants simply posit the question "Are they trouble?" in their factor longlists. DCC equally suggest that a client's ability to make a decision can have influence. This is not exclusively a matter of personality, but also experience and expectations too.

Client Organisation

The organisation that the client works for, or is part of, is an additional aspect of the client factor which was not considered in the literature review findings. DCB identified that university projects can have an influence on project duration, noting in informal discussions the additional bureaucracy that comes with a large organisation such as a university. Notably this is not reflected in DCB's FEES for "Client "Gut Feeling"", which suggests that under "Team Setup", the worse state a client could be in is as an "individual inventor" and at best they are a "corporate". The DCB participants were asked about this and they said that although there was likely more paperwork from a corporate client, the level of engagement and micromanagement from an individual inventor would be much worse.

Client Proximity

How close the PDC is to the client ("Client Proximity") is another aspect of the client that is not mentioned in the literature. DCA stated that the further the client is from the PDC, the less frequent the visits were, but the more logistically challenging they would be – consider travel, accommodation, subsistence, additional meetings, etc. More clarity would be needed to make a judgement on how this factor would influence design project resources, as it was not included in the top factors during Case 1.

In comparison to the findings of literature, this analysis of case data has shown that there are three client qualities which are not addressed in literature considering the resources demands of design projects and how client-based factors influence them, and should be addressed in future research. These three qualities: Client Experience, Client Personality and Client Organisation each are covered in at least one case and should be explored further as at the current level of data gathered, no meaningful research output can be derived.

7.4.f Research Output – Priorities of Factors Influencing Product Complexity in PDC Projects

Further to the identification of a new factor categorisation, is the difference in significance given to each categorisation between the cases data and the literature review findings. Assuming each instance within both literature and case as an individual point, those factors with the most mentions may too be potentially most influential. Considering the percentages of each, shown in Figure 54, the literature places far greater emphasis on Team Management factors (24%) and Product Factors (21%), than those found in the case findings (16.13% and 12.90% respectively). In the literature, these two categories are by far the most mentioned, whereas in the cases, the distribution of percentages is more even.

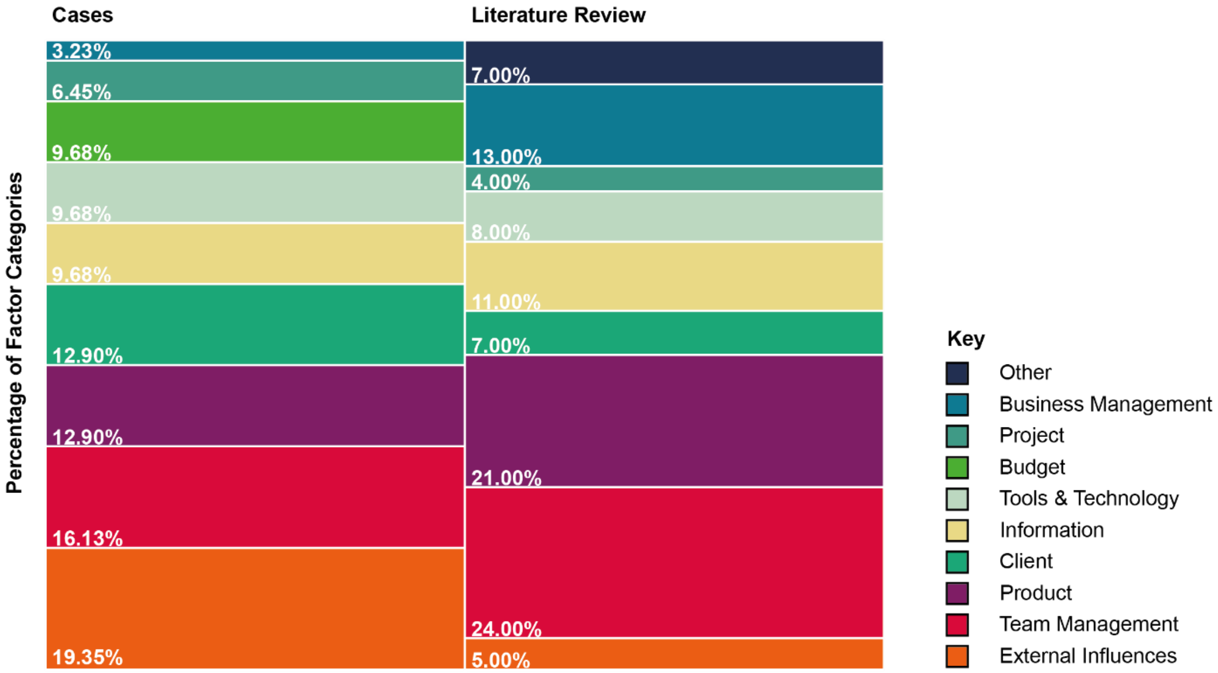


Figure 54 Cross Case Analysis Factor Category Percentage Graphical Comparison

A further discrepancy between the two datasets is the stark difference in the frequency of factors categorised as "External Influences". "Regulatory complexity" in Cases 1 and 2, "Stuff happens" and "Geography" in Case 2, and "Subcontractors" and "Logistics" in Case 3. Like the discussion of the "budget" category, this may be due to the types of projects (and the businesses that conduct them), and therefore similar rationale can apply. Large organisations with specific use case methods will have departments to support compliance with standards and regulations, will have office locations internationally, or the budget to fly team members to other locations to address possible issues.

The "Stuff Happens" factor from Case 2 is a vague term, relating to the fact that sometimes there are risks that are out of the control of the design team. How a design team might assess the likelihood of these risks will require them to fall back on common project management practices, such as including mitigations or avoidance. But, as the factor states, sometimes "stuff happens" so including contingencies may be the best solution. Again, this term or ones like it are not discussed in the literature specifically, focusing more on the more tangible factors of regulations, stakeholders and logistics.

The difference in the frequency of instances of each factor category within the datasets is distinct and therefore remarkable. As mentioned previously, the greater the number of mentions of a factor for a specific category, the more significance is placed on that category within the data sources. From the perspective of the case PDCs, there is a more even distribution of significance for each factor, which is in contrast to the voting that was applied to their self-generated lists. Perhaps there is little truth to the working assumption that more mentions correlate to greater significance.

7.4.g Research Output – Factor Categorisation

In combination with the synthesised factor categorisation, this cross-case analysis presents a factor categorisation that can be used to analyse the factors identified by design teams, enabling comparison. As shown even between the three cases, the terms used by each design team may be different, yet their general sentiment or intent is the same. As such, the use of these nine categories (Team Management, Product, Business Management, Information, Tools & Technology, Client, Project, External Influences and Budget).

The development of factor categories has indirect value to PDCs, as it can enable cross-comparison between current and future studies into PDC design practices. The findings of such studies can provide further value to PDCs. The differences between the case data and the literature review findings emphasise that there is a clear mandate to continue to study PDCs and to bring the opinions and beliefs of academia in line with the industry.

7.5 Developing a Method to Identify and Model Influential Factors

7.5.a Introduction

Throughout this reserarch, a formalised method for evaluating project briefs against an established set of influential factors has been developed. With this method, the knowledge and experience of design teams can be captured to identify and model the most influential factors of design effort demands in PDC projects. This section will discuss the features of the method developed during the execution of the three cases.

From the outset, the application of modified variants of the DOE process throughout this multi-case approach has generated data which, when analysed, provided a means to characterise the design space through the modelling of the factors which influence the design effort demands of product design projects.

The following two parts consider the processes developed to characterise said factors, through a means of assessment, the Factor Evaluation Scoring Scheme (FESS) (an example of which is shown in Table 92); and through their graphical modelling to communicate factor behaviours, how they influence a project and how that influence changes during a project. The analysis and development of these findings for these two sections are shown in Table 93.

Table 92 - Case 2 FESS for Product Complexity

Feature	**1**	**2**	**3**	**4**
Number of parts	1	Up to 5	Up to 30	30 +
Static of Dynamic	Fixed	Fixed with some moving parts	Fixed with lots of moving parts	Moving with lots of moving parts
Electronics to be developed	None	Yes, no UI/UX	Yes, UI/UX (buttons and screen)	Yes, UI/UX, sensors control etc.
Level of problem-solving	None	Basic	Medium	Complex
Standard VS Custom parts	All standard	Most standard	Most Custom	All Custom
Difficulty of CAD	1	2	3	4
Definition Level Score	I	II	III	IV
Definition Level Range	6 to 10	11 to 15	16 to 20	20 to 24

7.5.b FESS - Factors Need Multi-Level Scoring

During Case 1, it was identified that there is notable value to design teams in defining multiple levels of design effort influencing factors. The initial setting of high/low, or minimum/maximum levels kept these factors and their levels at a level of abstraction. This abstraction could present a challenge for design team members to fully consider the implications their levels have over design effort demands. Identifying what attributes, or elements, that contribute to the influence of each factor provides insight and definition to each factor.

In Case 1, the focus was on the factor identified to be the most influential (Product Complexity) and therefore a range of elements was identified for that factor, based on similar definitions by Hubka and Eder (1988). Reflecting upon Case 1, the development of multi-level scoring for all factors would improve the ease of comprehension for all the factors for design teams. Case 2 offered a structure to identify these elements and how determine the levels of each. These elements further provide definitions for each factor ensuring that each element is observable and measurable from the project outset (i.e. from

Table 93 - Cross-Case Analysis: Table of Findings Relating to Factor Identification Method Development

Finding			Case 1	Case 2	Case 3	Analysis
Factor Evaluation & Scoring Scheme (FESS)	**Factor Evaluation & Scoring Scheme (FESS)**		**New Concept** Formalised procedure to produce an evaluation scheme to improve estimation and comprehension of project briefs	**Develop / Test** FESS offered value when considering project briefs. FESS Development set ahead of estimation (collect) step to aid comprehension of HPs.	**Verify** FESS development had a positive influence over design teams' understanding over estimation process.	FESS provides project evaluation tool, allowing for projects to be compared against series of universal factors.
	Features	**All factors need multi-level scoring scheme**	Novel Observation	Develop / Test	Verify	Multi-level scales needed for each factor
		All factors have contributing elements	-	Novel Observation	Verify	All factors require observable elements with own multi-level range
		Binary options (Y/N) in scoring	-	-	Novel Observation	Recommendation: Prevent binary options in FESS structure
		Scorecard for project comparison	-	-	Novel Observation	Production of project scorecards can aid comparison/reflection.
Communicating Perceived Factor Influence Graphically	**Percentage Influence Graphs (PIG)**		**Develop / Test** PIGs effective for communicating influential factor characteristics.	**Verify** PIGs effective for communicating influential factor characteristics.	**Verify** PIGs effective for communicating influential factor characteristics.	PIGs should be incorporated into FESS development to assist with the understanding of factors' behaviour.
	Feat.	**Linear "pie chart" layout**	-	Novel Observation	Verify	Recommendation: Linear layout to improve comparison / comprehension.
		Project Length Line Graph	-	Novel Observation	Verify	Recommendation: Project-length aids comparison / behaviour understanding
	Mean Effect Plots (MEP)		**New Concept** MEPs used as communication tool for discussion facilitation: influence characteristics and behaviour.	**Develop / Test** MEPs aided understanding of factors, fostering mutual understanding in design team.	**Verify** MEPs aided understanding of factors.	MEPs should be incorporated into FESS development to assist with the understanding of factors' behaviour.
	Feat	**MEPs for single factor and phase**	Novel Observation	Develop / Test	Verify	Recommendation: MEP single factor & phase presentation to aid comparison.

conversations with the client and extracting directly from the project brief) further improves the design teams' ability to characterise their projects based on these factors.

7.5.c FESS – All Factors Have Contributing Elements

Further adding to the need for multi-level scoring, during Case 2, it was determined that each factor would require some contributing elements as part of their definition. This approach produces a concrete definition for each factor, but further enables the means to measure each factor, through its corresponding elements. Case 2 initially presented an approach whereby each factor had corresponding elements, developed as part of the factor identification process. This method intends that all factors must be observable, or indeed measurable, from the project's outset. This requirement extends to each factor's elements, each being observable with its own multi-level range. By making each element multi-levelled, it allows those evaluating a project brief to follow an established checklist to produce an evaluation effectively. It is recommended that each factor have a range of measurable elements with their own multi-level evaluation.

7.5.d FESS – Binary options (Y/N) in scoring

The participants of Case 3 opted for some factors to have only a binary option for their classification: yes or no, all or nothing. In principle this is an adequate approach to take, however by presenting only maximum and minimum values, it restricts some of the functionality of the scoring scheme. Furthermore, it was observed that participants found this binary option a greater challenge to perceive when considering the hypothetical design projects during the estimation phase. It is recommended that future creations of the FESS should prevent binary options in the FESS structure

7.5.e FESS – Scorecard for project comparison

An additional observation during Case 3 was the suggestion that the evaluations of projects could be logged for future cross-comparison. To facilitate this, it was proposed that a scorecard format could be created for each evaluation to be collated against. Further discussion of this is covered later in this chapter.

7.5.f FESS – Section Summary

The formalised method for the creation of the Factor Evaluation & Scoring Scheme (FESS) is a notable contribution of this study. With the aforementioned refinements and contributing findings, it is a valuable tool for PDCs for the characterisation of the factors which influence the design effort needs of their projects.

7.6 Communicating Perceived Factor Influence Graphically (Communicating Graphically)

7.6.a Introduction

Throughout this research, various common graphical approaches to communicate information have been considered; specifically, to communicate the perceived influence each factor has over design effort for product design projects. As with the modifications and improvements made to the overall approach of the multiple round quasi-experimental case-based investigation, the graphical approaches have been modified and improved to maximise the ease and efficacy of communicating the information shown to their intended audience, design team members and design team management. It can be assumed that, although they may have education and experience with regression equations and statistical analysis, this audience may not have the depth of understanding in such areas to fully comprehend the meanings behind abstract equations. As such, participants of cases were asked to assess each graphical representation of the insight and information and determine whether they found what each illustrated as being valuable.

These approaches and the changes made to them are outlined in Table 94 and are discussed in the following section.

7.6.b Communicating Graphically - Regression Values

Regression values refer to the numerical values attributed to each of the coefficients and the constant value for each regression equation that is produced during the statistical analysis. This, of course, is only the case when identifying which factor has the greatest influence; when considering the behaviour of the factors, whether the value is positive or negative does play an important role.

Placed in a table, these values are the magnitude of each coefficient, signifying their level of influence, but not the directionality of that influence, i.e. whether a coefficient is a positive or negative value. Tabulating this data is an effective way to concisely represent a body of data, however it does not provide an immediate, visual means of identifying which factor has the greatest influence over design effort for that project phase. An example of this can be seen in Table 95. Tables of data were not shown to participants as, after initial assessment by the researcher, it was determined that it was not possible for them to be as quickly understood as more visual means.

Initially, plotting the specific values of each factor's coefficient in a bar chart enabled participants to quickly see the magnitude of influence each factor had. However, in many examples, the constant value would be a far greater value than the coefficient values for each factor. This leads to the dwarfing of the values of interest vs. the constant, as shown in Figure 55.

Table 94 - Cross-Case Analysis - Types of Graphical Communication Approaches

Information	Use of information	Potential information display method	Case	Evaluation
Regression Values	Identify which factors had greatest influence as specific value	Table	1	Offers insight, non-visual output
		Bar chart (incl. c)	1	Included constant value undermines value
		Bar chart (excl. c)	n/a	Offers insight visually, lacks direct comparison
Percentage of influence (calculated from regression values)	Identify which factors had greatest influence as percentage of whole influence	Table	1	Offers insight, non-visual output
		Bar chart	1	Offers clear insight
		Linear pie chart	1	Offers clear, valuable insight visually
		Project Length line	2	Offers clear, valuable insight visually
Mean Effect Values	Identify specific behaviour of influence each factor has per project phase	Table	2	Non-visual output
		Mean Effect Plot	2	Offers clear, valuable insight visually

Table 95 Regression Values for Process Phase (Case 1)

Participant	Constant	Project Scope	Product Complexity	Regulatory Complexity	Prior Knowledge	Material Budget
1	64.06	-7.81	-10.94	1.56	-4.69	-1.56
2	12.5	0	-2.5	0	0	0
3	13.125	-3.75	-4.375	0	0	0
4	15.375	-0.875	-2.75	1.375	-0.75	0.125
5	11.25	-1.25	-3.75	0	0	0
6	9.625	-0.875	-2.625	-0.875	-1.75	0
7	12	0.5	-3	-2.25	-3.75	2.25
8	13.25	-2	-2.875	-0.875	-0.375	-0.375

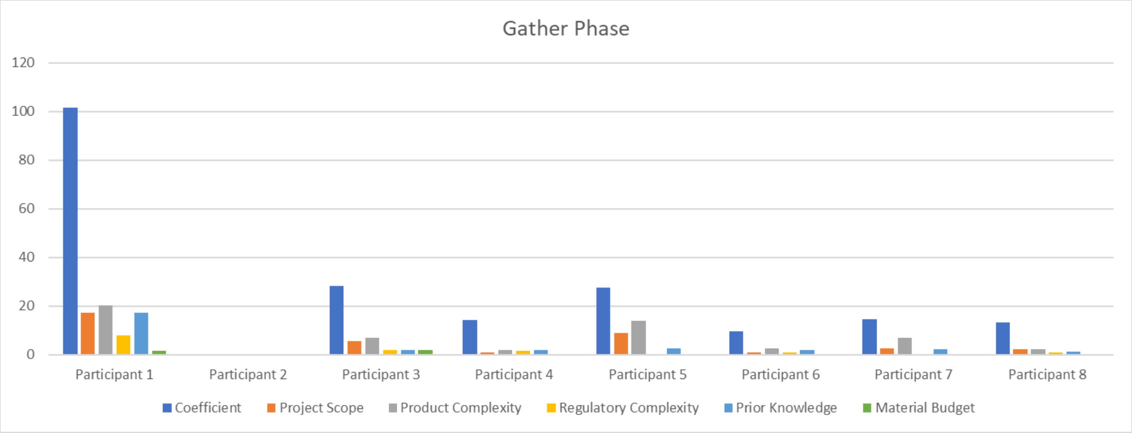


Figure 55 Regression Equation Value Bar Chart of Influential Factors for Gather Phase (Case 1)

By removing the constant value from the analysis, these bar charts did indeed become clearer to interpret. However, there is still a level of evaluation that a designer considering these graphs would have to undertake to offer a comparison between any two designers' perceptions of each factor's influence, as shown in Figure 56.

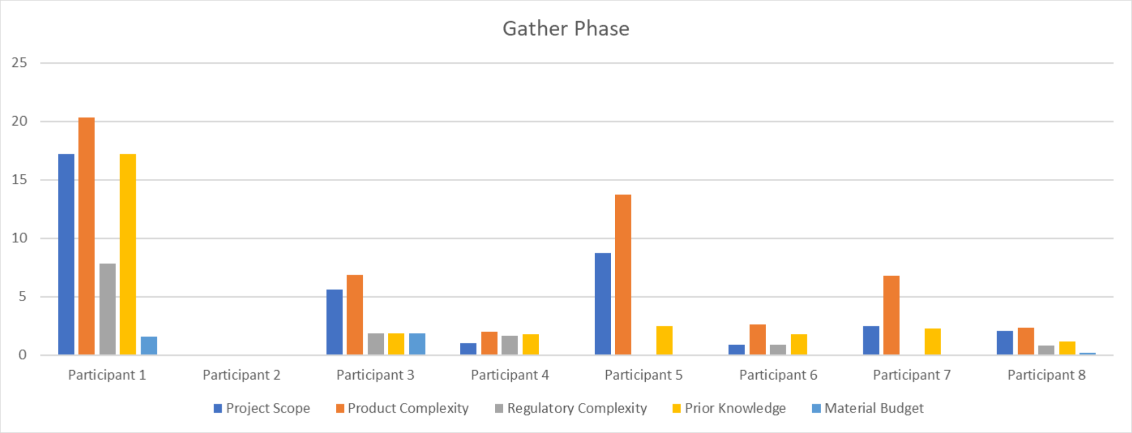


Figure 56 Regression Equation Value Bar Chart of Influential Factors for Gather Phase (Case 1)

From the informal discussions and semi-structured interviews, the participants of Case 1 who were shown these graphs found it feasible to understand the information it was communicating, although all participants commented on the need to *study* the graphs, rather than being able to fully understand what the graph represented.

7.6.c Communicating Graphically - Percentage Influence Graphs (PIG)

By totalling the coefficient values for each factor and representing them as a percentage, designers can identify more clearly which factors have the greatest influence over design effort levels in product design projects per project phase. However, the issues identified in Case 1 around the inclusion of the constant value from each participant's regression equations are further exacerbated when considering the percentage of influence each factor has when considering the constant value. Similarly to the specific regression equation values, presenting the percentage of influence in a table is concise, yet presents the same limit to quick digestion of information through a graphical (visual) layout. An example of this is shown in Table 96.

Table 96 Percentage Influence of Factors Calculated from Regression Values for Creative & Strategic Phase (Case 1)

Participant	Project Scope	Product Complexity	Regulatory Complexity	Prior Knowledge	Material Budget
1	17.14%	45.25%	16.12%	14.57%	6.91%
2	12.00%	76.00%	4.00%	4.00%	4.00%
3	6.24%	85.46%	2.07%	2.07%	4.17%
4	7.72%	80.20%	1.34%	8.05%	2.68%
5	4.32%	63.20%	17.76%	3.04%	11.68%
6	14.23%	43.09%	14.23%	28.46%	0.00%
7	0.00%	100.00%	0.00%	0.00%	0.00%
8	15.43%	61.17%	15.43%	7.45%	0.53%

7.6.d Communicating Graphically - PIG - Linear "pie chart" layout

Rather than the (traditional) approach of representing percentages in pie charts, the percentage of influence each factor has over design effort levels of product design projects was represented linearly. This has the potential to maintain the concise nature of a table of data, with the visual nature of a pie chart. Additionally, this approach allows for a direct comparison between participants and the factors they consider. In the example shown in Figure 57, it is clear that the participants consider Product Complexity as the most influential factor. Furthermore, this visual approach further enables designers to note the absence of particular factors from participants' data, showing a negligible degree of influence over design effort levels for a given project phase. This too is valuable insight, as it allows for such factors and their influence to be disregarded for a given phase, allowing design teams to focus on those factors which have the greatest influence.

Recommendation:

The use of percentage influence is an effective means of communicating which factors have the greatest influence over design effort levels in product design projects. Furthermore, the use of a linear layout to such graphs enables improved comparison/comprehension of the insight that it offers. As such, when developing a means of gathering and communicating insight into product design projects, this approach should be included.

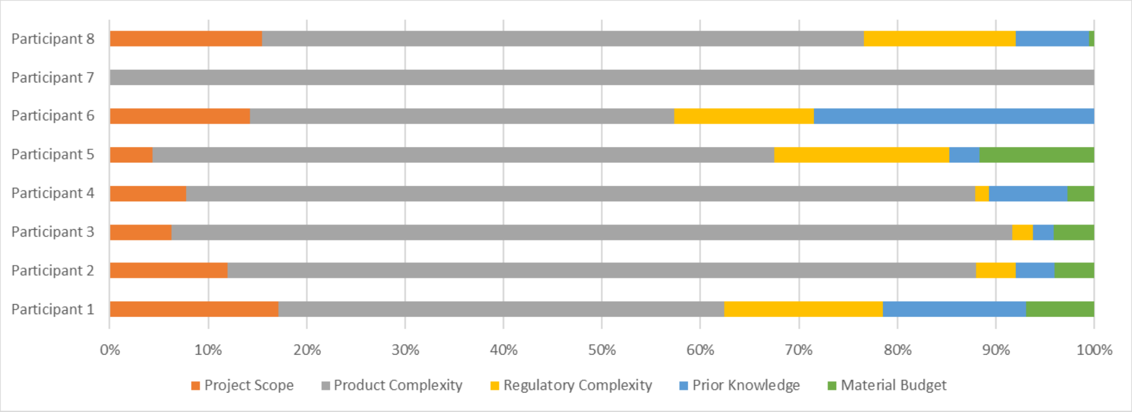


Figure 57 Percentage Influence Graphs for Creative & Strategic Phase (Case 1)

7.6.e Communicating Graphically - PIG – Percentage Influence over Project Graphs.

During Case 2, a further set of graphs were developed to investigate the influence of factors over design effort levels of product design projects. By mapping the percentage influence each factor has throughout an entire project, it is possible to quickly identify when a given factor has the greatest influence (and conversely when in a project a factor's influence is least). This is illustrated by the Project Complexity factor, shown in Figure 58, where it is clear that its influence has the greatest influence during the Design phase of a project. From the informal discussions and semi-structured interviews, the participants of Case 2 found this representation of data to be easy to understand and informative.

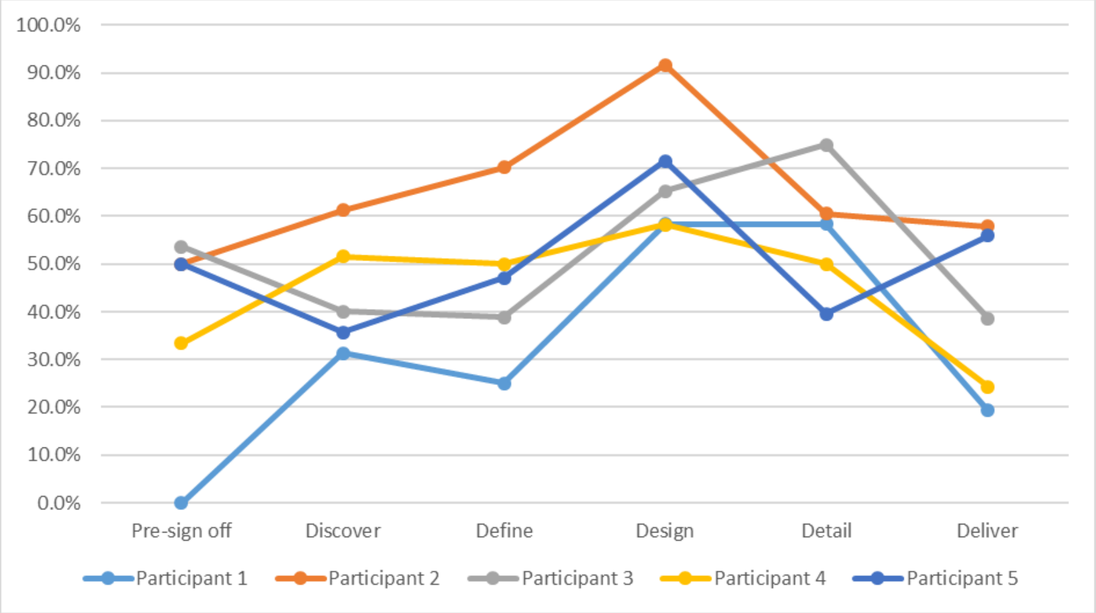


Figure 58 Percentage Influence of Product Complexity Factor Throughout A Design Project (Case 2)

Recommendation:
The use of percentage influence over project line graphs is an effective means of communicating when factors have the greatest influence over design effort levels throughout a product design project. As such, when developing a means of gathering and communicating insight into product design projects, this approach should be included.

7.6.f Communicating Graphically - Mean Effect Values

A product of the Design of Experiments statistical analysis (of the designers' estimates) is the creation of mean effects. This calculation represents the average (mean) effect each factor has over design effort at the two minimum and maximum values. Comparing the difference between the values can indicate whether the factor has a positive or negative influence over design effort levels. By collating the mean effect values into a table, it is possible to make these comparisons. As with the other table-based data representation, it is not as quickly understood what each pair of data points represents, shown in Table 97.

Additionally, an inter-participant comparison is more challenging as one has to compare multiple sets of numbers, which, although might be considered a viable comparative method, is not efficient or simple.

Table 97 Mean Effect Values for Influential Factors of Discover Phase (Case 2)

Factor	**Level**	**Participant**				
		1	**2**	**3**	**4**	**5**
Client "Gut Feeling"	1	33	168	32	37	22.5
	4	46.75	132.5	34	40	20.5
Definition Levels (Inputs)	1	52.5	206.75	50	44	25
	4	27.25	93.75	16	33	18
Product Complexity	Simple	27.25	24.25	17	55	16.5
	Complex	52.5	276.25	49	22	26.5
Delivery Output Complexity	Low	31.75	155.5	27	30	17
	High	48	145	39	47	26

7.6.g Communicating Graphically - Mean Effect Plots (MEP)

Taking the mean effect values and plotting them onto a simple line graph created mean effect plots. From these plots, an example of which can be seen in Figure 59, it is a simple effort to consider the perception data from all members of a design team and compare them. From this, a consensus of the behaviour of a factor can be observed and understood. In the included example, it is clear that as product complexity increases (represented from 1 to 4, where 1 is low and 4 is high), the average (mean) influence over design effort requirements increases, i.e. the more complex a product is perceived to be, the longer the project will take. During the informal discussions and semi-structured interviews, the participants of Cases 1 and 2 found this representation of data to be easy to understand and informative.

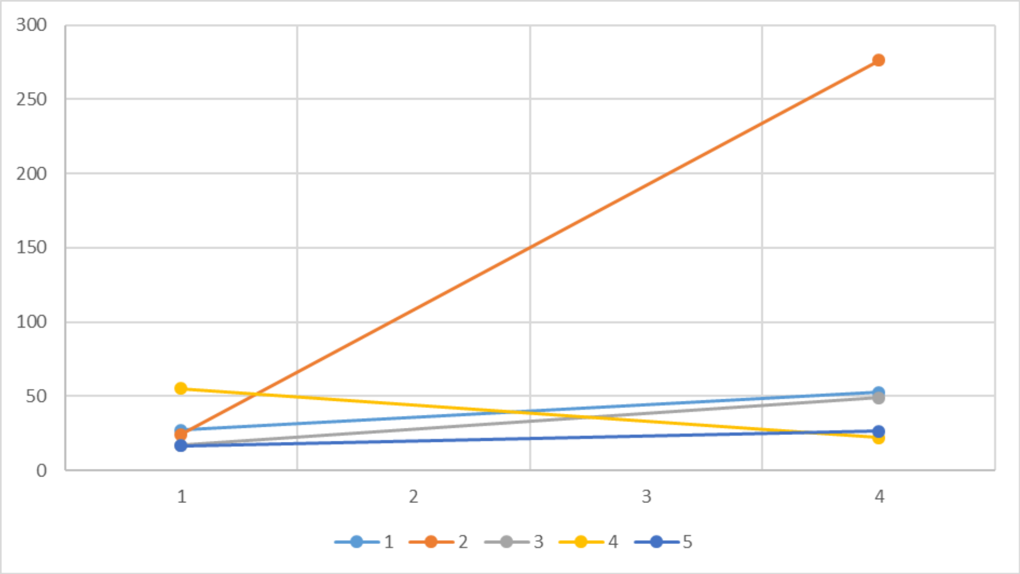


Figure 59 Mean Effect Plot of Product Complexity Factor during Discovery Phase of Design Project (Case 2)

Recommendation:
Mean Effect Plots should be utilised to effectively communicate the behaviour of influential factors of design effort levels of product design projects. As such, when developing a means of gathering and communicating insight into product design projects, this approach should be included.

7.6.h Communicating Graphically – Section Summary

The work of a product designer can, in part, be defined by the tools and media with which they work. Sketches, CAD models, technical drawings, physical models, etc. all have a visual (that is to say, non-textual) element to how they communicate information. It is therefore reasonable to assume that visual communication tools should be considered one of the most appropriate approaches to relaying new information to product designers. When considering the value of the insight offered through this approach, effectively communicating this to those who will most benefit from it is key.

The types of information generated from this approach, the insight that it grants and the communication methods considered in this section have been outlined in Table 98. Each has been evaluated on its clarity, its visual nature and its ability to offer a comparison between data sets have been considered. Those approaches that have succeeded in this have been considered valuable to the design team and their use should be adopted into future applications of this method.

Table 98 - Cross-Case Analysis - Types of Graphical Communication Approaches

Information	**Use of information**	**Potential information display method**	**Insight**	**Clear**	**Visual**	**Offers comparison**	**Valuable**
Regression Values	Identify which factors had greatest influence as specific value	Table	▲				
		Bar chart (incl. c)	▲	▲	▲		
		Bar chart (excl. c)	▲	▲	▲		
Percentage of influence (calculated from regression values)	Identify which factors had greatest influence as percentage of whole influence	Table	▲				
		Bar chart	▲	▲	▲		
		Linear pie chart	▲	▲	▲	▲	▲
		Project-length Line	▲	▲	▲	▲	▲
Mean Effect Values	Identify specific behaviour of influence each factor has per project phase	Table	▲				
		Mean Effect Plot	▲	▲	▲	▲	▲

Displaying the influence that each factor has as a percentage is key to the understanding of which factors have the greatest influence both per project phase, in the form of linear pie charts; but also plotted per factor across the length of a project to identify where the highest levels of influence are to be experienced. Furthermore, the plotting of mean effect data generated from the Design of Experiments analysis offers a clear, visual way of communicating at what state (i.e. at a minimum or maximum level) a factor will demand more design effort for a project. Through a combination of these three graphs, it is possible to characterise the design space, enabling design teams to have a clearer understanding of how each factor influences the design effort needs of a project.

7.7 Conclusion

This chapter has presented various research outputs relating to the factors influencing product design company projects and the design effort needed to complete them, presented in Table 99. An analysis of the case data has determined which factors have the greatest influence from the PDC industry perspective. The behaviour of these factors has been determined based on the behaviour of their constituent factors from each case. The factor "Product Complexity" was found to be of particular significance, so Part 1 of this chapter has included an analysis of the dimensions of product complexity, to define measurable qualities for PDCs to use. s

Table 99 Cross Case Analysis: Table of Findings Relating to Factor Categorisations

Finding	Analysis	Contribution	Value to PDCs
Most influential factors collation and analysis	Data gathered from cases providing definitions of various factors were voted as being the most influential. Factors assessed and evaluated to identify commonalities in meanings	Four factors identified: "Brief Clarity" "Design Knowledge & Experience" "Regulatory Complexity" "Designer's Intuition of the Client"	Defined factors to consider when planning a project and the insight to inform planning-related decision making, i.e. allocating resources (design effort), including dimensions and scales to assess with which formalised factor assessment can be made.
Modelled behaviour of factor influence over design effort in PDC projects	Using Percentage Influence Graphs (PIGs) and Mean Effect Plots (MEPs) the behaviour of the factors stated above have been modelled	The influence of each factor (above) varies at each stage of a project	
Definition of the dimensions of "Product Complexity"	Case data providing definitions of various dimensions of "product complexity". Dimensions identified within the literature. Definitions used to identify areas of agreement to generate dimensions considered to be most influential.	Three dimensions identified: "Number of components" "Functionality" "Creativity"	
Novel factor category identified not found in the literature	Analysis of case data identifies commonality between factors that do not fit within categorisation presented in Literature Review.	The identification of a novel factor categorisation not found in the literature "Budget".	Provides means of comparison of unique terms, facilitating further research which can lead to further value to PDCs.
Factor categorisation developed for cross-PDC factor comparison	Through the synthesis of factor categories in the literature review, and the addition of the new factor category identified from case data, a factor categorisation has been developed	Nine categories identified: "Team Management", "Product", "Business Management", "Information", "Tools & Technology", "Client", "Project", "External Influences" and "Budget".	
Differing priorities in factor categorisations identified	Case data categorised using the same categorisation presented in the literature review. Difference in instances compared between datasets.	Factor categorisations derived from literature review findings have different frequencies in their occurrence to those found in industry.	Indicates mandate for further research to be conducted to inform academia of the issues faced by PDCs, leading to further value for PDCs

Categories for these factors were developed from the literature review, which has been verified and built upon, with the introduction of "budget" as a novel category found in the case stdy data. This categorisation can be used for cross-PDC comparison to enable (in effect) translation between organisations. Additionally, a comparison between the literature and case in the frequency of mentions of each of these categories has been presented to identify whether the literature reflects the attitudes of practising designers in PDCs.

This chapter has contextualised each of its the findings to the PDC industry, highlighting the value that each offers. The insight provided by the research outputs enables PDCs to have improved decision-making, through the assessment of their project against those factors identified to be most influential overall, including scales with which to measure these factors.

7.10.a Conclusion – Aim 1

The factors which have the greatest influence over PDC project resources have been identified as: "Brief Clarity", "Designer Experience", "Designer's Intuition of the Client", "Delivery Output Complexity", and "Product Complexity", based on the perceptions of the designers within three PDCs.

7.10.b Conclusion – Aim 2

Each of the influential factors stated above have had their behaviour modelled. "Designer Experience" and "Designer's Intuition of the Client" having an even influence over the duration of the project, where the better the experience and better the opinion of the client, the fewer resources needed for the project. The influence of "Brief Clarity" peaks at the project outset, with a more clarified brief correlating to reduced resource need; and the influence of "Delivery Output Complexity" peaks at the later stages of a project, with the higher anticipated complexity leading to an increase in project resource demands. Unlike any of the other factors discussed, the influence of "Product Complexity" does not diminish to near-negligible levels. It has been found to be a constant significant influence, peaking in the concept generation and development phases.

7.10.c Conclusion – Aim 3

By adopting a categorisation approach, a comparison can be made between the factors found to be most influential in literature and by PDC designers were identified. Nine categories were identified (Team Management, Product, Business Management, Information, Tools & Technology, Client, Project, External Influences and Budget). In literature, there is an emphasis on "team management" and "product-centric" factors, with other categories being acknowledged. In contrast, the data categorised from the case shows a more balanced consideration of each of the categories of factor.

From the analysis of the collated case data and its comparison to the literature review findings, a novel factor category has been identified. Featured in all three cases, "budget" (or similar) was identified by participants as influencing the design effort needs of a design project. As a category, this has yet to be mentioned within the PDC (or the wider design engineering) literature in this context. Therefore, this is a clear gap in the understanding of the phenomena influencing design projects by academia and therefore must be considered a contribution to knowledge.

7.10.d Conclusion – Aim 4

Various approaches have been explored throughout this multiple round quasi-experimental case-based investigation to identify which graphical method best communicated the information generated through the regression analysis of estimate values, these are summarised in Table 100.

Table 100 Cross-Case Analysis: Summary of Graphical Modelling Approaches Examined in Cross-Case Analysis

Information	**Use of information**
Regression Values (generated from Design of Experiments analysis)	Identify which factors had greatest influence as specific value
Percentage of influence (calculated from regression values)	Identify which factors had greatest influence as percentage of whole influence
Mean Effect Values (generated from Design of Experiments analysis)	Identify specific behaviour of influence each factor has per project phase

7.10.e Conclusion – Aim 5

A synthesised output of this study is described in detail in the next chapter.

8. A Proposed Method: the Collaborative Factor Identification for Design Effort (CoFIDE) Method

""Music is a journey, so enjoy the ride. Don't worry about the destination. Just enjoy the process and keep learning." -– Dave Grohl

8.1 Introduction

This chapter addresses Research Question 3:

> *How might PDC teams enhance their understanding of the project planning process and of their own teams through the collaborative capture and modelling of their own understanding?*

and fulfils Aim 5 of the Cross Case Analysis:

> *To synthesise an output from this analysis that can offer practical value to PDCs.*

By proposing a collaborative method which PDCs can follow to capture the tacit knowledge and experience of their designers in order to enhance their understanding of their project planning process. This chapter firstly presents the Collaborative Factor Identification for Design Effort (CoFIDE) method. CoFIDE is derived from an analysis of the experimental approach and the approach findings of each of its applications. CoFIDE includes the creation of a FESS and the use of PIGs and MEPs in its approach, whose discussion can be found in Chapter 7. The second part of this chapter proposes a variation of the CoFIDE method, the Collaborative Project Brief Scorecard (CPBS) method, which suggests an adaptation of the FESS to create project scorecards for project brief comparison.

8.1.a A note on CoFIDE Method

The following discussion is an adaptation of the publication titled "*What's taking so long? A collaborative method of collecting designers' insight into what factors increase design effort levels in projects*" (Holliman, Thomson, Hird, et al., 2020), published in a special issue Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM) on Fablabs, Makerspaces and Design Spaces, September 2020. Said paper describes the Collaborative Factor Identification for Design Effort (CoFIDE) Method, which formalises this approach to factor identification and evaluation for design teams. Although the discussion in this publication focuses on the benefits to hackathon teams, the method and the insight that it offers can benefit formal product design teams equally.

8.2 CoFIDE Method

The following section presents CoFIDE, a method which enables the collection of novel data on the collaborative perceptions and understanding of those factors which are most influential over design effort levels required to complete design projects. This method further enables the characterisation of these factors, modelling their behaviour to provide insight into how the influence of each factor changes during a product design project.

CoFIDE Method - Background

Developed through the application of this investigation, the CoFIDE method builds upon the work of Hird (2012) and their five-step process. CoFIDE sees three main changes to this approach: collaborative development, broader application, and graphical output.

Collaborative Development

CoFIDE is specifically developed to work collaboratively with all members of a design team, rather than just management and higher-level members. This prevents the users of CoFIDE from overlooking the knowledge and insight held by all members of a design team.

Not just for NPD

Hird’s method was developed specifically for new product development teams and their projects. As such, the potential range of projects that Hird’s method was developed for is limited in scope. On the other hand, CoFIDE was developed with PDCs, where the range of potential projects is far greater. As a result, the factors which are being identified are more general, and therefore potentially universal.

Graphical Output

CoFIDE offers the graphical modelling of each designer’s perceptions. Doing so offers the means to compare each other’s perceptions of the same factors and offers a greater understanding of the behaviour and characteristics of each factor throughout a product design project.

8.3 CoFIDE Method - Process

CoFIDE is a five-step method providing a means for data collection into a design team’s collaborative understanding of the most influential factors of design effort levels in product design projects. This section will discuss each stage of the CoFIDE process depicted in Figure 60.

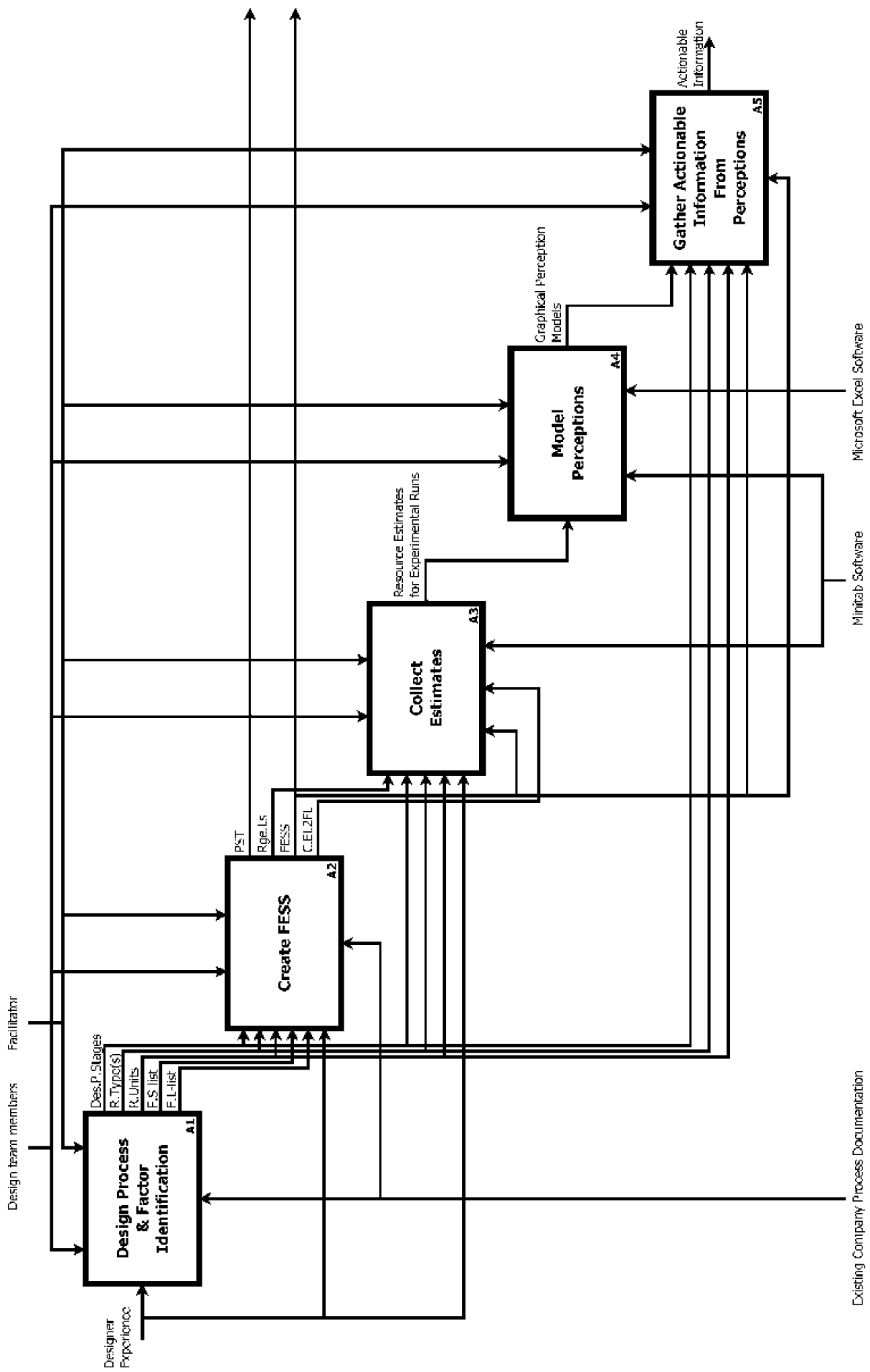


Figure 60 Collaborative Factor Identification for Design Effort (CoFIDE) Method IDEF0 Diagram

CoFIDE Method - Design Process and Factor Identification

This first stage of the CoFIDE method is shown in Appendix 10.1[1]. The design team agree on their (ideally) pre-established design process and the design effort resource that they will use when considering their design projects. The team then collaboratively identify all potential factors which influence the design effort level demands of a project phase-by-phase. These factors should all be assessable from the project brief, not just retrospectively. The factors are then collated and privately voted for, to identify the top four factors, by their degree of influence.

CoFIDE Method - Create Factor Evaluation Scoring Scheme

The second phase of the CoFIDE Method sees the design team consider all the collated factors that were used to describe the factors voted for in the previous phase, shown in Appendix 10.1[1]. Each of the top four factors should have contributing elements identified from these collated terms and each should have a range of levels attributed to them. These levels should be assessable from the project brief, not just retrospectively. The factors, their elements and corresponding levels are used to create a Factor Evaluation and Scoring Scheme (FESS).

CoFIDE Method – Collect Estimates

In the third stage of the CoFIDE Method (shown in Appendix 10.1[4]), the facilitator uses the FESS produced in the second phase is used to inform the creation of a four-factor, two-level half-factorial experimental design, based on Design of Experiments. Each experimental run describes a design project in which each member of the design team should estimate the design effort needs independently. These results are collated by the facilitator.

CoFIDE Method – Model Perceptions

The fourth stage of the CoFIDE method requires the facilitator to perform statistical analysis on the results to create a series of regression equations, shown in Appendix 10.1[4]. The results of this analysis are used to create three sets of diagrams to graphically model the perceptions of each member of the design team; Percentage Influence Graphs are created in the form of linear pie charts to aid in the identification of which factor(s) have the greatest influence per project phase; and Project Length Lines are generated for each factor to illustrate when in a design project, a given factor has the greatest influence over design effort needs. Mean Effect Plots are also created to model the behaviour of each factor during each project phase.

CoFIDE Method – Gather Actionable Information from Perceptions

In the fifth and final phase of the CoFIDE method (shown in Appendix 10.1[6]**Error! Reference source not found.**), the facilitator interviews the remaining design team members to consider the perceptions shown through the three graphical means produced in the previous section. From this, it is possible to identify areas of consensus and disagreement between team members over each factor's influence and behaviour. This can act as a conversational catalyst, encouraging the team to discuss the specific ways and means that each factor influences. From such discussions it may be possible to identify actionable information which may be used to guide changes to the design space.

8.3.a CoFIDE Discussion

Applying the CoFIDE method in a PDC will provide design teams with a rich set of data from which various insights can be achieved. Modelling the behaviour of influential factors provides the opportunity to optimise their work by targeting specific factors at their most influential. These models can demonstrate the differences in perceptions between PDC team members, offering a discussion point for teams to address these differences.

Unlike Xu & Yan (2006), Zirger & Hartley (1994), Ittner & Larcker (1997) and Tatikonda & Rosenthal (2000), the CoFIDE method identifies its factors based on the perceptions of a PDC design team, like that found in Serrat et al. (2013). Unlike many approaches, such as those proposed by Salam and Bhuiyn (2016) that are use-case specific, CoFIDE can be applied within any PDC design team. Similarly, although the CoFIDE method does use statistical analysis within its process, it does so without the need for sophisticated software or knowledge, nor large sets of data, that would be required for methods such as those proposed by Dittman et al. (2017).

Limitations of the CoFIDE Method

The use of the CoFIDE method to identify the most influential factors depends on at least one member of any design team to think of the factor in some form during the process. This can be considered as a clear limitation of the method, however possible solution to this would be to have some predetermined factors included in the process as a prompt. This has its own limitations as it may sway the participants to place greater importance on a suggested factor, rather than those that the participants identify.

The CoFIDE method works exclusively within the team that is using it and therefore will need to be repeated for each PDC design team in order to build up a global view of the influential factors. This presents a clear challenge as gaining access to a suitable number of PDC design teams will be logistically problematic.

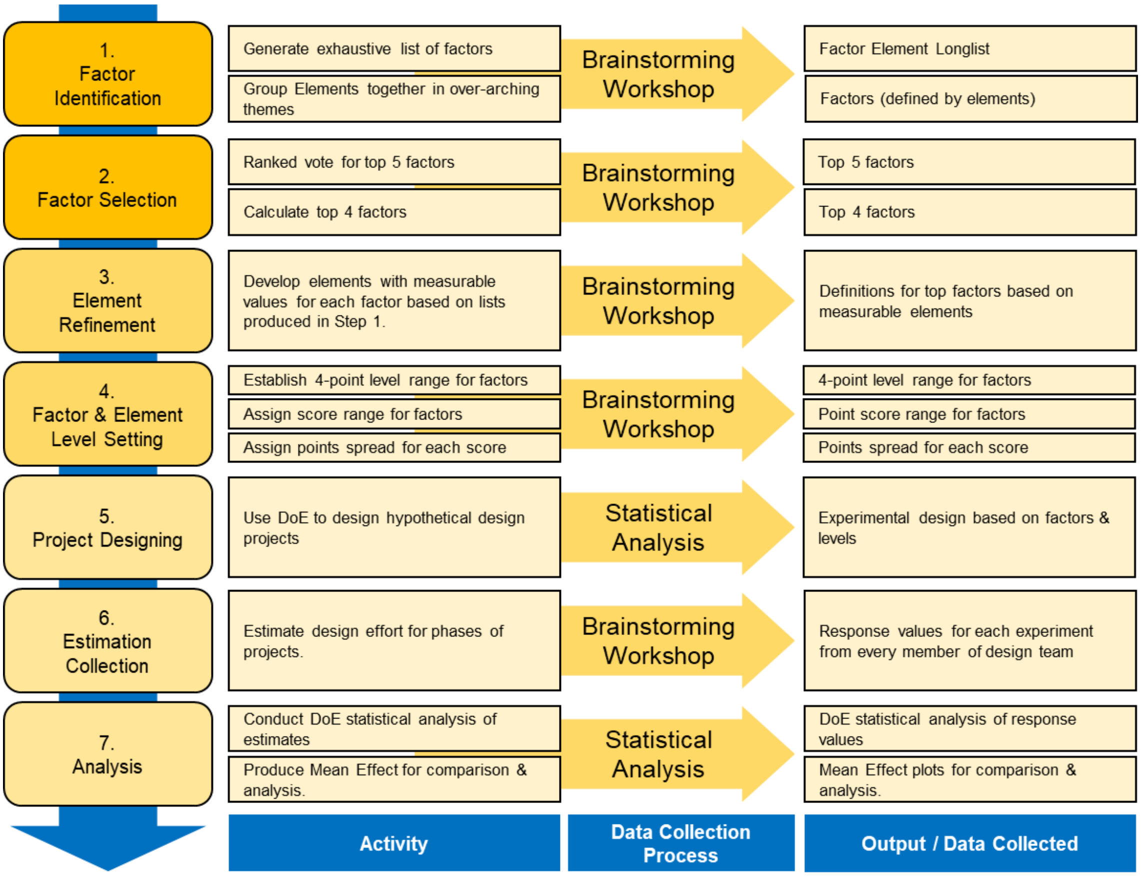
8.4 Proposed Method Development: Collaborative Project Brief Scorecard (CPBS) Method

8.4.a CPBS

An additional output of this study, building upon the main CoFIDE output, modification (and subsequent application) to the FESS process, to create a scorecard with which seemingly incomparable projects can be compared, as each project will be evaluated, their scores and the performance of the project (i.e. the actual amount of design effort required to complete it are recorded and stored. Due to many similarities between the CPBS and CoFIDE methods, this section will not discuss the proposed CPBS process in any detail, rather will discuss the potential benefits of its use in the future.

A note on CPBS Method

A version of the discussion in the following section is covered in a paper titled "*Collaborative Project Brief Scorecard (CPBS) Method: Evaluating Product Design Projects To Aid Design Effort Estimation*", published in Proceedings of the Design Society: DESIGN Conference, Volume 1, May 2020. A copy of this publication is included at the back of this thesis.



	Activity	Data Collection Process	Output / Data Collected
1. Factor Identification	Generate exhaustive list of factors Group Elements together in over-arching themes	Brainstorming Workshop	Factor Element Longlist Factors (defined by elements)
2. Factor Selection	Ranked vote for top 5 factors Calculate top 4 factors	Brainstorming Workshop	Top 5 factors Top 4 factors
3. Element Refinement	Develop elements with measurable values for each factor based on lists produced in Step 1.	Brainstorming Workshop	Definitions for top factors based on measurable elements
4. Factor & Element Level Setting	Establish 4-point level range for factors Assign score range for factors Assign points spread for each score	Brainstorming Workshop	4-point level range for factors Point score range for factors Points spread for each score
5. Project Designing	Use DoE to design hypothetical design projects	Statistical Analysis	Experimental design based on factors & levels
6. Estimation Collection	Estimate design effort for phases of projects.	Brainstorming Workshop	Response values for each experiment from every member of design team
7. Analysis	Conduct DoE statistical analysis of estimates Produce Mean Effect for comparison & analysis.	Statistical Analysis	DoE statistical analysis of response values Mean Effect plots for comparison & analysis.

Figure 61 Collaborative Project Brief Scorecard (CPBS) Method. Adapted from Holliman et al.(2020)

CPBS - Factor Identification

During the estimation phase of the CPBS Method, participants can use the scorecard as an aid when estimating design effort. By using tables similar to those shown in the scorecards created in Chapters 5 and 6, designers have a clearer understanding of factor characteristics at the levels described in the experimental designs generated in Step 4 of the Evaluation Method.

CPBS – Project Assessment

Although the insight offered by Evaluation Method enables designers and managers to assess future projects to aid in the overall understanding, this understanding has limited clarity due to the possible abstract nature of the factors identified. With the introduction of a scorecard in the CPBS Method, creating listed and quantified elements, project briefs can be evaluated in greater detail. This improved detail enables project planners to not only make improved, informed estimates of design effort based on generated scores, but also identify potential additional project resources required based on the levels of each element.

CPBS – Project Comparison

Using the scorecard reflectively to evaluate past projects can provide significant additional benefits to designers and managers. By recording the scores of past projects, and comparing them to the evaluation of future projects, designers and managers are able to make comparisons and make further informed decisions on design effort estimation and broader project planning decision-making.

The CPBS Method Scorecard offers two levels of comparison between projects. At a higher level, projects can be evaluated by the overall scores for each factor. However, as various combinations of element levels can result in the same score, comparing projects based on the element levels provides more specific comparisons with the potential for greater value. Furthermore, by comparing at this granular level, projects that have different factor scores can still be compared for the same element scores.

Furthermore, this activity could be regularly conducted collaboratively with the entire design team to maximise the utility of the scorecard, by providing a focal point for a conversation about the performance of such projects. These discussions could further be enhanced when the scorecard is used in conjunction with the Mean Effect plots.

8.5 CoFIDE Summary

This chapter presents a proposed method derived from the multiple round quasi-experimental case-based approach used in this research study. The Collaborative Factor Identification for Design Effort (CoFIDE) is a method for product design teams to gather valuable insight into their own design space, modelling the factors which influence the design effort level demands of their projects. CoFIDE enables design teams to identify and address these factors, offering a starting point from which a design team can make effective changes to their design space to improve their design processes and how factors influence their design effort demands. This is covered in greater detail in the earlier discussion of the CoFIDE method (Holliman, Thomson, Hird, et al., 2020).

Furthermore, this chapter presents a proposed development of the CoFIDE method, the CPBS method, to create a formalised scorecard to enable greater comparison between design projects in the future. This is covered in greater detail in the earlier discussion of the CPBS method (Holliman, Thomson and Hird, 2020).

9. Conclusion

"I'm sorry, if you were right, I'd agree with you." -– Robin Williams

This study introduced the issues surrounding the design industry as a whole and considered the fragility of the SMEs that make up the majority of the businesses in the field. In particular the under studied industry of product design companies (PDCs) that face several challenges which they must successfully overcome to remain profitable and successful in their craft.

This thesis aims to provide an approach to identifying the factors influencing resource demands of product design projects in product design companies. With a view that by understanding such factors, it may be possible to control their levels and therefore mitigate the negative influence. From existing literature, there is a wide range of factors which can be of influence, yet there was no clear agreement between studies on which factors were most influential. Similarly, the examples in the literature of approaches to identify such factors vary, with many capitalising on the insight to estimate design effort needs of projects. This thesis outlines several limitations that these varied approaches have including, most notably, the need for large bodies of past project data and sophisticated analysis tools and expertise to complete an analysis. One approach was highlighted as using Design of Experiments to generate the very data that would be required for a similar analysis.

9.1 Thesis Overview

At the core of this research are three cases, each conducted with UK-based product design companies. Each case contributes towards the identification and modelling of the factors that most significantly influence the resource demands of product design projects through the capture of tacit knowledge and experience of design teams.

This is achieved through the adaptation of the Design of Experiments process, moving its application from practical experimentation, to the creation of hypothetical design projects, with various improvements developed to enhance both the process itself and the details of the factors captured. Taking a collaborative approach enables the comparison of models between each participant, which has various applications of potential value.

Creating two graphical outputs were identified through this study which each effectively describe different characteristics of an influential factor's behaviour. The Mean Effect Plots (MEPs) indicate the directionality of a factor's influence, indicating whether there is a direct correlation or indirect correlation between the level of a factor (how present it is, etc.) and the anticipated design effort resource needs for a design project phase. The Percentage Influence Graphs (PIGs) indicate the magnitude of each factor's influence per project phase.

In combination, the MEPs and PIGs can graphically illustrate how each factor's behaviour changes over the duration of the project.

By comparing the findings of each case, this research has further identified which factors have the greatest influence over design effort demands of PDC design projects and through an analysis of their MEPs and PIGs collaboratively capture said perceptions of the factors which influence the design effort needed to complete a given product design project. Case 1 saw the implementation of this approach, using collaborative processes such as brainstorming, which the design team were familiar with, as it is used frequently in their design practice. Through these processes, participants were able to identify a range of factors which influence design effort needs of product design projects, and through a series of votes, those considered to be most influential were identified.

Following the DOE process, an experimental design was selected and used to describe a series of hypothetical design projects, defined by specific combinations of levels of each of the factors. Participants estimated the design effort needed for each hypothetical project and the results were analysed, as per the DOE process. This process generated a series of regression equations, and the values for each factor could be used to determine their magnitude of influence. The DOE process generates several Mean Effect plots (MEP) which can be used to determine the "direction of influence" each factor has, by showing each factor's influence in the extremes of its state. Case 1 also determined that the number of factors to be included in such a process should not exceed 4, as to do so would require the selection of an experimental design with more experimental runs than any participant could comfortably estimate.

Case 1 also saw the creation of a factor scoring approach, where factors could have a series of contributing elements which, in turn, influence the overall effect (and level) of a given factor (this process would be expanded upon in Case 2). This was only developed for the factor of *product complexity* as it was shown to have the greatest influence. This resulted in a second round of hypothetical design project estimates, using a Taguchi-based experimental design to include *product complexity* at four levels. It was determined that a Taguchi-based experimental design was not the best approach, due to the limitations of the resulting analysis relating to the interactions between factors and their influence.

Case 2 implemented the formalised factor scoring approach (FESS) for each of the identified influential factors, using the output of the brainstorming exercise to inform the elements for each factor. Case 2 also introduced the concept of using mean effect plots from the regression analysis to model the behaviour of each factor as it relates to the magnitude (or presence) of any given factor. Case 2 identified the use of linear percentage influence graphs (PIG) as an effective means of comparing all factors' influence and also comparing the perceptions of each member of a design team.

Case 3 saw the verification of the practicality of the FESS, MEPs and PIGs, observing that adding binary (yes/no) options into a FESS should be discouraged if at all possible for practical and modelling purposes. Additionally in Case 3, the development of a scorecard creation process to further enhance the insight gained from the method and the facilitation of the cataloguing of project evaluations for future insight gathering.

The cross-case analysis presented in this thesis collated the datasets from all three cases and conducted various analyses to identify various trends in the findings, to address the research questions. Additions were made to the categories synthesised from literature review findings, adding "budget" factors into consideration. The top five most influential factors for design effort demands were identified ("Brief Clarity", "Designer's Experience", "Designer's Intuition of the Client", "Delivery Output Complexity" and "Product Complexity"), with their influence on behaviour modelled. "Product Complexity" was specifically identified for its frequency within the datasets, with dimensions and proposed scales identified with which the factor could be measured.

In addition, the research process adopted has been adapted to produce the Collaborative Factor Identification for Design Effort (CoFIDE) method. This method provides design teams with the processes required to identify the factors most influential over design effort requirements of product design projects using the captured tacit knowledge and experience of design teams. CoFIDE also provides modelling of each factor's behaviour throughout a project using the same captured insight. In addition, this study presents a suggestion for an addition to the CoFIDE process, the Collaborative Project Brief Scorecard (CPBS) method a project evaluation tool and scorecard model to enable the quick assessment of design projects (based on project briefs), enabling comparison between projects.

9.2 Answering the Research Questions

The main aim of this research project is to make a significant contribution to knowledge. A vital goal for this research was to provide an approach which is not only valuable to product design agencies of all sizes but also practicable for them too. What is the point of industry-based research if it does not benefit the industry that it studies? By working with the very SME's that can benefit most from the research findings, not just in terms of the lengths of time, and therefore sums of money, that can be saved, but the impact on the livelihood of a business that those savings can make, this research has provided real value.

9.2.a Contribution to Theory

To determine the contributions to knowledge offered by this research, the research questions posited within this thesis need to be answered.

> *RQ1: What factors are considered to have the greatest influence over product design company project resources and how do those considered by product design company teams differ from those in the literature?*

Through the analysis of the findings of each of the cases, five factors were found to have the greatest influence over product design company project resources: *Brief Clarity, Designer Experience, Designer's Intuition of the Client, Delivery Output Complexity* and *Product Complexity.* The factors found in literature and in the cases were categorised to facilitate comparison, from which a difference in instance (the number of times a factor category is found) can be observed. This difference shows that in literature, there is more significance placed on Team Management factors (24% in literature, 16.13% in cases) and Product (21% in literature, 12.90% in cases), whereas in the cases, there is a more even distribution of instances between factor categories.

Additionally, the case data revealed a novel factor category, not covered in the literature. *Budget* factors were found to have the same percentage of instances from the cases as the *Tools and Technology* category, at 9.86%.

> *RQ2: How do factors influence the resource demands of product design company projects and how does that influence changes throughout a project?*

By modelling the perceptions of professional product designers using a DOE-based approach, it has been possible to model the behaviour of the most influential factors on resource demands of PDCs. Analysis of the Mean Effect Plots (MEPs) and Percentage Influence Graphs (PIGs), a visual model of the behaviour for each of these factors has been achieved. These five factors have behaviour that is either *Top-heavy* (where the greatest influence is at the project outset, tapering off as the project progresses); *Bottom-Heavy* (the opposite of *Top-heavy,* with influence low at the project outset and increasing towards the later stages of the project); or *Even*, where the magnitude of influence remains mostly constant throughout the project. The correlation between a factor's presence and how it influences design effort demands has also been found. There are two correlation types: when an increase in a factor leads to an increase in resource demand; and where an increase in factor leads to a decrease in resource demand. These behaviours and correlations are presented in Table 101.

Table 101 Conclusion: Factor Influence Behaviour

Factor	Behaviour	Correlation	Scale
Brief Clarity	Top-heavy, reducing over project duration	Increased clarity, decreased design effort	Ambiguous – Defined
Designer Experience	Even	Increased experience, decreased design effort	Novice – Expert
Designer's Intuition of the Client	Even	Increased opinion, decreased design effort	Bad – Good
Delivery Output Complexity	Bottom-heavy (*Documentation & Testing Phases)	Increased complexity, increased design effort	Simple - Complex
Product Complexity	Even	Increased complexity, increased design effort	See *Contribution 2*

> *RQ3: How might PDC teams enhance their understanding of the project planning process and their own teams through the collaborative capture and modelling of their own understanding?*

This study has developed and presented a method for capturing the tacit knowledge and experience of designers to model the behaviour of influential factors on product design project resource demands. By applying this collaborative method, PDC teams are able to identify which factors have the greatest influence and then model their influence over the duration of a project. Considering these models will enable PDC teams to enhance their understanding of the project planning process, providing opportunities to allocate additional project resources where required.

9.3 Contribution of the Research

Four main contributions are claimed, each relating to the research questions stated.

Contribution 1

The identification and modelling of which factors have the greatest influence on design effort demands of PDC projects, based on the PDC team's tacit knowledge and experience.

To answer all three research questions, an analysis of the three case datasets was conducted, with five factors with the greatest influence on design effort needs of PDC projects being identified: "Brief Clarity", "Designer's Experience", "Designer's Intuition of the Client", "Delivery Output Complexity" and "Product Complexity". Having captured the tacit knowledge and experience of three design teams, a broader understanding of the perceptions of the PDC industry has started to be established. These findings have been summarised in Analysis of the Mean Effect Plots (MEPs) and Percentage Influence Graphs (PIGs), a visual model of the behaviour for each of these factors has been achieved. These five factors have behaviour that is either Top-heavy (where the greatest influence is at the project outset, tapering off as the project progresses); Bottom-Heavy (the opposite of Top-heavy, with influence low at the project outset and increasing towards the later stages of the project); or Even, where the magnitude of influence remains mostly constant throughout the project. The correlation between a factor's presence and how it influences design effort demands has also been found. There are two correlation types: when an increase in a factor leads to an increase in resource demand; and where an increase in factor leads to a decrease in resource demand. These behaviours and correlations are presented in Table .

Contribution 2

The identification and synthesis of various dimensions of product complexity

Expanding upon the answer to RQ1 and RQ2, is deeper dive into the most commonly mentioned factor, product complexity. Through the analysis of case data findings, and in comparison to findings of a literature review, various dimensions of product complexity were synthesised. Each dimension has various scales on which product complexity can be measured. design effort influencing factors found in literature, several categories were synthesised. The dimensions identified were based on the number of parts a product is anticipated to have and whether they need to be custom designed; the intended functionality of the product, including its degrees of freedom, and the technologies required to enable those freedoms and functionalities; and the creativity required of the design team to design the project. The latter has two distinct scales proposed, based on either the confidence of the design team's abilities or as a derivation of the functionality dimension, applying a level of understanding of the various function-fulfilling technologies required for the product. These dimensions and scales of product complexity are summarised in Table 102.

Table 102 Conclusion: Dimensions and Scales of Product Complexity

Dimension	Scale	Units
Number of Parts	Number of Parts	-
	Percentage of Parts to be Custom Designed	Percentage
Functionality	Number of Functions	-
	Degrees of Freedom	0-7
	Number of function-facilitating technologies	-
Creativity	[EITHER] Percentage Confidence of Design Team Abilities [OR] Percentage of understanding of function-facilitation technologies* identified	Percentage

Contribution 3

The identification of "budget" as a novel category for design effort influencing factors and the synthesis of a novel set of categories to apply to design effort influencing factors in design projects derived from literature.

Through the analysis of design effort influencing factors found in literature, several categories were synthesised. Through the findings of the cross-case analysis, an additional, novel category of "budget" was identified, resulting in the following nine categories: Team Management, Product, Business Management, Information, Tools & Technology, Client, Project, External Influences and Budget

Contribution 4 (Practical Contribution)

The development of the proposed CoFIDE method, a novel, tacit knowledge capturing, influential factor identification and modelling method for design effort level influencing factors in PDC projects.

To address RQ3, a method was developed to identify and model the behaviour of the most influential factors of design effort demands of design projects. Based on the experimental approach, CoFIDE is a method which models the behaviour of the most influential factors per phase of a design project, utilising two graphical methods to produce the models. The Mean Effect Plots (MEP) of each design team member for a given factor overlaid in a simple line graph provide a clean means of identifying the behaviour of a factor, and how its average influence changes from being at its perceived lowest state to its perceived highest. The Percentage Influence Graphs (PIG) provide a direct means of identifying which factors exert the greatest influence over design effort requirements. By representing percentage influence in linear bars, direct comparisons between designers and their perceptions of factors can be made quickly. In combination, these models enable design teams to identify which factors have the greatest influence and how that influence behaves based on the magnitude of their presence. This provides design teams with potential opportunities to take action to reduce negative impacts, and increase positive impacts, on projects.

9.4 Research Impact

9.4.a Industrial Impact of Factor Findings

As discussed in the introduction and literature review, the body of research within the PDC industry is profoundly limited, therefore any research and subsequent publication that does consider this industry can have significant value. Research into the factors which influence the resource demands of PDC projects is no exception. Although this study only considers three PDCs, it is the foundation of understanding in this under-represented field. By identifying which factors have the greatest influence, and modelling that influence, PDCs can contextualise their own projects against these factors, something they may not have done previously, and reflect on how these factors influence their own projects. PDCs can also consider what other factors might influence their projects, and with the categories that this thesis presents, can compare their set of factors to other PDCs.

Furthermore, having identified that "product complexity" is the most significant and influential of factors, PDCs can use the dimensions presented in this thesis to assess their own projects. With a better understanding of how product complexity impacts their projects, PDCs can draw comparisons between past projects to determine trends and identify potential training opportunities for staff, in particular relating to the measure of "creativity" (shown in Table 102) which can mitigate the impact of that dimension of "product complexity".

9.4.b Academic Impact of Factor Findings

The academic impact of the factor-related findings of this study is the holistic understanding of influential factors has been presented. Unlike the findings from literature, which are derived from studies involving larger engineering organisations which have a specific market they develop products for and therefore have perspectives on factors framed within the context of their markets. This section will provide detail on specific impacts made by this research.

Impact on Influential Factor Research

The lack of academic research into PDCs is significant, as discussed in chapter 1. This may be due to various reasons, but the holistic perspective held by PDC design teams is different to those in NPD teams, or similar and therefore the perceptions on the design practice and what influences it is equally different and holistic. This includes the perceptions held on which factors have the greatest influence over design project resource demands and their behaviour. It has been indicated in each of the case chapters, as well as in the Cross Case Analysis, that there are some differences between the factors in literature and in industry that are considered to be most influential of PDC project resources. The contribution statements earlier in this chapter highlight these differences and act as a mandate for further study. With factors such as "budget" and the differences in makeup of the "client" factors, there is a need to update and refresh the understanding academia has on these factors in general. Each of the factors found in this study and their proposed elements and scales ("Brief Clarity", "Designer's Experience", "Designer's Intuition of the Client" and "Delivery Output Complexity") require further, deeper exploration to understand what contributes to each. Additionally, if differences can be found in the data of three cases (when compared to literature), then many more could be found in in broader studies.

Examples of research questions which could be derived from this study include:

From the perspective of Product Design Companies, what elements are most critical to the "Designer's Intuition of the Client" and how might they be manipulated to mitigate its negative effects, or enhance its positive effects on project resource demands?

Indeed each factor could itself be studied to the same depth as this study has considered the factors as a whole, with the behaviour of each element being modelled. Further study could also be conducted into how factors influence other project performance characteristics. Logically project cost would be a likely focus, as the costing for most design projects is a function of its time. However, this could be extended much further, to product characteristics from product cost (itself a likely influenced by the cost of the project to design it) but also product appeal.

Impact on the Academic Understanding of Product Complexity

"Product Complexity" is a factor which this study has found agreement between literature and PDCs. It is widely understood to have influence over design project resource demands. However, the same lack of investigation into PDCs and similar organisations presents a similar issue for its understanding in academia. Sources discussing "product complexity" tend to relate to specific project types, giving a more focused and biased) view on the factor. By identifying a set of general dimensions for product complexity, this study offers a more holistic view on this significant factor and can be used as a basis for further study into this pervasive factor. Unlike the definitions of product complexity found in the review presented in the cross case analysis which are derived from studies conducted with larger, limited market-focused engineering organisations, the dimensions presented in this thesis reflect the perceptions of designers with a greater, holistic understanding of product complexity. However, this presents its own question for further study:

How accurately does the proposed general dimensions of product complexity reflect the experiences of practicing product designers?

Impact on the Academic Understanding of the Behaviour of Influential Factors

Identifying that each factor behaves differently is not intrinsically novel, however by using a graphical approach to model the captured perceptions of practicing PDC designers is, as mapping the behaviour to design project phases offers rich insight into each factor. Academic value can be found, for example, when drawing comparisons can be made between PDCs (or other organisations) from different countries. This could provide insight into what factors are most influential and how their influence differs between PDCs and countries. A research question derived from this could be:

What are the differences between the factors considered to be influential on design project resource demands issues faced by Product Design Companies based in different countries and how does factor behaviour differ?

Impact on the Academic Understanding on Comparing Designer Perceptions of Influential Factors

Similar comparisons can be made between at an organisation level, between individual members of a design team. How each designer perceives these factors, and differences between these perceptions, are subject to each designer's experience and education. With comparisons made, any differences identified may provide areas of further research.

9.4.c Industrial Impact of CoFIDE

Product design companies that apply the CoFIDE method are provided with a range of insights into the factors which influence their projects. Through the identification of such factors, such companies can adopt management styles/approaches and coping strategies to mitigate the effects of some factors. Conversely, such a study may provide details of means of enhancing the effects of other factors advantageously. Such actions provide opportunities to optimise practices and processes, the CPBS method in conjunction with the insight offered by CoFIDE's modelling of factors enables more accurate project planning with a means of evaluating projects to determine the significance of each factor and its influence on such a project. With more accurate planning comes more efficient costing, which enables product design companies to be more competitive and therefore more successful.

As the CoFIDE method produces models of the perceptions of the individual members of their design teams, this presents additional benefits for product design companies. The models created may provide a means of describing design team perceptions that they were unable to articulate. Similarly, these models can help identify which design team members have differing perceptions. This would allow for management to offer opportunities for discussion, identify needs for training, and provide profiles of team members which could enable decision-making around project team membership, etc.

Impact on the Design Economy and the Economy at large

As discussed in Chapter 1, the majority of businesses operating as part of the UK design economy are SMEs with a 60% survival rate. With the advantages outlined in the previous paragraphs, the use of CoFIDE in product design companies can lead to increased success. This benefit can be extended to other businesses that are part of the UK design economy. Any increase in the survivability of SMEs will have a profound impact on the UK economy as a whole, in particular around increased employment rates. This can be extended to the global design economy and can therefore have a positive influence on the design industry as a whole.

9.4.d Academic Impact of CoFIDE

Several research insights are offered by the CoFIDE method, which were summarised by Holliman et al (2020) in Figure 62 and are discussed in this section.

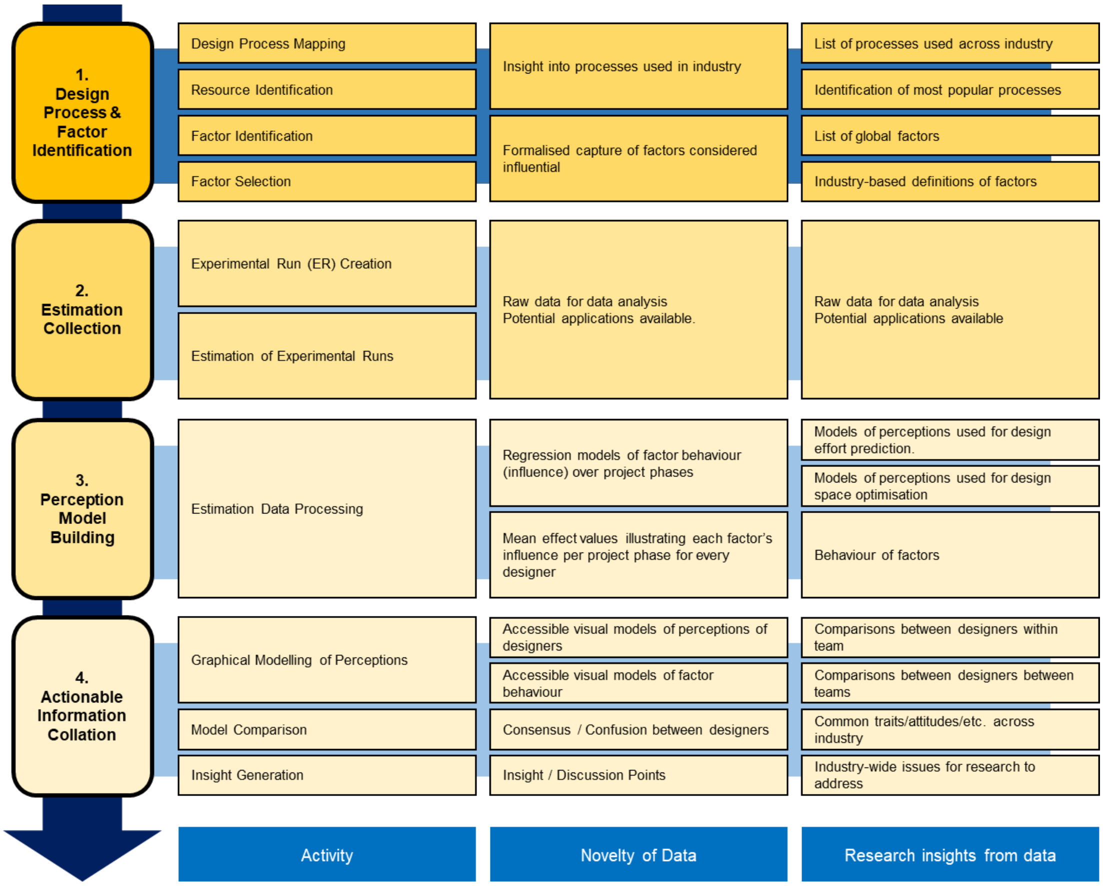


Figure 62 CoFIDE Method. Adapted from Holliman et al (2020)

Design processes used in Industry

Many design processes have been discussed and published in academic research. Many of which were covered in Chapter 2. Yet to date, there has not been a national or global study into what design processes are used by practising product designers in an industrial setting. The larger application of the CoFIDE method would facilitate such an investigation, which would highlight which, if any, of the processes derived from academic studies best reflect the industry practices and potentially inform the development of guidance for best practices.

Global List of Factors Influencing Product Design Projects

In a similar vein to the previous section, the larger application of the CoFIDE method would enable the development of an exhaustive list of which factors are considered to influence design effort needs of product design projects. From this, it would be possible to identify trends in which factors have this influence. It would be possible to determine if there are differences in perceptions based on several variables: the country the business operates, the education of design team members, the socio-economic backgrounds of design team members, and the processes that design teams adopt in their practice, to name a few. Building upon this, it would be possible to develop robust definitions for each of these factors once sufficient examples were collected from larger number of uses of CoFIDE.

Raw data collected during process application

It is likely that there are uses for the data beyond those explored within this study. Therefore there may be a need to experiment with the collected data to identify novel insight and uses for them.

Models of perceptions used for design effort prediction and design space optimisation

By developing a range of influential factor models, it may be possible to estimate the resources needed for a given project based on factor levels. These models could also be used to mitigate the impact of influential factors, in effect optimising the design space, the environment and processes used by PDCs. This would require further investigation but presents many avenues for further investigation.

Spotting industry trends

Additional comparison between results of multiple uses of CoFIDE will enable the identification of trends between industries, which may have value in academic research.

9.5 Quality of the Research

If claims of contribution to knowledge are to be accepted, this research must be critically assessed and shown to be valid and of quality.

9.5.a Construct Validity

Construct validity is a means of determining how well an experiment lives true to its claims, and the extent to which the study relates to the accurate observation of reality (Denzin and Lincoln, 2017). Several methods and approaches can be used to ensure construct validity. One which is often used in management research is linking the research construct to existing literature. This research does not link directly to any given research on the influential factors of the design effort demands of product design projects. That said, the use of the widely accepted approach, Design of Experiments (Fisher, 1949) has been well-documented in countless fields. That in itself is not enough for validity, so other approaches are presented as being achievable:

Establishing a chain of evidence (Yin, 2014); although, as mentioned previously, literature cannot support the construct presented, what has been presented is a logical argument moving from existing research, with logical arguments given when critiquing and "disproving" existing methods.

Using multiple sources of evidence (Denzin and Lincoln, 2017): A constructivist research stance requires the collaborative creation of knowledge. With each participant being its own source and each case its own discrete pool of participants.

Thick descriptions: The development of a modelling process has been covered and fully discussed in depth, including analysis of drawbacks to a chosen approach for each case influenced the development of further studies.

9.5.b Internal Validity

Internal validity is the logical testing of relationships between various variables within research. In particular, the use of open discussions regarding assumptions and cross-case analysis of results can aid in the establishment of internal validity. The disproval of alternative approaches is considered a suitable alternative to the provision of a hypothesis (Popper, 1965).

Cross-case analysis: multiple cases were conducted as part of this research.

Reporting of deviant results: All cases had their successes, although some assumptions and steps taken did not perform as well as hoped. These were discussed within their corresponding case and the cross-case analysis.

An open discussion on assumptions made: Throughout the research process, the assumptions made, as well as the findings found, were reported to the stakeholders of this investigation, namely the participating organisations for each case. These updates would occur regularly and would allow for any discrepancies (in either assumptions or opinions) to be promptly identified and addressed. This enabled the development of strong working relationships and to build a level of trust and understanding, as well as faith in the research process. This dialogue further enabled a means of offering feedback and process improvement.

9.5.c External Validity

External validity considers the applicability of research findings beyond the immediate case. Although research using a experimental approach is typically used to study the effects of phenomena within a particular context of a particular case (Coughlan and Coghlan, 2002), the field within which the findings can be generalised must be clear (Yin, 2014). In the cases outlined in this thesis, the models and insights that they offer are specific to each organisation and the team within. However, the method that is discussed in this thesis to produce such insight is generalizable, not just in the field of product design, or even, perhaps, the design industry as a whole, but may apply to a vast range of applications. Although the method addresses factors influencing design effort, this is merely a resource for a project. There may be applications to consider other types of resources in other kinds of projects. Or, for that matter, other scenarios beyond that – ones where expert judgement is still widely used, where there are high levels of uncertainty and complexity.

This research process has been applied in three complex and uncertain contexts, each with positive results. Each model identifies the factors which influence design effort levels needed for design projects as described by a series of factors and their perceived levels.

9.5.d Reliability

Reliability, in this context, relates to the repeatability of the research process, with research being considered reliable if the process can be repeated at some different point in time, by different researchers in the same environment resulting in the same conclusions (Yin, 2014). It is extremely unlikely that the exact same regression values will come from the same process conducted in a year, as tacit knowledge and experience are constantly developing. However, it is anticipated that similar results would be achieved in the short term.

The process of the developed method has been documented in a step-by-step manner, with simple instructions and detailed analysis produced, enabling repeatability by others if required; as stated previously, what is the point of industry-based research if it is not to benefit the industries involved?

9.6 Limitations of Research Approach

No research is without limitations. Resource and time constraints of the participating companies are inevitable and had an impact on the research output. It is important to identify the limitations in a study, to strengthen the validity of the findings made and to reinforce the reliability of the research process.

9.6.a Developing a Process Between Cases

By conducting an evolutionary multiple round quasi-experimental case-based approach in this study, the experimental method changed between each cases. Although the core of the method fundamentally remained the same per case at a "tactical" level (the collaborative brainstorming of factors; the use of design of experiments, including regression analysis; etc.), the variations at an "operational" level (the voting procedure, when and how factor levels were identified, etc.). Opportunities for comparison between these approaches were missed as each case was conducted with a different PDC design team. This was ultimately unavoidable due to the availability and willingness of each of the PDCs. This leaves some insight into the efficacy and viability of some of these changes unidentified.

9.6.b Participant Participation

As alluded to previously, one significant limitation of this research is the time constraints made by the participating companies. Indeed, the very issue that was addressed in the introduction to this thesis – that design companies are under high levels of pressure and taking any time away from the act of "designing" impacts the performance of a business – resulted in limited time made available to conduct research. With more time to participate in research, more discussions could be made with

9.6.c Long-Term Value

The long-term value of the insight offered by the implementation of this method could not be investigated. This links to the limited time made available for research, but is also a greater issue, as there is no clear means to measure the impact that such insight and tools offered would have on the productivity of a design team or the design company they are a part of. Indeed there may be ways to measure the time taken to do "old way of doing things" vs. the "new way" enabled by the insight and tools offered, but the long-term benefits of these savings are unclear.

9.6.d Statistics, Statistical Analysis and Design of Experiments

This researcher is by no means an expert in statistical analysis, or statistics as a whole, with no prior experience in using Design of Experiments. Although training in these areas was undertaken, the method developed uses the basic approach and perhaps only scratches the surface of what the method development could offer. This itself may well be a limitation of the approach as a whole, yet by using only the fundamentals, the method was more easily explainable to design teams, who themselves are likely not to be experts in statistical analysis.

9.6.e Factors in Literature

As stated repeatedly throughout this thesis, the body of literature reviewed to derive research questions and other assumptions were far broader than the PDC industry (the area of focus). Therefore it must be acknowledged that there are many possible issues related to this discrepancy. Issues faced by PDCs are not individually unique, they are issues faced by many organisations in many industries. However, in the aggregate, these issues are highly specific. Therefore, the issues faced by related industries (i.e. design engineering, new product development, etc. all included within the literature search terms) may differ significantly from those of PDCs. The illustrative example eluded to in the cross-case analysis of project funding is an important one. Such issues may not be faced by design teams of larger organisations, therefore would not even be considered. As such, some caution must be had when jumping to conclusions from the direct comparison between the literature review findings and the case datasets.

9.6.f Drawing Conclusions from the Cases

In a similar vein, caution must be had when drawing conclusions from the findings of only three cases as one cannot form a world view from the perspectives of three PDCs alone. Naturally, many limitations can be applied to the case dataset. Many of the designers and engineers of all participants were educated in the same two universities. These universities may imbue a particular worldview upon their students, bringing them to the workforce. Likewise, as all three PDCs were located in the UK, there are UK-centric issues that might not be relevant to PDCs of other countries and vice versa. As such, an academic *pinch of salt* must be had while considering such findings.

Additionally, the variations between each PDC must be acknowledged. Each organisation has their own management structure, ways of working and culture. From this, we must consider that although the applied approach has been considered successful in this study, without further study, it is not possible to conclude that this success will be the same for the whole industry. These differences also highlight that the data and outcomes from each case my not be wholly comparable. The perspectives of each participant group may align, but they may equally not. The factors that have been identified in these studies have been largely found to mean the same, yet the underlying attitudes towards each might differ. These potential discrepancies can be addressed through greater, wider study into the PDC field.

9.6.g New Industry-Wide Issues Post Case

It must also be noted that Brexit may have an impact on some of the factors considered within these studies. As the data from each study was collected prior to Brexit, it is unknown how this may influence the decision making and perceptions of the participants. Perhaps there’s a need to conduct the same studies again with the same PDCs to determine how Brexit has influenced such perspectives.

9.7 Future Work

As this research describes the novel application of Design of Experiments and regression analysis in the identification of and modelling of design effort-influencing factors in PDC projects. However, there are various directions that this research and its method can be taken.

9.7.a Testing of the proposed CPBS method

As identified and proposed in the cross-case analysis, the CPBS could offer value to PDCs, enabling the comparison of different (seemingly incompatible) projects. This would require a detailed, multi-participant longitudinal study to determine the value of such a scorecard in its own right.

9.7.b The amalgamation of CoFIDE and CPBS

Building upon the first point, the integration of the CPBS method within the CoFIDE method may enhance the benefits of the CoFIDE method. This would in effect produce a toolkit for PDCs to use to gain a better understanding of the factors which influence their projects and enable a broader and deeper analysis of their projects, both past and present. This too would require a detailed, multi-participant longitudinal study to fully assess this value.

9.7.c Refinement and Optimisation of Method

Naturally, one of the avenues for further work is in the improvement of the process. Using the CoFIDE method across several design teams, varying in both size (number of team members) and diversity of experience between team members. Doing so will allow for the capabilities of CoFIDE and its tools to be fully realised. In addition, this would provide insight into understanding how design team members with different experiences and backgrounds perceive the challenges and influences exerted by factors on design effort levels.

9.7.d Global application of CoFIDE Method

As discussed in the impact section of this chapter, by applying the CoFIDE method within multiple product design companies globally, it may be possible to identify which factors have an influence over design effort levels at global, country and regional levels. This, of course, may also prove that the opposite is true, that there are no globally influencing factors over design effort requirements of product design projects. This may open potential avenues for further investigation, as different companies may employ different management and coping strategies to mitigate some factors. Such insight could be valuable to improving other companies and lowering the barrier to entry for future designers.

9.7.e Estimating Design Effort in Product Design Companies

Within the CoFIDE method is the creation of regression analysis data, which has the potential to be extended for the use of design effort estimation. Therefore an additional avenue of research would be in the creation of bespoke tools for design teams to estimate design effort for their projects. This that the potential to enable design companies to significantly save on time (and money), through the quick assessment of project briefs and generating accurate design effort estimates.

9.7.f Developing a Global Understanding of Design Effort Level-Influencing Factors in Product Design Companies

Through the refinement and expansion of the study to include a significant percentage of practising PDCs, a holistic understanding of these influential factors can be understood. Such global understanding could identify many avenues for further research into, including but not limited to, the effects of the globally recognised most influential factors, the different perceptions of these factors based on geography, socioeconomic and other differences; and comparisons with other related industries, such as New Product Development teams, etc. The findings of such research may identify potential commercial opportunities, addressing these factors at a national and international level (i.e. new educational opportunities (CPD, etc.), new project support tools, equipment, etc.)

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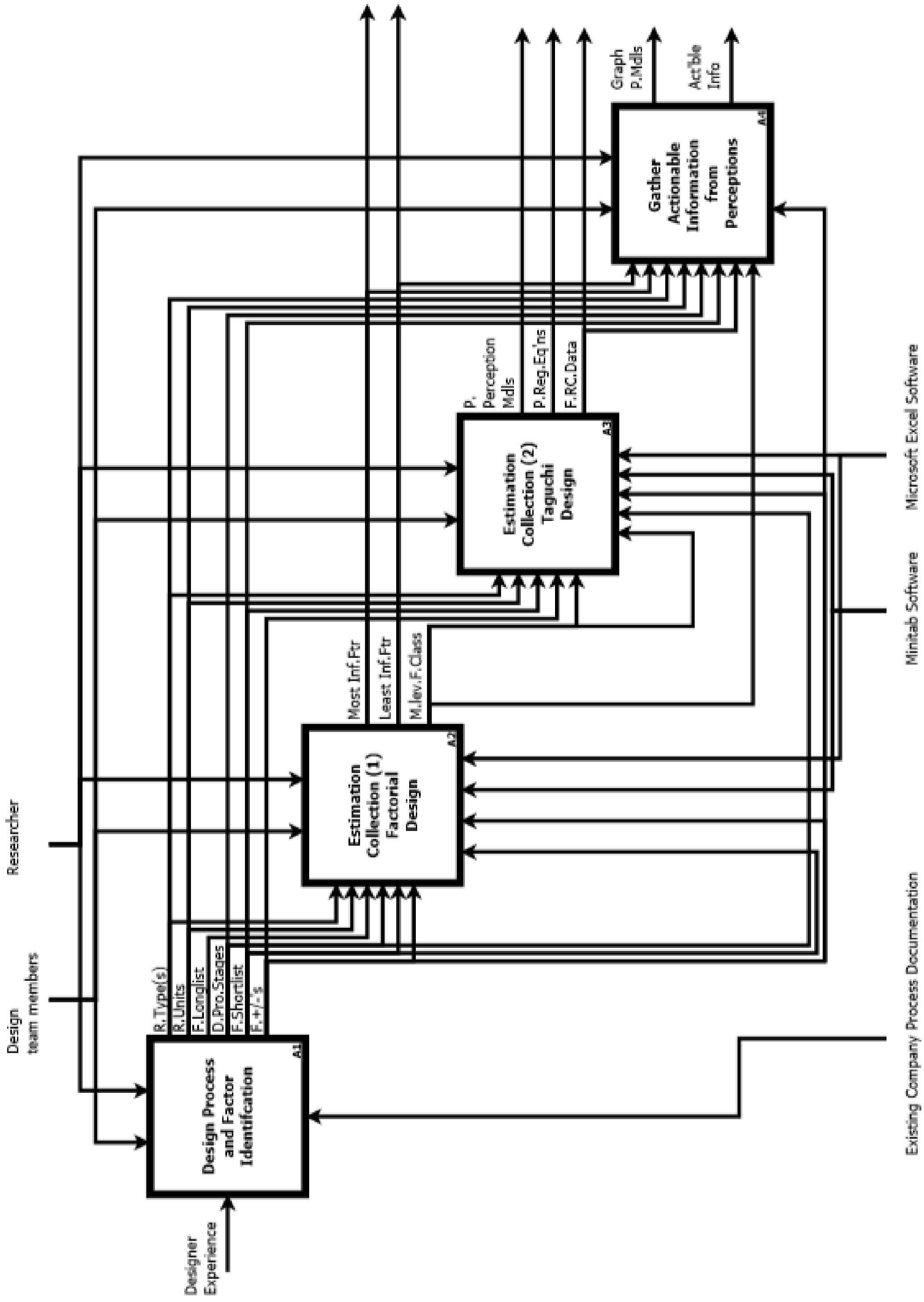
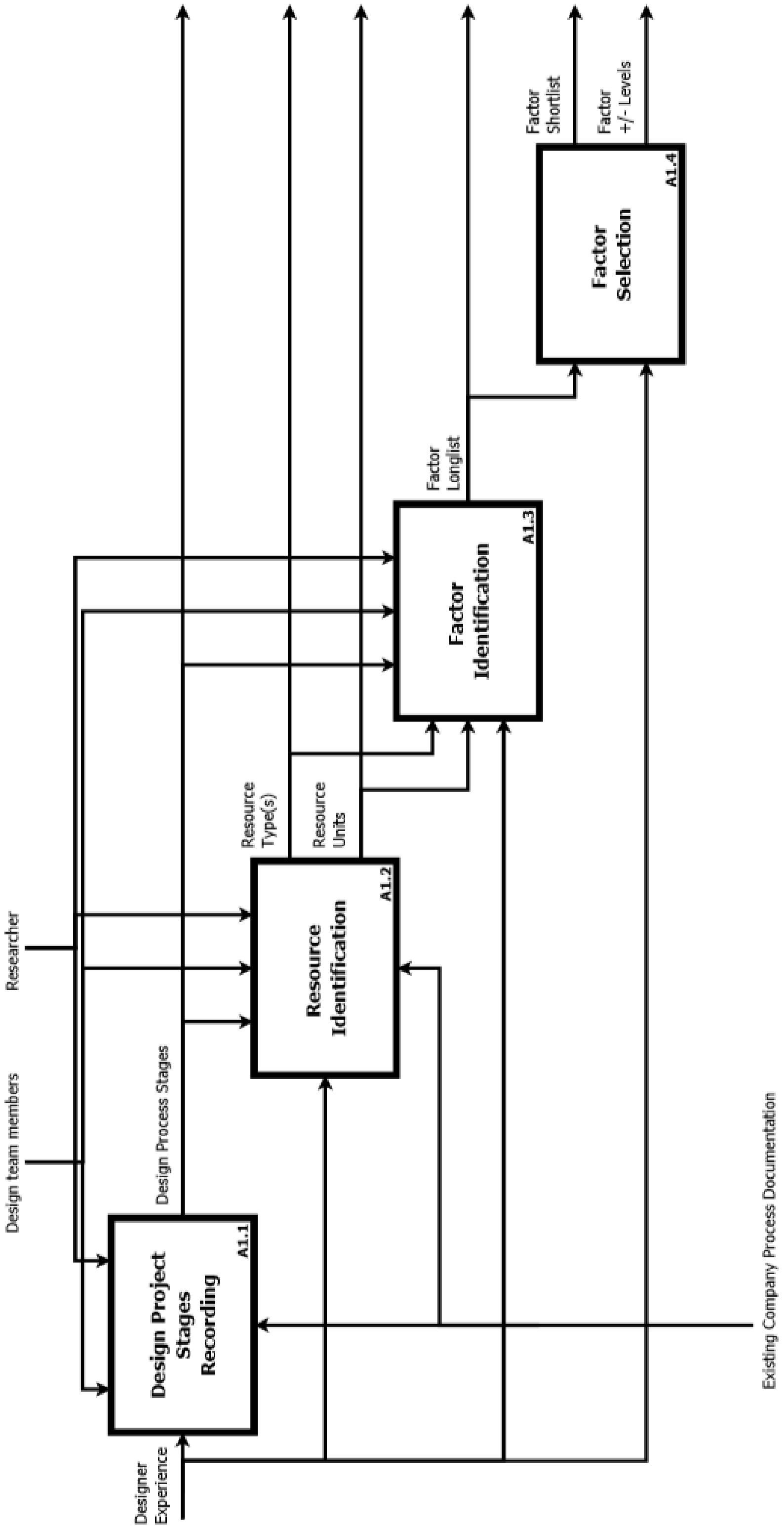
Appendices

Case Study 1: Appendices

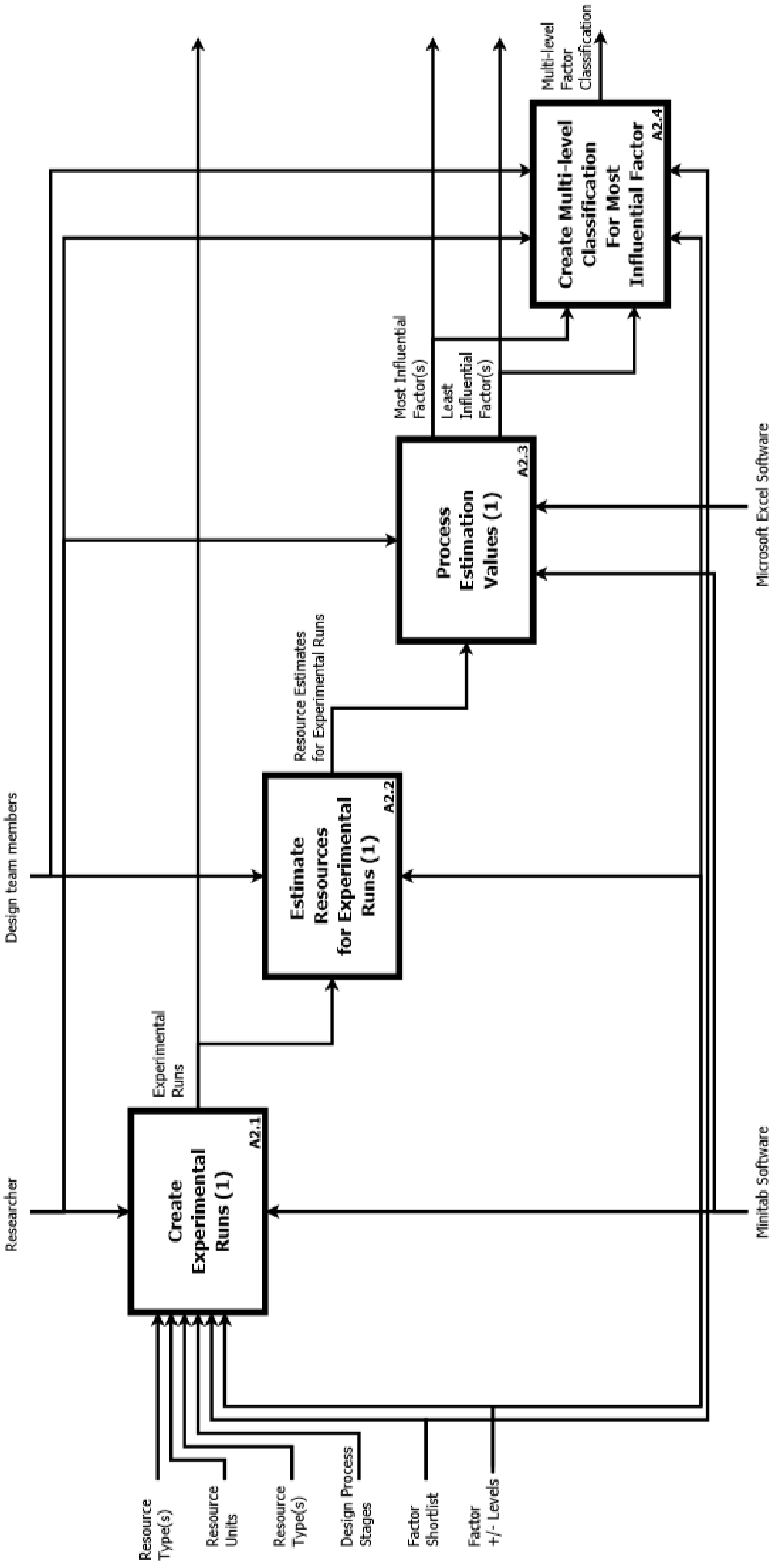
Appendix 4.1 - Applied Case Study Approach IDEF0



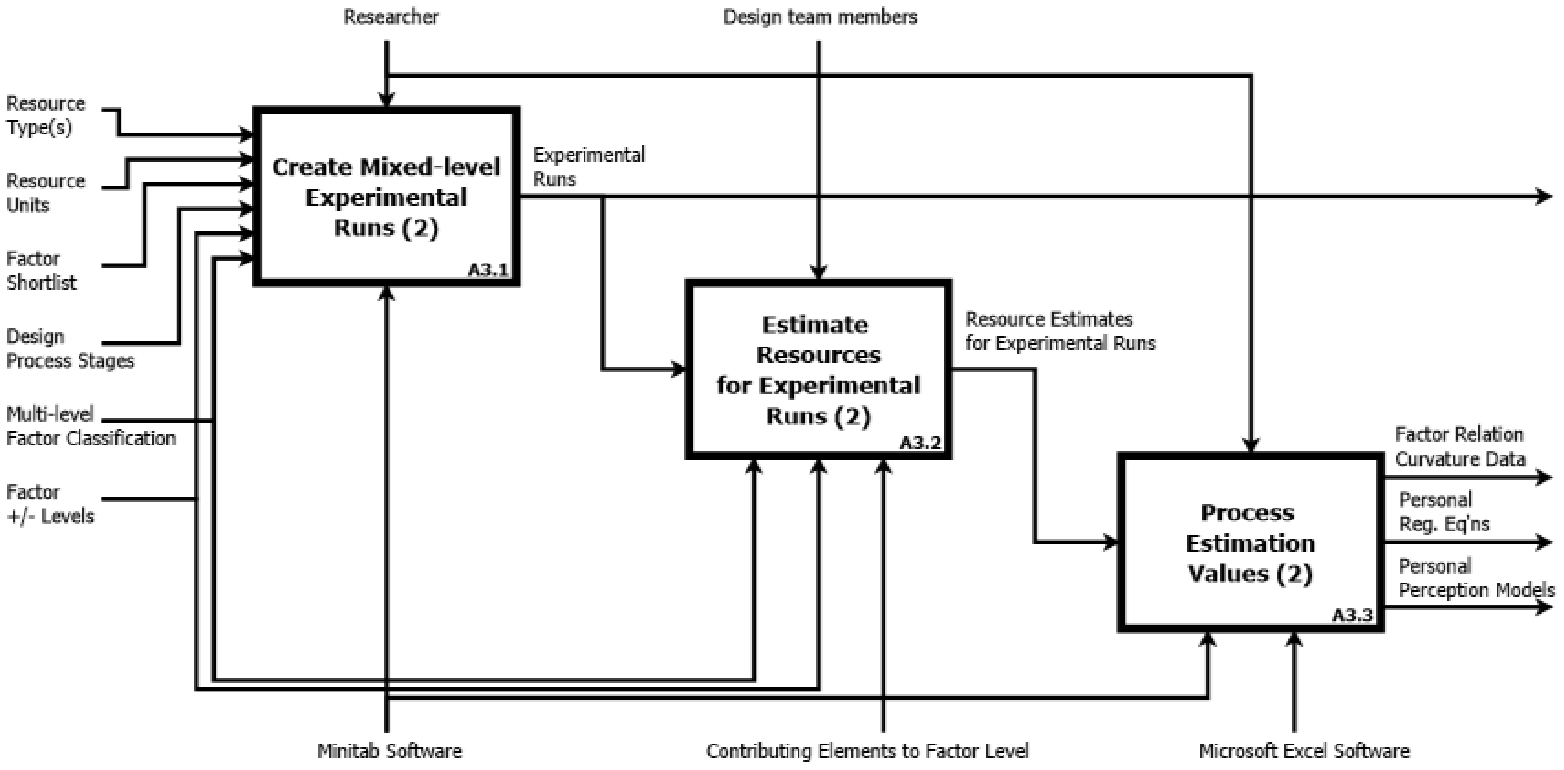
Appendix 4.2 - Design Process & Factor Identification IDEF0



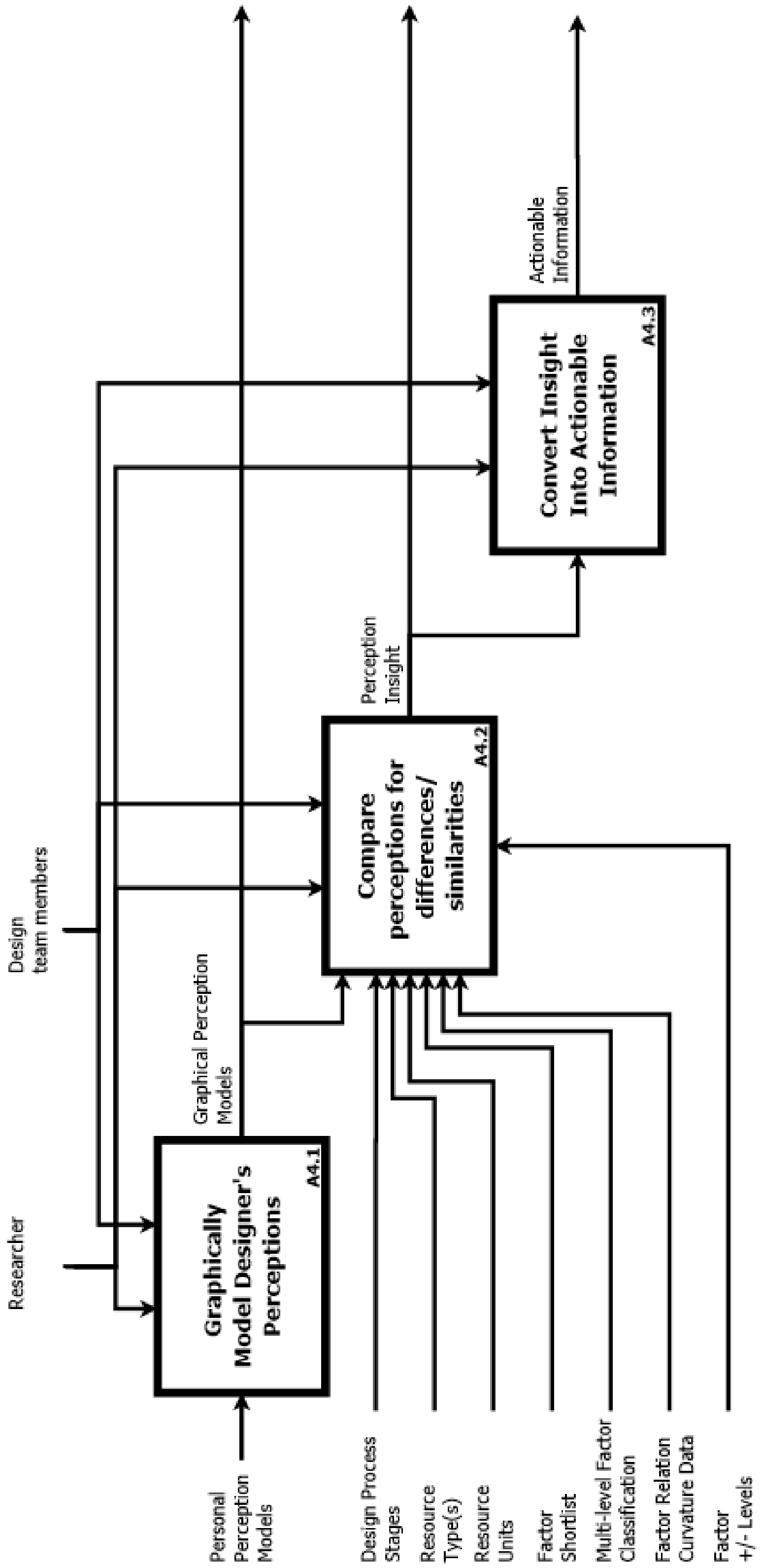
Appendix 4.3 - Estimation Collection (1) IDEF0



Appendix 4.4 – Estimation Collection (2) Taguchi IDEF0



Appendix 4.5 - Gather Actionable Information from Perception Data IDEF0



Appendix 4.6 - Participant Estimations (1 – 4)

	Experiment	Gather	Process	Imagine	Creative & Strategic	Doc 1	Refinement	Manufacture	Docu 2	Discover	Define	Develop	Deliver
Participant 1	1	200	100	100	600	600	1200	300	300	400	1200	1200	600
	2	100	50	100	400	600	800	200	300	250	1000	800	500
	3	100	75	100	300	600	500	150	300	275	900	500	450
	4	100	50	100	200	600	400	200	300	250	800	400	500
	5	150	100	50	500	400	1000	250	200	300	900	1000	450
	6	100	75	50	400	400	800	300	200	225	800	800	500
	7	100	50	50	200	400	600	200	200	200	600	600	400
	8	100	50	50	200	400	400	100	200	200	600	400	300
	9	150	75	75	500	500	100	200	300	300	1000	100	500
	10	100	50	75	500	500	100	300	300	225	1000	100	600
	11	75	50	50	300	300	700	150	200	175	600	700	350
	12	50	50	50	30	300	600	100	200	150	330	600	300
	13	100	75	75	250	300	800	200	100	250	550	800	300
	14	75	75	75	250	300	800	150	100	225	550	800	250
	15	75	50	50	200	200	500	100	100	175	400	500	200
	16	50	50	50	200	200	500	100	100	150	400	500	200
Participant 2	1	20	15	10	40	40	400	120	80	45	80	400	200
	2	20	15	10	40	40	400	120	80	45	80	400	200
	3	20	10	10	20	20	30	20	40	40	40	30	60
	4	20	10	10	10	20	30	20	20	40	30	30	40
	5	20	15	10	40	20	340	120	60	45	60	340	180
	6	20	15	10	40	20	340	120	60	45	60	340	180
	7	20	10	10	20	10	20	20	20	40	30	20	40
	8	20	10	10	20	10	20	20	20	40	30	20	40
	9	20	15	10	40	20	300	100	60	45	60	300	160
	10	20	15	10	40	20	300	100	60	45	60	300	160
	11	20	10	10	20	10	20	20	20	40	30	20	40
	12	20	10	10	10	10	20	20	20	40	20	20	40
	13	20	15	10	40	20	300	100	50	45	60	300	150
	14	20	15	10	40	20	300	100	50	45	60	300	150
	15	20	10	10	20	10	20	20	15	40	30	20	35
	16	20	10	10	10	10	20	20	15	40	20	20	35
Participant 3	1	50	25	10	75	25	200	50	50	85	100	200	100
	2	20	10	10	100	25	250	50	50	40	125	250	100
	3	20	10	5	25	15	100	25	20	35	40	100	45
	4	10	5	5	20	10	500	20	10	20	30	500	30
	5	50	25	10	75	20	150	50	30	85	95	150	80
	6	20	10	10	75	20	150	50	30	40	95	150	80
	7	20	10	5	25	10	150	25	20	35	35	150	45
	8	20	10	5	30	10	75	25	20	35	40	75	45
	9	40	20	10	70	20	150	40	40	70	90	150	80
	10	30	15	10	75	15	150	40	40	55	90	150	80
	11	30	15	5	30	15	75	30	25	50	45	75	55
	12	40	5	5	30	15	75	25	20	50	45	75	45
	13	40	20	10	80	20	200	40	40	70	100	200	80
	14	30	15	10	75	20	150	40	40	55	95	150	80
	15	20	10	5	25	10	50	25	20	35	35	50	45
	16	10	5	5	30	10	50	25	15	20	40	50	40
Participant 4	1	20	20	20	80	80	200	50	50	60	160	200	100
	2	15	15	10	80	80	200	50	50	40	160	200	100
	3	15	15	15	15	5	20	10	10	45	20	20	20
	4	12	12	5	10	5	20	10	10	29	15	20	20
	5	20	20	20	80	40	150	50	30	60	120	150	80
	6	20	20	10	70	40	150	50	30	50	110	150	80
	7	15	15	15	15	5	20	10	10	45	20	20	20
	8	12	12	5	10	5	20	10	10	29	15	20	20
	9	10	15	15	70	80	180	50	50	45	150	180	100
	10	10	15	10	60	80	180	50	50	40	140	180	100
	11	10	10	10	15	5	20	10	10	30	20	20	20
	12	10	10	8	10	5	20	10	10	28	15	20	20
	13	18	20	18	70	40	140	50	25	56	110	140	75
	14	18	20	10	65	35	140	50	25	48	100	140	75
	15	15	15	15	14	5	20	10	10	45	19	20	20
	16	10	12	5	8	5	20	10	8	27	13	20	18

Appendix 4.7 - Participant Estimations (5 – 8)

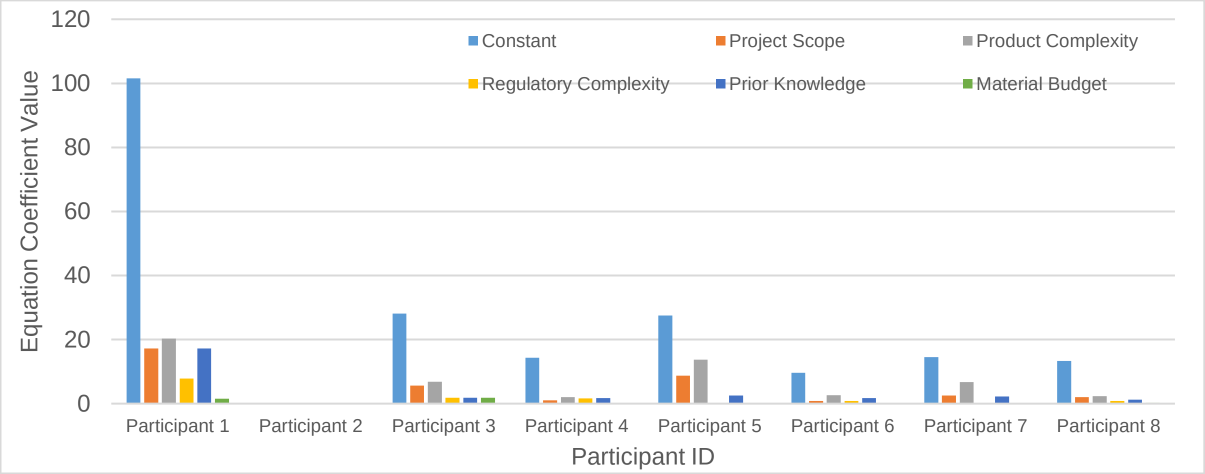
	Experiment	Gather	Process	Imagine	Creative & Strategic	Doc 1	Refinement	Manufacture	Docu 2	Discover	Define	Develop	Deliver
Participant 5	1	60	15	15	20	30	500	60	50	90	50	500	110
	2	30	15	10	150	25	500	60	50	55	175	500	110
	3	20	10	10	30	20	100	5	20	40	50	100	25
	4	10	5	50	30	20	100	5	20	65	50	100	25
	5	60	15	15	200	20	450	60	40	90	220	450	100
	6	30	15	15	200	20	450	60	40	60	220	450	100
	7	20	10	10	30	10	100	5	20	40	40	100	25
	8	10	5	5	30	10	100	5	20	20	40	100	25
	9	50	15	15	180	20	350	60	40	80	200	350	100
	10	25	15	10	120	15	350	60	40	50	135	350	100
	11	15	10	10	20	10	50	5	15	35	30	50	20
	12	10	5	5	20	10	50	5	15	20	30	50	20
	13	50	15	15	180	10	350	60	30	80	190	350	90
	14	25	15	15	180	10	350	60	30	55	190	350	90
	15	15	10	10	20	5	50	5	15	35	25	50	20
	16	10	5	5	20	5	50	5	15	20	25	50	20
Participant 6	1	21	21	7	42	42	70	70	35	49	84	70	105
	2	14	14	7	35	35	63	70	35	35	70	63	105
	3	7	7	7	28	28	35	56	35	21	56	35	91
	4	7	7	7	28	28	35	56	35	21	56	35	91
	5	14	14	7	35	35	63	70	21	35	70	63	91
	6	14	14	7	35	35	63	70	21	35	70	63	91
	7	7	7	7	28	28	35	56	21	21	56	35	77
	8	7	7	7	28	28	35	56	21	21	56	35	77
	9	14	14	7	35	35	63	70	35	35	70	63	105
	10	7	7	7	28	28	35	70	35	21	56	35	105
	11	7	7	7	28	28	35	56	35	21	56	35	91
	12	7	7	7	28	28	35	56	35	21	56	35	91
	13	7	7	7	28	28	35	70	35	21	56	35	105
	14	7	7	7	28	28	35	70	35	21	56	35	105
	15	7	7	7	28	28	35	56	35	21	56	35	91
	16	7	7	7	28	28	33	56	35	21	56	33	91
Participant 7	1	30	20	10	30	15	300	80	50	60	45	300	130
	2	20	15	8	30	15	300	80	50	43	45	300	130
	3	10	6	3	10	6	30	10	8	19	16	30	18
	4	7	40	2	10	6	30	10	8	49	16	30	18
	5	30	20	10	30	5	300	60	30	60	35	300	90
	6	20	15	8	30	5	300	60	30	43	35	300	90
	7	10	6	3	10	4	30	8	6	19	14	30	14
	8	7	4	2	10	4	30	8	6	13	14	30	14
	9	20	15	8	30	12	300	70	40	43	42	300	110
	10	15	10	5	30	12	300	70	40	30	42	300	110
	11	8	5	3	10	5	30	10	7	16	15	30	17
	12	6	3	2	10	5	30	10	7	11	15	30	17
	13	20	15	8	30	6	300	50	20	43	36	300	70
	14	15	10	5	30	6	300	50	20	30	36	300	70
	15	8	5	3	10	4	30	7	5	16	14	30	12
	16	6	3	2	10	4	30	7	5	11	14	30	12
Participant 8	1	20	20	20	60	18	120	50	25	60	78	120	75
	2	15	15	15	50	18	120	50	25	45	68	120	75
	3	15	12	5	25	14	60	35	20	32	39	60	55
	4	10	10	4	20	11	60	35	20	24	31	60	55
	5	18	20	20	50	11	90	40	15	58	61	90	55
	6	15	12	5	40	6	90	40	15	32	46	90	55
	7	13	10	5	20	6	45	30	10	28	26	45	40
	8	10	10	3	15	16	45	30	10	23	31	45	40
	9	17	18	17	55	16	100	45	25	52	71	100	70
	10	15	15	15	45	12	100	45	25	45	57	100	70
	11	13	15	5	22	12	50	30	20	33	34	50	50
	12	8	8	4	18	9	50	30	20	20	27	50	50
	13	15	18	18	45	9	70	35	15	51	54	70	50
	14	10	11	5	36	4	70	35	15	26	40	70	50
	15	12	9	5	18	4	35	25	10	26	22	35	35
	16	7	9	3	13	4	35	25	10	19	17	35	35

Appendix 4.8 - Participant Regression Equation Values

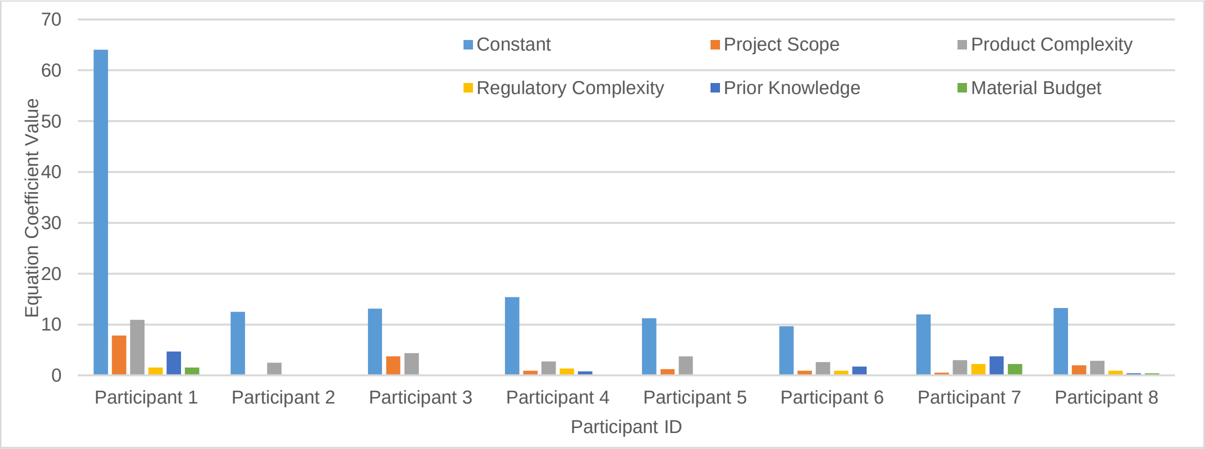
	Gather	Process	Imagine	C & S	Doc.1	Ref.	Manuf.	Doc. 2	Gather	Process	Imagine	C & S	Doc. 1	Ref.	Manuf.	Doc. 2
	Participant 1								**Participant 5**							
Cn	101.6	64.1	68.8	314.4	412.5	612.5	187.5	212.5	27.5	11.3	13.4	89.4	15.0	243.8	32.5	28.8
A	-17.2	-7.8	0	-41.9	0	-62.5	0	0	-8.8	-1.3	0	0	0	0	0	0
B	-20.3	-10.9	-6.3	-110.6	-37.5	-87.5	-50.0	-12.5	-13.8	-3.8	0	-64.4	-3.8	-168.8	-27.5	-11.3
C	-7.8	0	-12.5	-39.4	-87.5	62.5	-12.5	-62.5	0	0	-2.2	18.1	-3.8	0	0	-2.5
D	-17.2	-4.7	-6.3	-35.6	-87.5	-100.0	-25.0	-37.5	-2.5	0	-2.8	0	-4.4	-43.8	0	-3.8
E	0	0	0	16.9	0	0	31.3	0	0	0	2.8	-11.9	0	0	0	0
AB	0	4.7	0	0	0	0	0	0	5.0	-1.3	2.2	0	0	0	0	0
AC	4.7	4.7	0	29.4	0	0	0	0	0	0	-2.2	0	0	0	0	0
AD	0	4.7	-6.3	8.1	0	50.0	0	0	1.3	0	-2.8	-11.9	0	18.8	0	0
AE	0	0	0	35.6	12.5	-125.0	12.5	12.5	0	0	2.8	10.6	0	0	0	0
BC	7.8	-4.7	0	35.6	12.5	-87.5	0	12.5	0	0	-3.4	-18.1	0	0	0	2.5
BD	0	0	0	14.4	-37.5	150.0	0	-12.5	1.3	0	-2.8	-8.1	0	0	0	1.3
BE	0	0	0	0	0	0	0	0	0	0	2.8	11.9	0	0	0	0
CD	0	0	12.5	-14.4	12.5	75.0	-12.5	-12.5	0	0	2.8	-10.6	0	0	0	0
CE	-7.8	0	0	-29.4	0	0	0	0	0	0	-2.8	11.9	0	0	0	0
DE	-4.7	0	0	16.9	0	0	0	0	0	0	-3.4	0	0	0	0	0
	Participant 2								**Participant 6**							
Cn	20.0	12.5	10.0	28.1	18.8	178.8	65.0	41.9	9.6	9.6	7.0	30.6	30.6	44.1	63.0	31.5
A	0	0	0	-1.9	0	0	0	0	-0.9	-0.9	0	-0.9	-0.9	0	0	0
B	0	-2.5	0	-11.9	-6.3	-156.3	-45.0	-20.6	-2.6	-2.6	0	-2.6	-2.6	-9.3	-7.0	0
C	0	0	0	0	-3.8	-8.8	0	-5.6	-0.9	-0.9	0	-0.9	-0.9	0	0	-3.5
D	0	0	0	0	-3.6	-18.8	-5.0	-5.6	-1.8	-1.8	0	-1.8	-1.8	-5.8	0	3.5
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AB	0	0	0	-1.9	0	0	0	0	0.9	0.9	0	-0.9	0.9	0	0	0
AC	0	0	0	0	0	0	0	0	0.9	0	0	-0.9	0.9	0	0	0
AD	0	0	0	0	0	0	0	0	1.8	0	0	0	0	0	0	0
AE	0	0	0	0	0	-6.3	0	0	0	0	0	0	0	0	0	0
BC	0	0	0	0	1.3	6.3	0	1.9	0	0.9	0	0.9	0.9	0	0	0
BD	0	0	0	0	1.3	16.3	5.0	1.9	0	1.8	0	1.8	1.8	5.6	0	0
BE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CD	0	0	0	0	3.8	8.8	0	1.9	0	0	0	0	0	0	0	3.5
CE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DE	0	0	0	0	0	0	0	0	-0.9	-0.9	0	-0.9	-0.9	0	0	0
	Participant 3								**Participant 7**							
Cn	28.1	13.1	7.5	52.5	16.3	154.7	35.0	29.4	14.5	12	5.125	20	7.125	165	36.875	20.75
A	-5.6	-3.8	0	1.9	-0.6	20.3	-0.6	-1.3	-2.5	0	-0.875	0	0	0	0	0
B	-6.9	-4.4	-2.5	-25.6	-4.4	-20.3	-10.0	-10.6	-6.75	-3	-2.625	-10	-2.375	-135	-28.12	-14.25
C	-1.9	0	0	0	-1.3	-32.8	0	-2.5	0	-2.25	0	0	-2.375	0	-5.625	-5.5
D	1.9	0	0	0	-0.6	-42.2	-1.9	0	-2.25	-3.75	-0.625	0	-0.375	0	-2.625	-2.75
E	-1.9	0	0	0	-0.6	29.7	0	0	0	0	0	0	0	0	0	0
AB	4.4	1.3	0	0	0	20.3	-0.6	-1.3	1.25	3	0.375	0	0	0	0	0
AC	0	0	0	0	0.6	-35.9	0.6	0	0	-2.25	0	0	0	0	0	0
AD	3.1	0	0	0	0	-26.6	0	0	0.75	-2.25	0.625	0	0	0	0	0
AE	-3.1	0	0	-3.1	-1.3	0	0	-3.8	0	2.25	0	0	-0.375	0	0	0
BC	-1.9	0	0	0	-0.6	-20.3	0	2.5	0	-2.25	0	0	1.625	0	4.375	4.5
BD	1.9	0	0	2.5	1.3	-29.7	3.1	0	1.5	2.25	0	0	0	0	2.375	2.25
BE	-1.9	0	0	0	0	29.7	0	0	0	-2.25	0	0	0	0	0	0
CD	-3.1	0	0	0	0.6	32.8	-0.6	1.3	0	2.25	0	0	0.625	0	0	0
CE	-1.9	-1.9	0	1.9	0.6	-14.1	0.6	0	0	0	0	0	0	0	0	0
DE	0	0	0	3.1	0	-23.4	0	0	0	-2.25	0	0	0	0	0	0
	Participant 4								**Participant 8**							
Cn	14.4	15.4	11.9	42.0	32.2	93.8	30.0	24.3	13.313	13.25	9.313	33.25	10.625	71.25	36.25	17.5
A	-1.0	-0.9	-4.1	-2.9	0	0	0	0	-2.063	-2	-2.562	-3.625	-0.625	0	0	0
B	-2.0	-2.8	-2.2	-29.9	-27.2	-73.8	-20.0	-14.5	-2.313	-2.875	-5.063	-14.37	-1.125	-23.75	-6.25	-2.5
C	1.6	1.4	0	0	-10.3	-11.3	0	-5.8	-0.813	-0.875	-1.313	-3.625	-3.125	-11.25	-3.75	-5
D	-1.8	-0.8	-0.6	-3.0	0	-3.8	0	0	-1.187	0	0	-1.75	-1.875	-7.5	-2.5	0
E	0	0	0	0	0	0	0	0	0	0	0	0	-0.875	0	0	0
AB	-0.4	0	0	0	0	0	0	0	0	0.875	1.813	0	1.125	0	0	0
AC	0	0	-0.7	0	0	0	0	0	0	0	-1.438	1.25	0.625	3.75	0	0
AD	0.4	0	9.4	0	0	0	0	0	0	0	0	0.625	-0.875	2.5	0	0
AE	-0.4	0	0	0	0	0	0	0	0.312	0	0	0	-0.875	0	0	0
BC	-1.0	0.5	0	0	10.3	11.3	0	5.5	0.313	0	1.063	0	1.125	0	1.25	0
BD	0.6	-0.5	0	2.6	0	3.8	0	0	0	0	0	0	0	0	0	0
BE	-0.6	0	-0.7	0	0	0	0	0	0.437	0	0	0	0	0	0	0
CD	1.0	0.8	0	0	0	0	0	0	-0.313	0	0	0	0	0	0	0
CE	-0.6	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0
DE	0	-0.5	0	0	0	0	0	0	0	1	1.188	0	1.375	0	0	0

Note: Factors are labelled: A. Project Scope; B. Product Complexity; C. Regulatory Complexity; D. Prior Knowledge; E. Material Budget; AB. Project Scope * Product Complexity; AC. Project Scope * Regulatory Complexity; AD. Project Scope * Prior Knowledge; AE. Project Scope * Material Budget; BC. Product Complexity * Regulatory Complexity; BD. Product Complexity * Prior Knowledge; BE. Product Complexity * Material Budget; CD. Regulatory Complexity * Prior Knowledge; CE. Regulatory Complexity * Material Budget; DE. Prior Knowledge * Material Budget

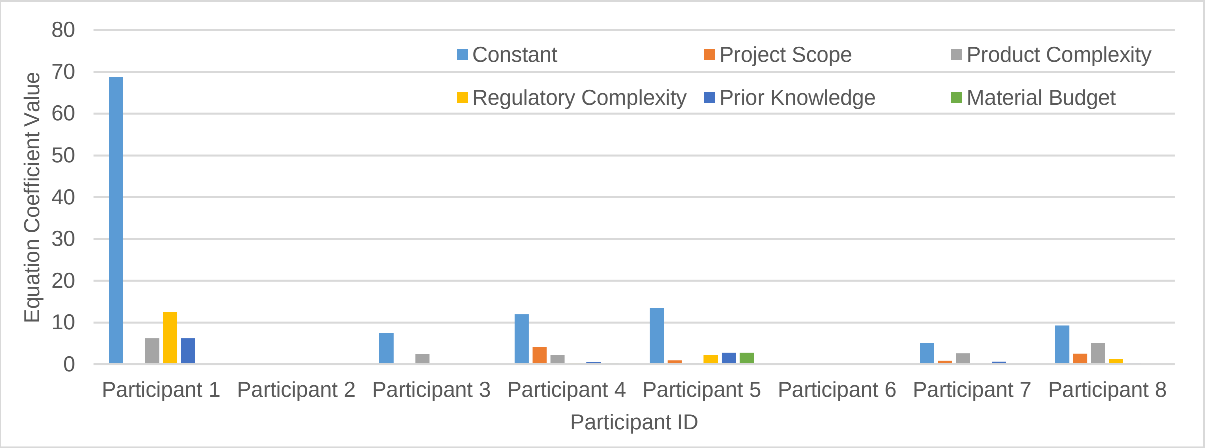
Appendix 4.9 - Graphical Regression Values Representation



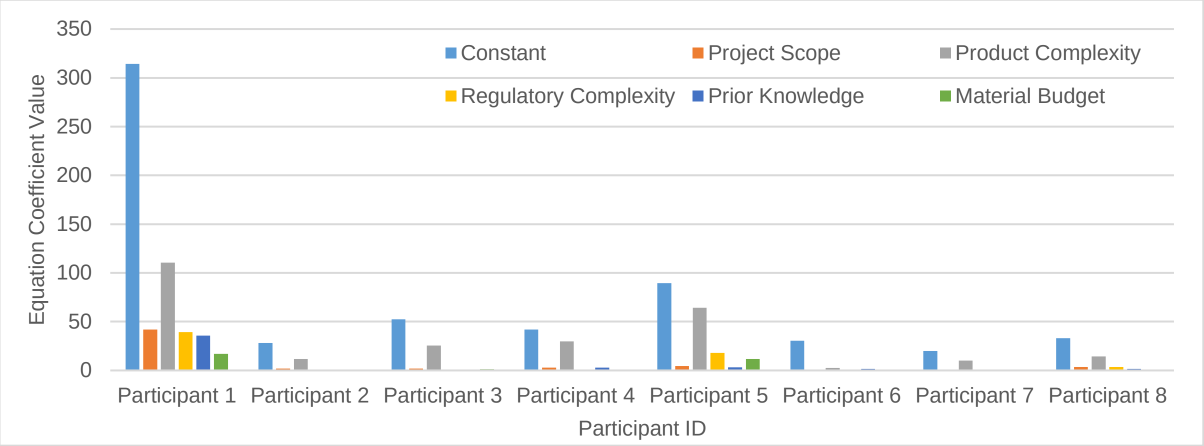
Gather Phase



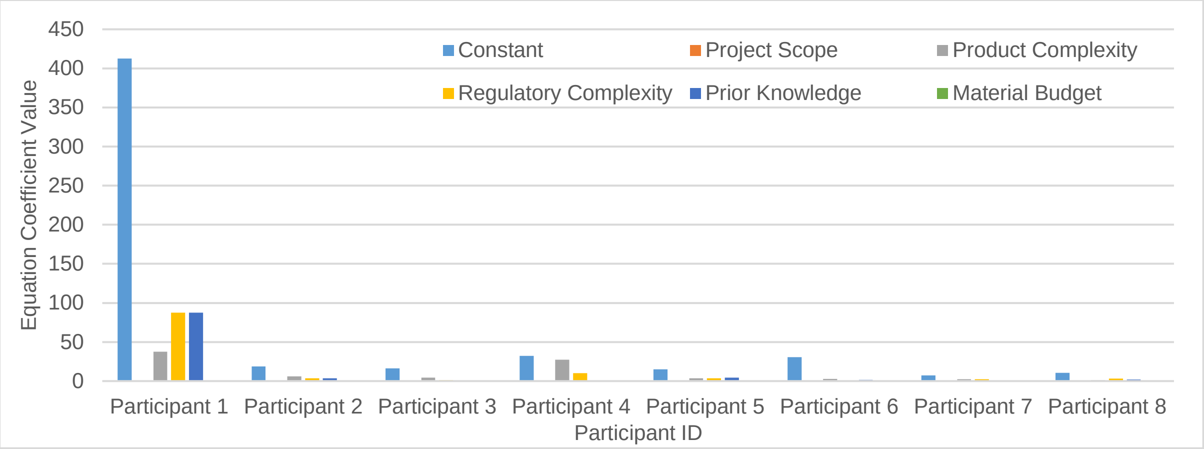
Process Phase



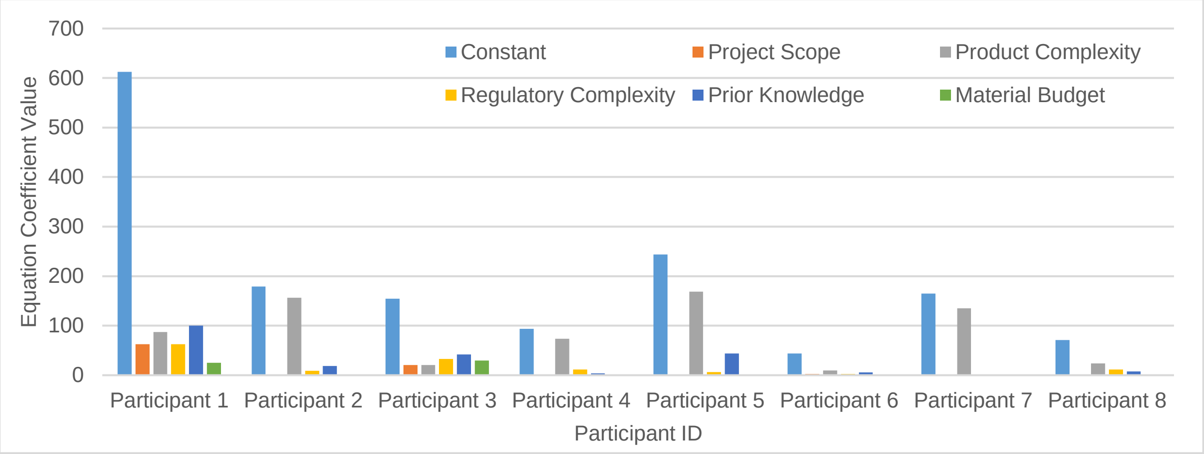
Imagine Phase



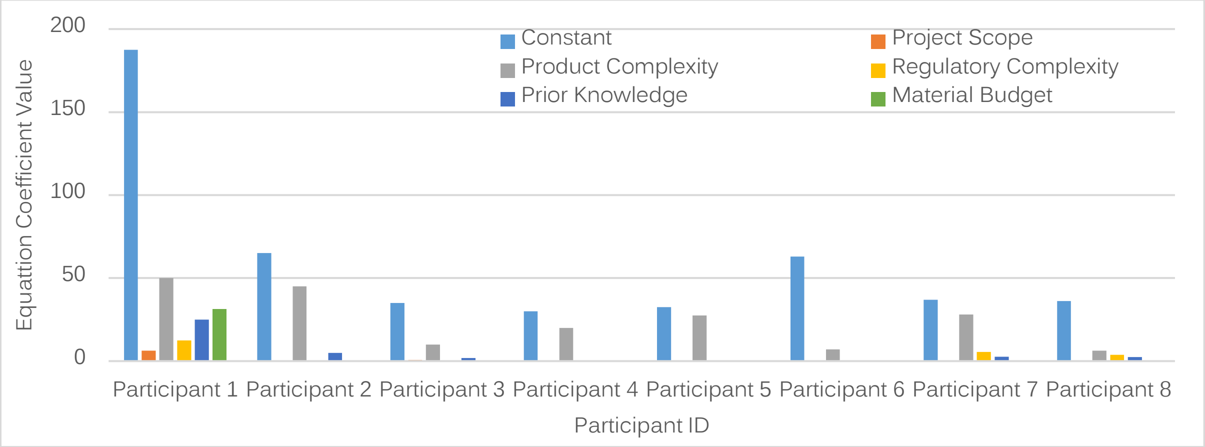
Creative & Strategic Phase



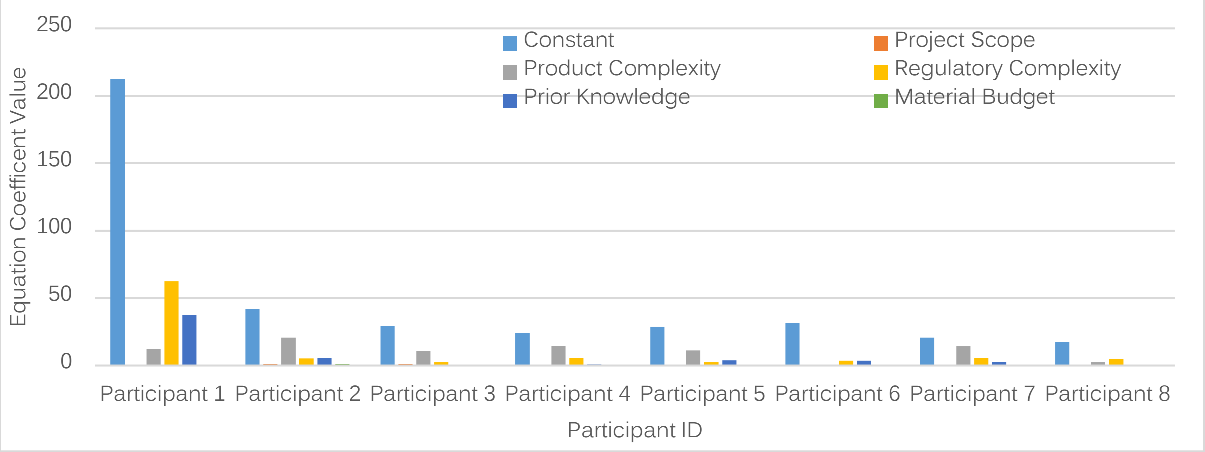
Documentation 1 Phase



Refinement Phase

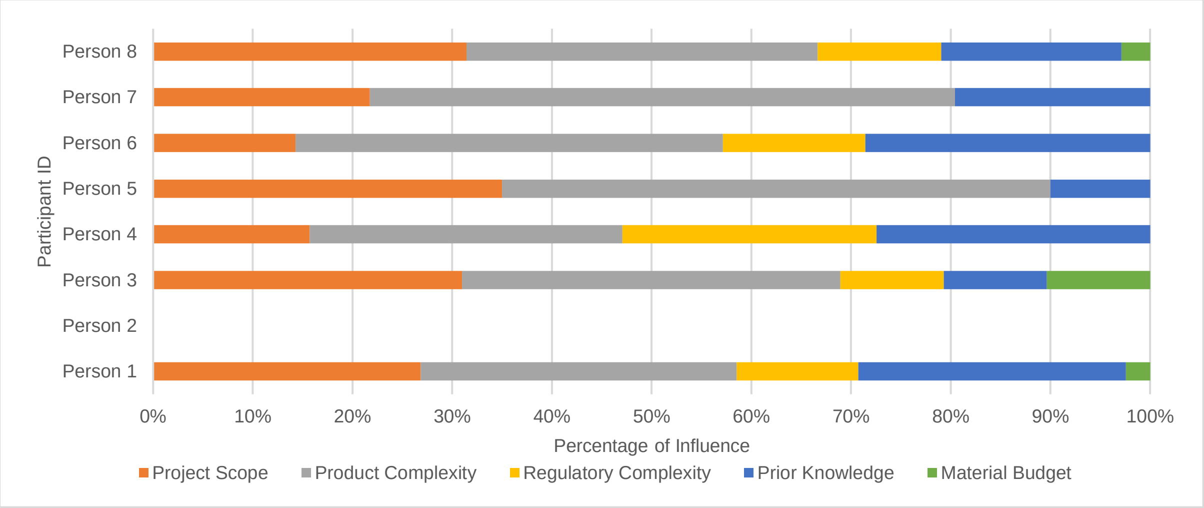


Manufacture Phase

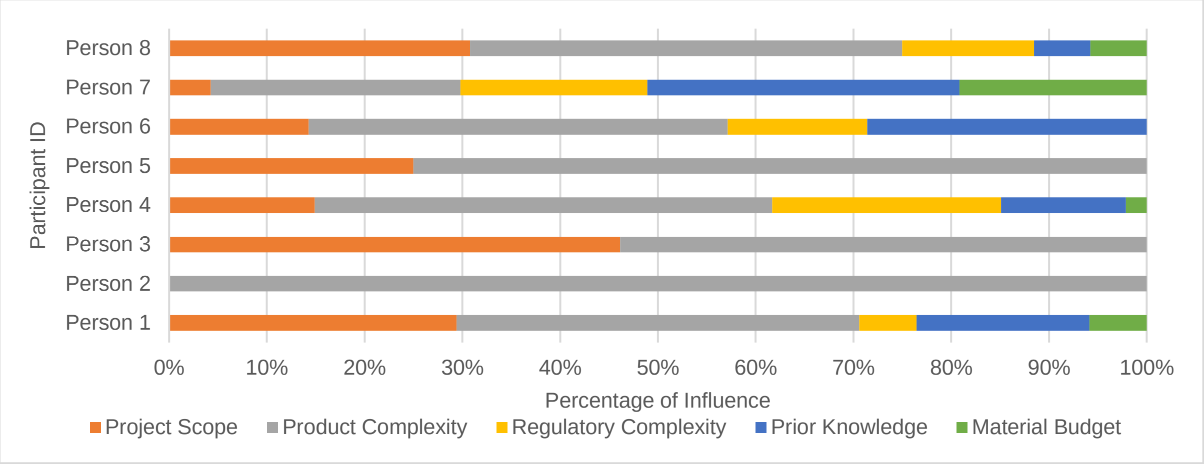


Documentation 2 Phase

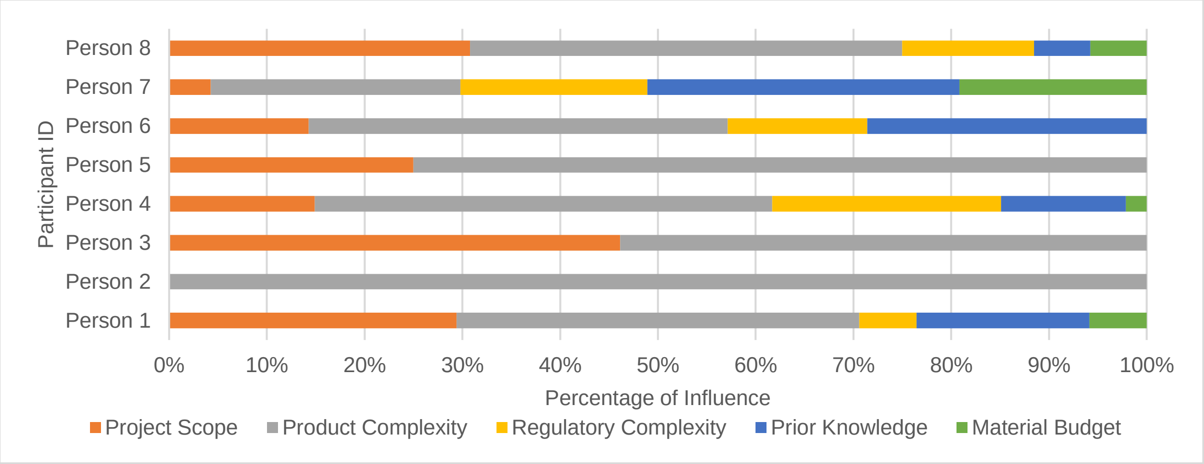
Appendix 4.10 - Percentage Influence Graphs



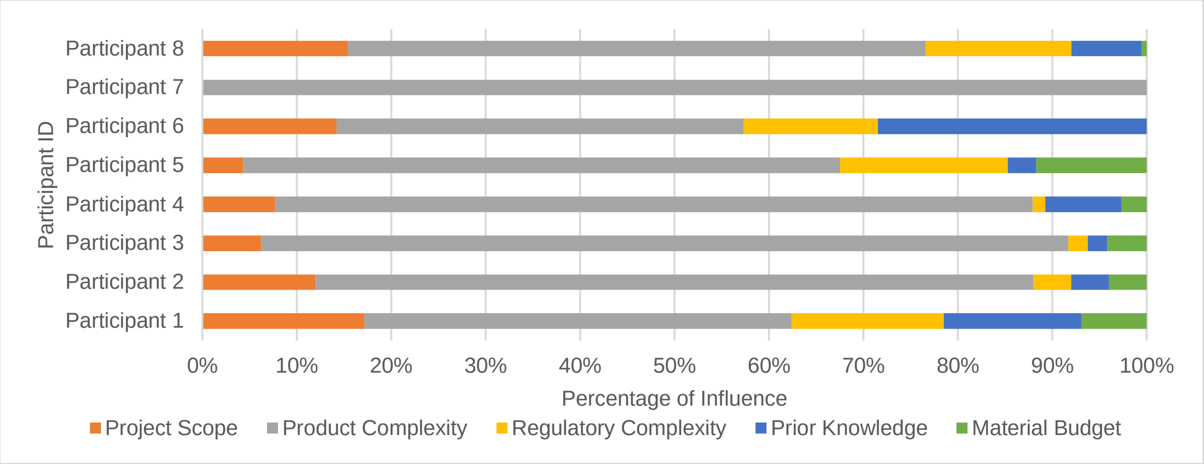
Gather Phase



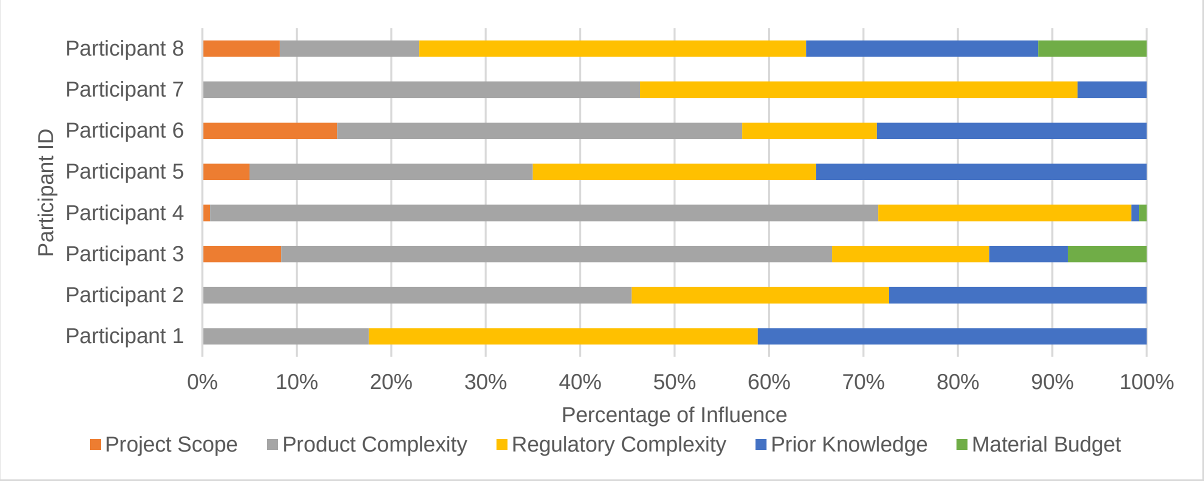
Process Phase



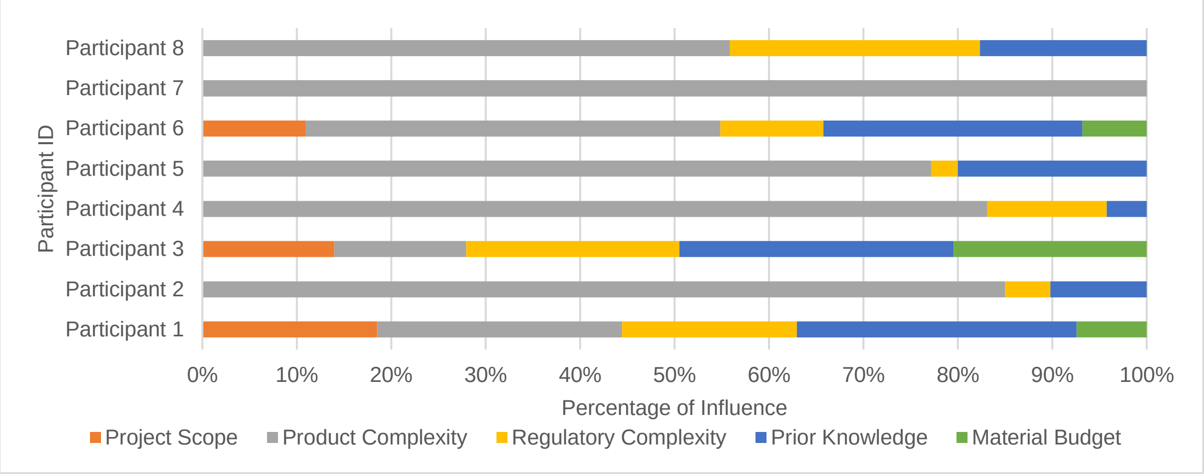
Imagine Phase



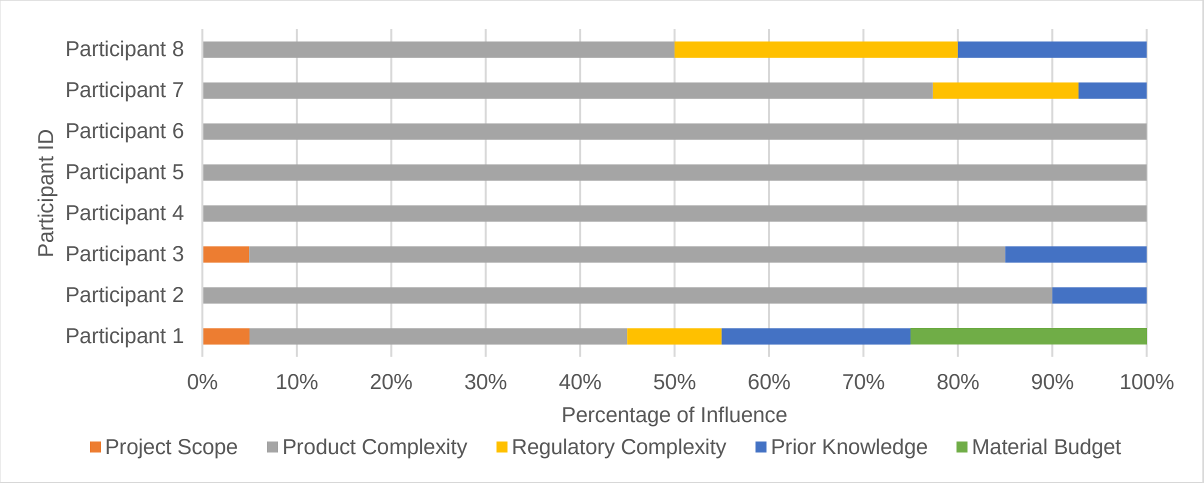
Creative & Strategic Phase



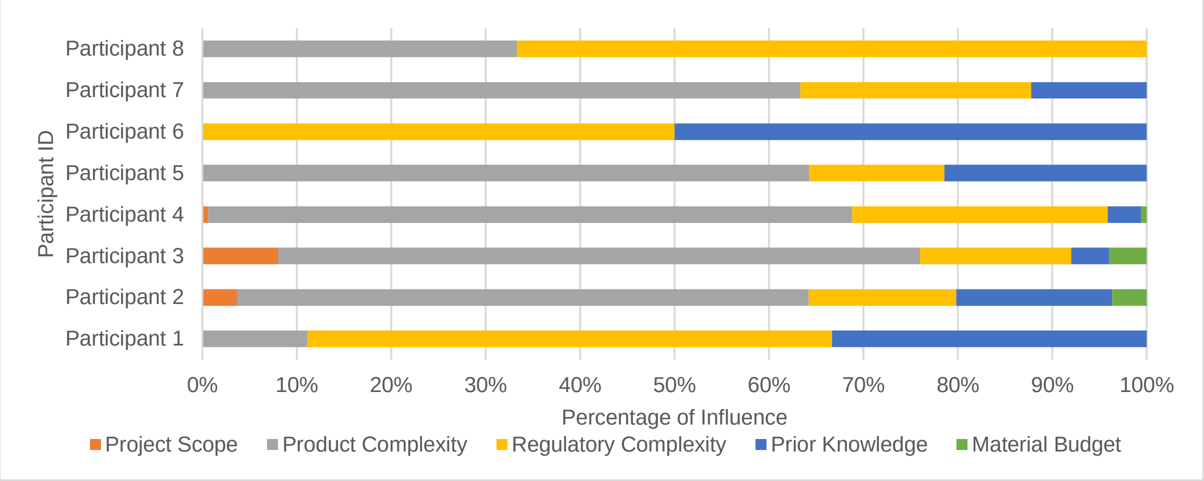
Documentation 1 Phase



Refinement Phase



Manufacture Phase

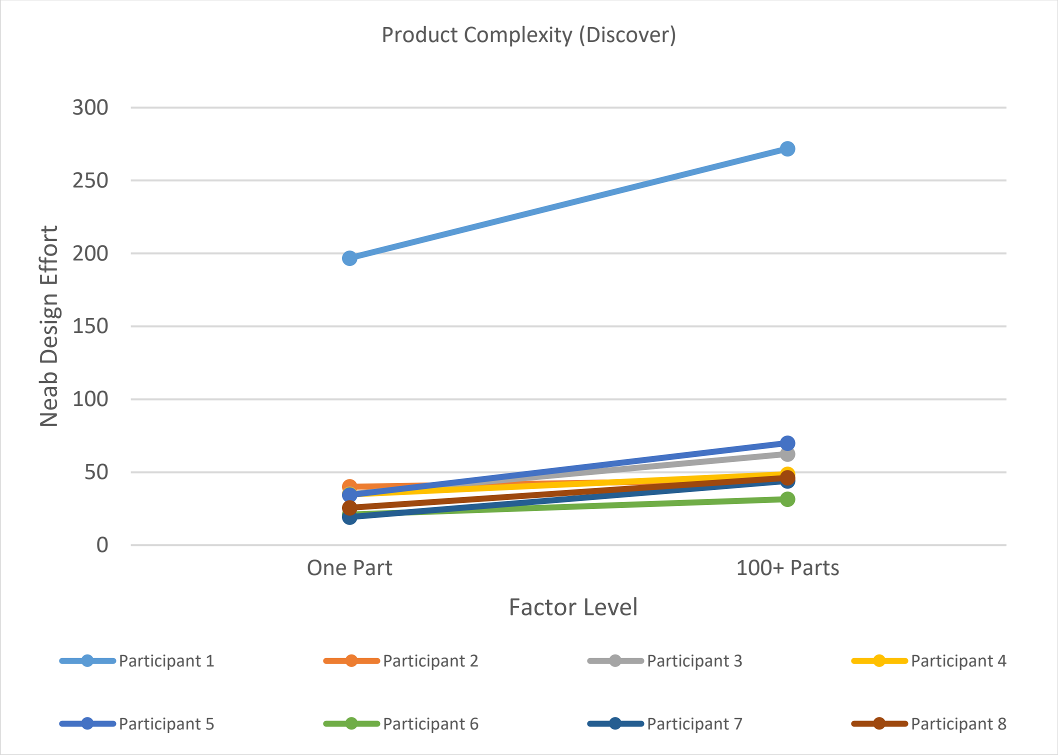


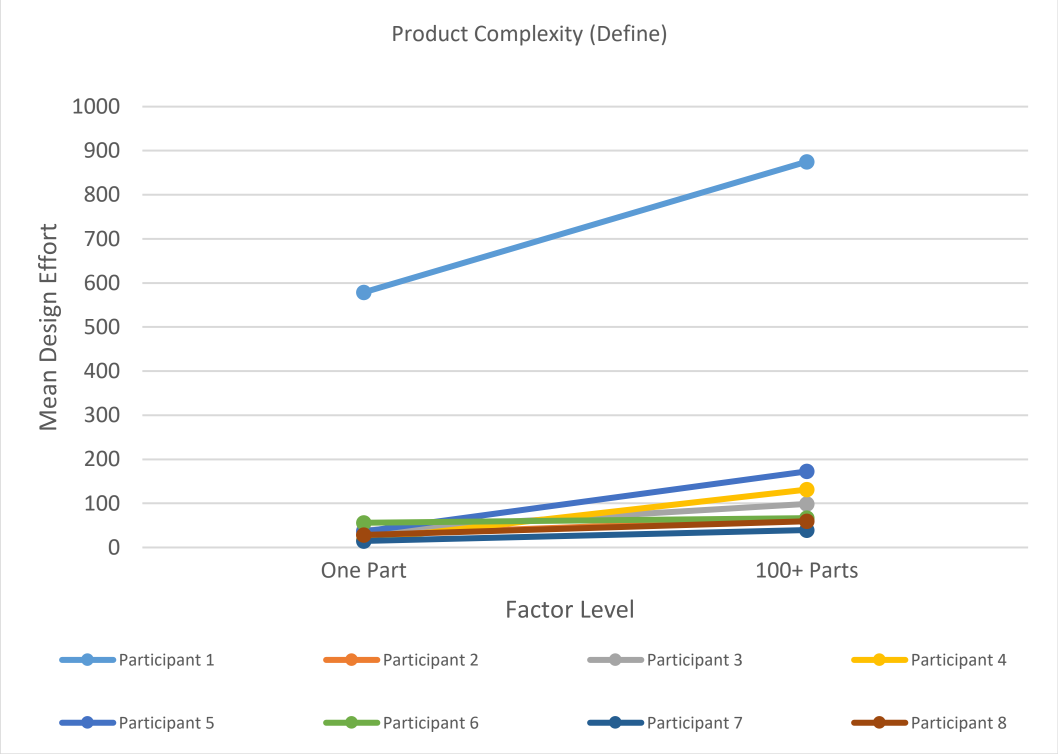
Documentation 2

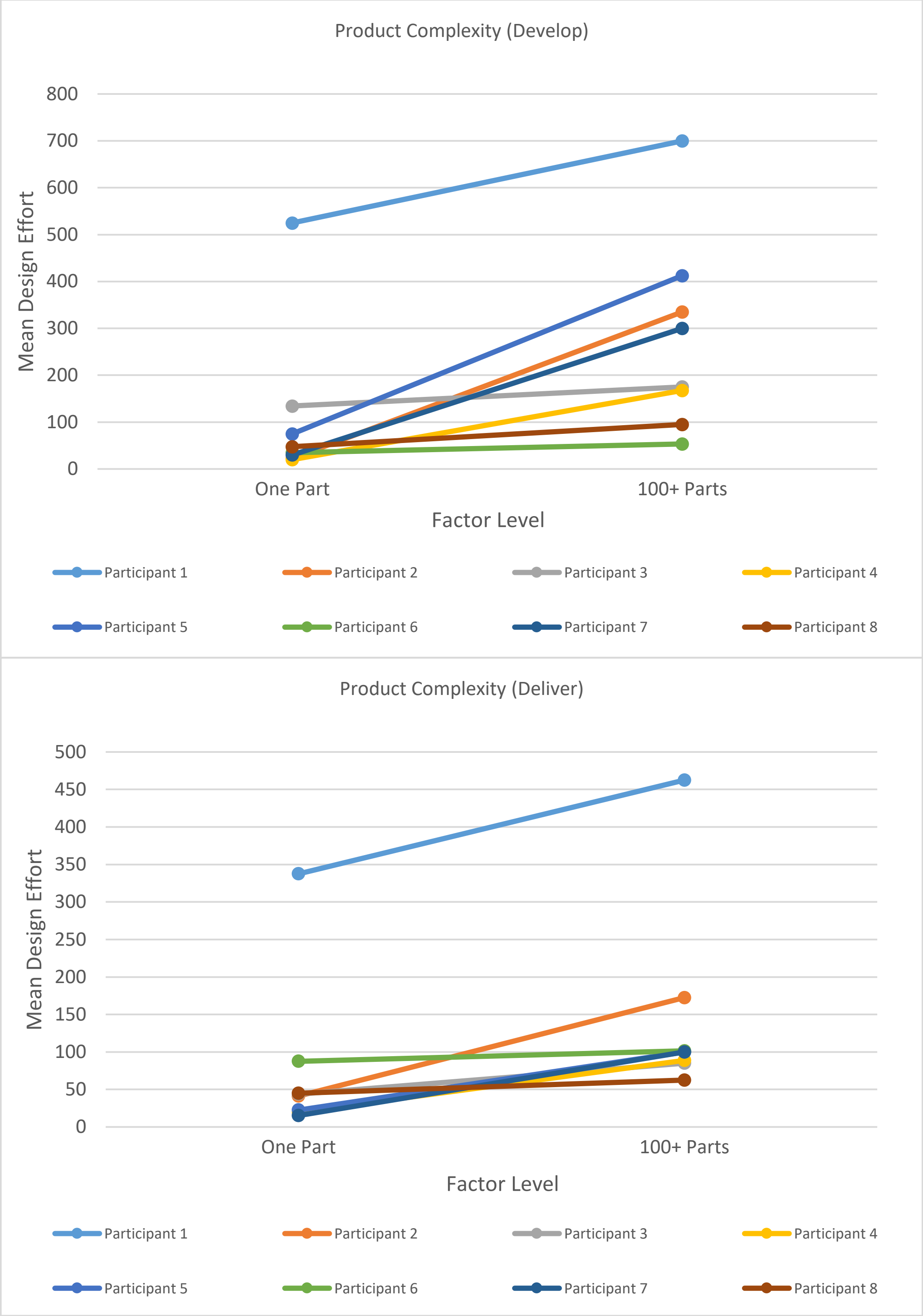
Appendix 4.11 - Mean Effects Plot Values

		Project Scope		Product Complexity		Regulatory Complexity		Prior Knowledge		Material Budget	
		Ambiguous	**Defined**	**100+ Parts**	**One Part**	**Highly Regulatory**	**No Regulations**	**No Knowledge**	**Expert Knowledge**	**£**	**£££**
Gather	**P1**	14.84375	10.546875	15.234375	10.15625	13.671875	11.71875	14.84375	10.546875	12.5	12.890625
	P2	20	20	20	20	20	20	20	20	20	20
	P3	33.75	22.5	35	21.25	30	26.25	26.25	30	30	26.25
	P4	15.375	13.375	16.375	12.375	12.75	16	16.125	12.625	14.375	14.375
	P5	36.25	18.75	41.25	13.75	27.5	27.5	30	25	27.5	27.5
	P6	10.5	8.75	12.25	7	10.5	8.75	11.375	7.875	9.625	9.625
	P7	17	12	21.25	7.75	14.5	14.5	16.75	12.25	14.5	14.5
	P8	15.375	11.25	15.625	11	14.125	12.5	14.5	12.125	13.125	13.5
Process	**P1**	8.984375	7.03125	9.375	6.640625	7.8125	8.203125	8.59375	7.421875	8.203125	7.8125
	P2	12.5	12.5	15	10	12.5	12.5	12.5	12.5	12.5	12.5
	P3	16.875	9.375	17.5	8.75	13.125	13.125	13.125	13.125	13.125	13.125
	P4	16.25	14.5	18.125	12.625	14	16.75	16.125	14.625	15.25	15.5
	P5	12.5	10	15	7.5	11.25	11.25	11.25	11.25	11.25	11.25
	P6	10.5	8.75	12.25	7	10.5	8.75	11.375	7.875	9.625	9.625
	P7	11.5	12.5	15	9	14.25	9.75	15.75	8.25	9.75	14.25
	P8	15.25	11.25	16.125	10.375	14.125	12.375	13.625	12.875	12.875	13.625
Imagine	**P1**	8.59375	8.59375	9.375	7.8125	10.15625	7.03125	9.375	7.8125	8.59375	8.59375
	P2	10	10	10	10	10	10	10	10	10	10
	P3	7.5	7.5	10	5	7.5	7.5	7.5	7.5	7.5	7.5
	P4	16	7.875	14.125	9.75	11.625	12.25	12.5	11.375	12.25	11.625
	P5	12.5	14.375	13.75	13.125	15.625	11.25	16.25	10.625	10.625	16.25
	P6	7	7	7	7	7	7	7	7	7	7
	P7	6	4.25	7.75	2.5	5.125	5.125	5.75	4.5	5.125	5.125
	P8	11.875	6.75	14.375	4.25	10.625	8	9.625	9	9.25	9.375
Creative & Strategic	**P1**	44.53125	34.0625	53.125	25.46875	44.21875	34.375	43.75	34.84375	37.1875	41.40625
	P2	30	26.25	40	16.25	27.5	28.75	28.75	27.5	28.75	27.5
	P3	50.625	54.375	78.125	26.875	53.125	51.875	53.125	51.875	53.75	51.25
	P4	44.875	39.125	71.875	12.125	42.5	41.5	45	39	43	41
	P5	85	93.75	153.75	25	71.25	107.5	86.25	92.5	101.25	77.5
	P6	31.5	29.75	33.25	28	31.5	29.75	32.375	28.875	30.675	30.675
	P7	20	20	30	10	20	20	20	20	20	20
	P8	36.875	29.625	47.625	18.875	36.875	29.625	35	31.5	33.375	33.125
Documentation 1	**P1**	51.5625	51.5625	56.25	46.875	62.5	40.625	62.5	40.625	51.5625	51.5625
	P2	18.75	18.75	25	12.5	22.5	15	22.5	15	18.75	18.75
	P3	16.875	15.625	20.625	11.875	17.5	15	16.875	15.625	16.875	15.625
	P4	32.5	31.875	59.375	5	42.5	21.875	32.5	31.875	31.875	32.5
	P5	15.625	14.375	18.75	11.25	18.75	11.25	19.375	10.625	15	15
	P6	31.5	29.75	33.25	28	31.5	29.75	32.375	28.875	30.625	30.625
	P7	7.125	7.125	9.5	4.75	9.5	4.75	7.5	6.75	7.125	7.125
	P8	11.25	10	11.75	9.5	13.75	7.5	12.5	8.75	11.5	9.75
Refinement	**P1**	84.375	68.75	87.5	65.625	68.75	84.375	89.0625	64.0625	73.4375	79.6875
	P2	178.75	178.75	335	22.5	187.5	170	197.5	160	178.75	178.75
	P3	134.375	175	175	134.375	187.5	121.875	196.875	112.5	125	184.375
	P4	93.75	93.75	167.5	20	105	82.5	97.5	90	93.75	93.75
	P5	243.75	243.75	412.5	75	250	237.5	287.5	200	243.75	243.75
	P6	46.375	41.75	53.375	34.75	46.375	41.75	49.875	38.25	45.5	42.625
	P7	165	165	300	30	165	165	165	165	165	165
	P8	71.25	71.25	95	47.5	82.5	60	78.75	63.75	71.25	71.25
Manufacture	**P1**	24.21875	22.65625	29.6875	17.1875	25	21.875	26.5625	20.3125	19.53125	27.34375
	P2	65	65	110	20	65	65	70	60	65	65
	P3	35.625	34.375	45	25	35	35	36.875	33.125	35	35
	P4	30	30	50	10	30	30	30	30	30	30
	P5	32.5	32.5	60	5	32.5	32.5	32.5	32.5	32.5	32.5
	P6	63	63	70	56	63	63	63	63	63	63
	P7	36.875	36.875	65	8.75	42.5	31.25	39.5	34.25	36.875	36.875
	P8	36.25	36.25	42.5	30	40	32.5	38.75	33.75	36.25	36.25
Documentation 2	**P1**	26.5625	26.5625	28.125	25	34.375	18.75	31.25	21.875	26.5625	26.5625
	P2	43.125	40.625	62.5	21.25	47.5	36.25	47.5	36.25	43.125	40.625
	P3	30.625	28.125	40	18.75	31.875	26.875	28.75	30	30	28.75
	P4	24.375	24.125	38.75	9.75	30	18.5	25	23.5	24.375	24.125
	P5	28.75	28.75	40	17.5	31.25	26.25	32.5	25	28.75	28.75
	P6	31.5	31.5	31.5	31.5	35	28	28	35	31.5	31.5
	P7	20.75	20.75	35	6.5	26.25	15.25	23.5	18	20.75	20.75
	P8	17.5	17.5	20	15	22.5	12.5	17.5	17.5	17.5	17.5

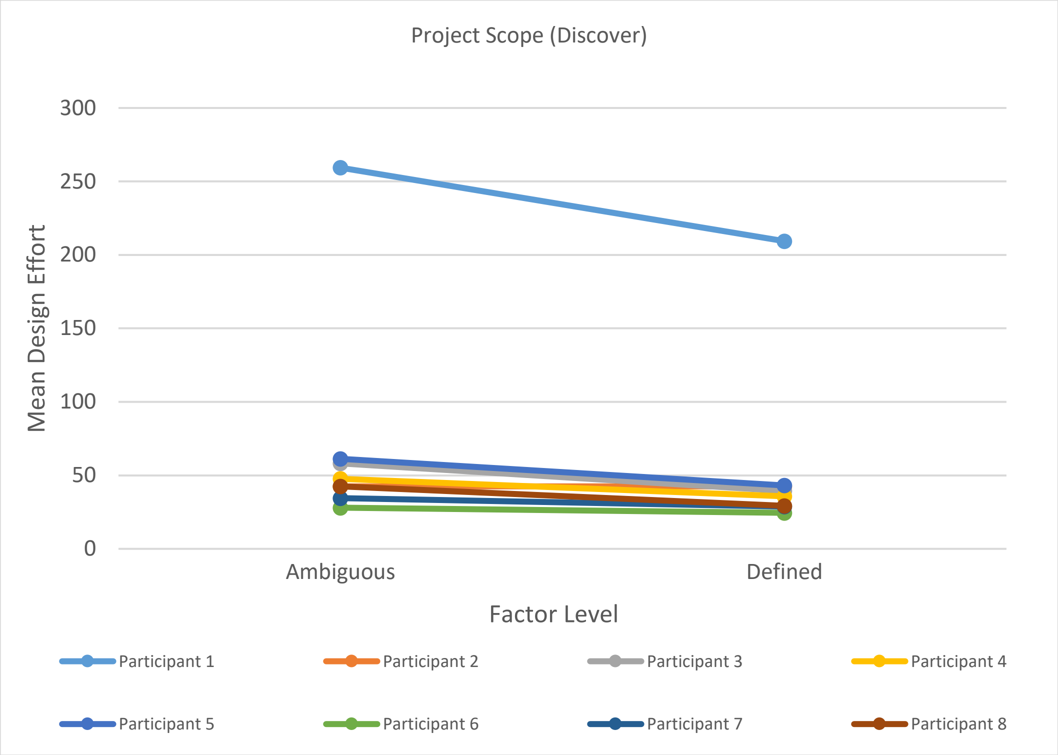
Appendix 4.12 – Mean Effect Plots

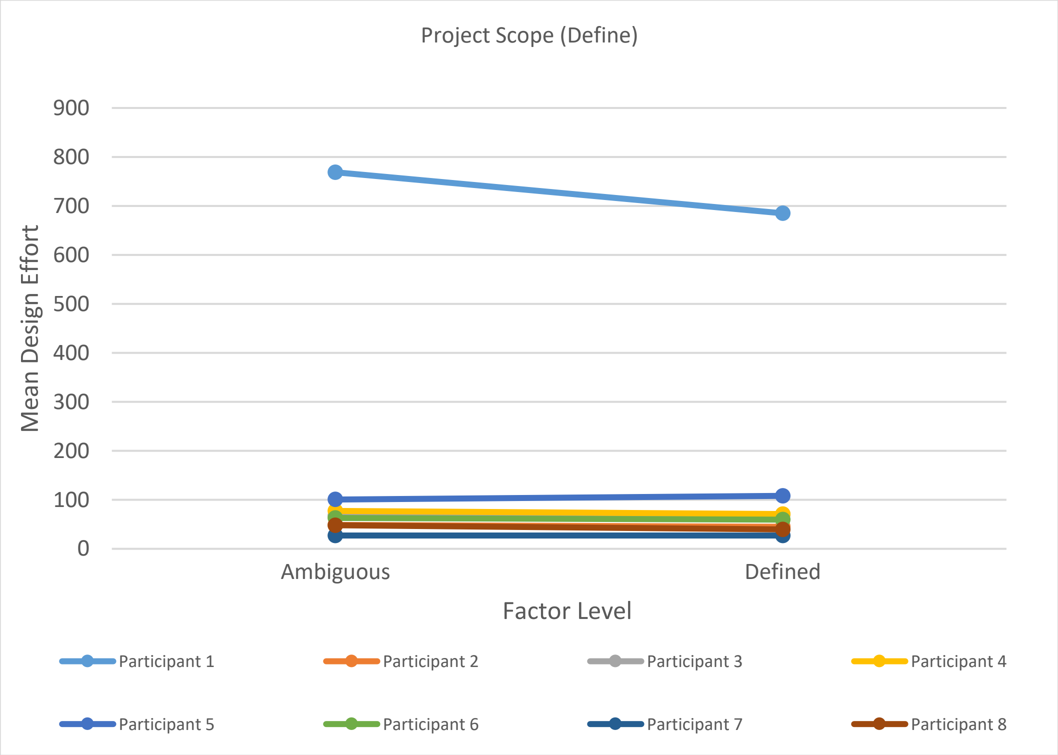


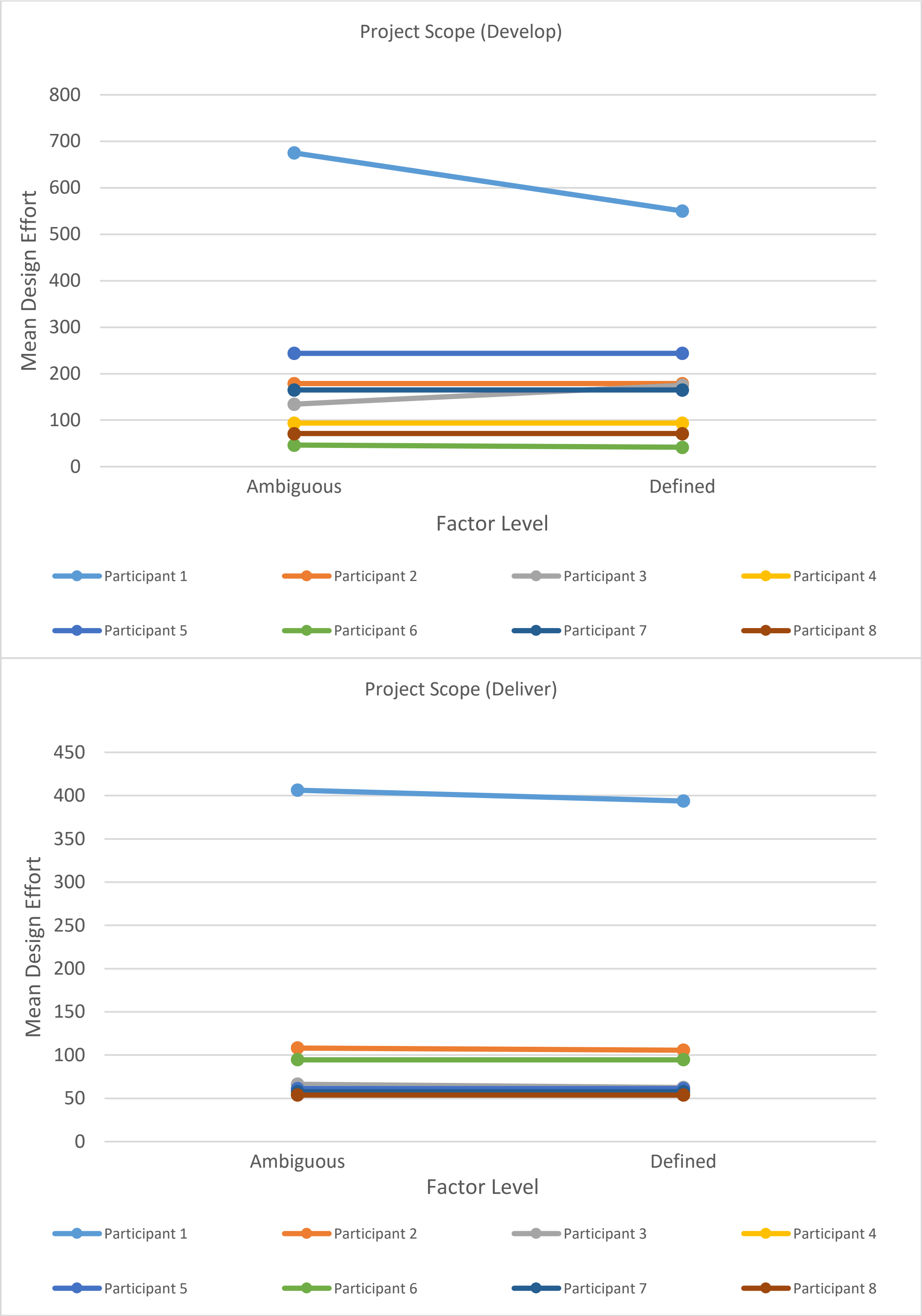




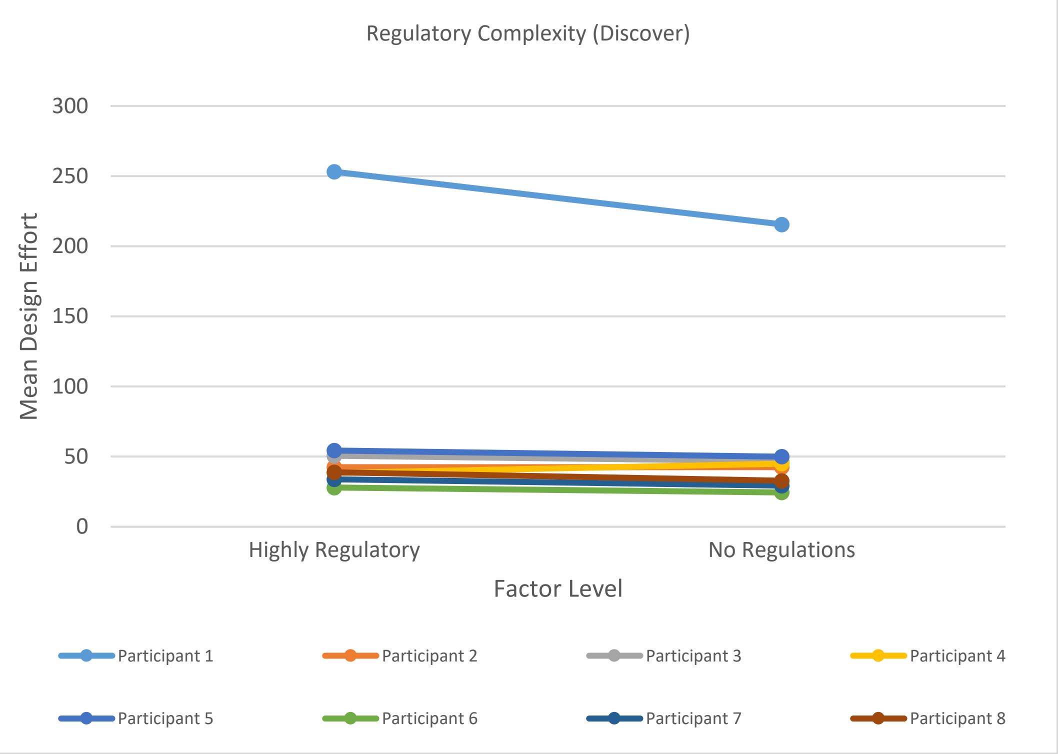
Mean Effect Plot of Product Complexity Factor

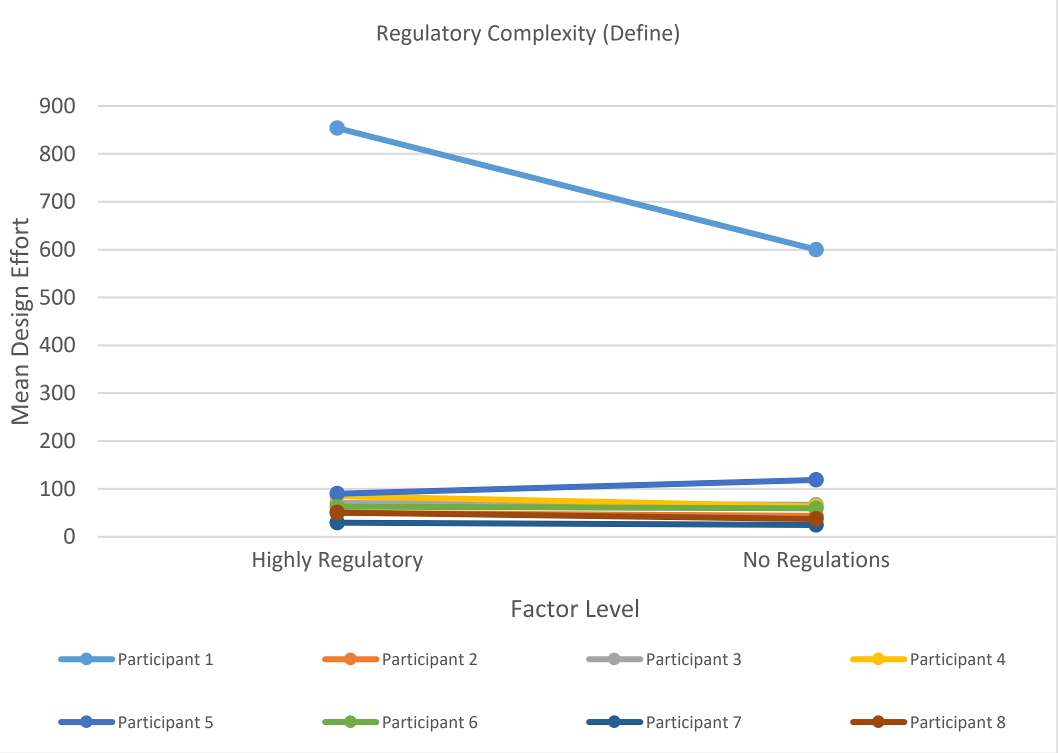

Project Scope (Discover)
Mean Design Effort
300
250
200
150
100
50
0
Ambiguous
Defined
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8

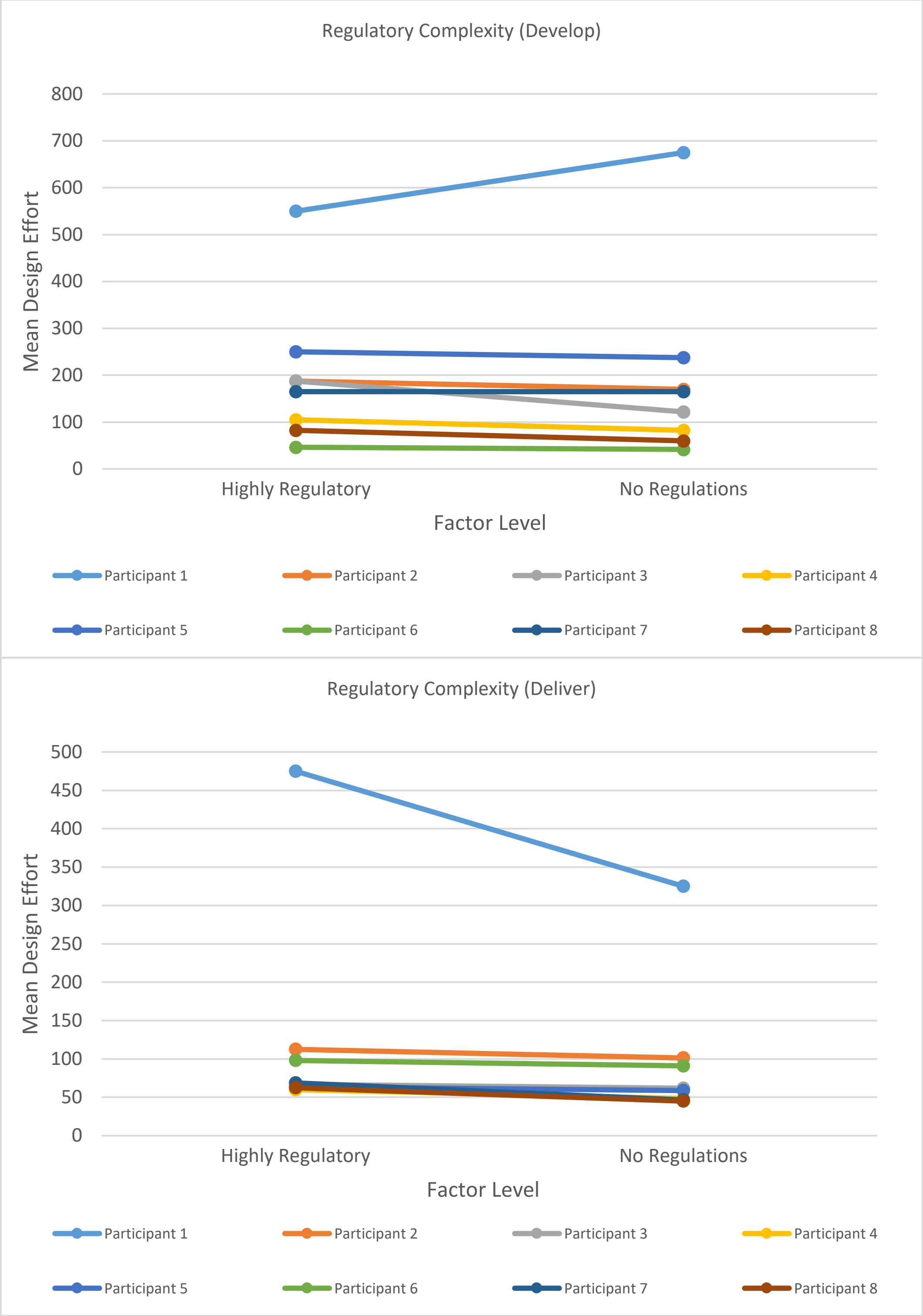

Project Scope (Define)
Mean Design Effort
900
800
700
600
500
400
300
200
100
0
Ambiguous
Defined
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8



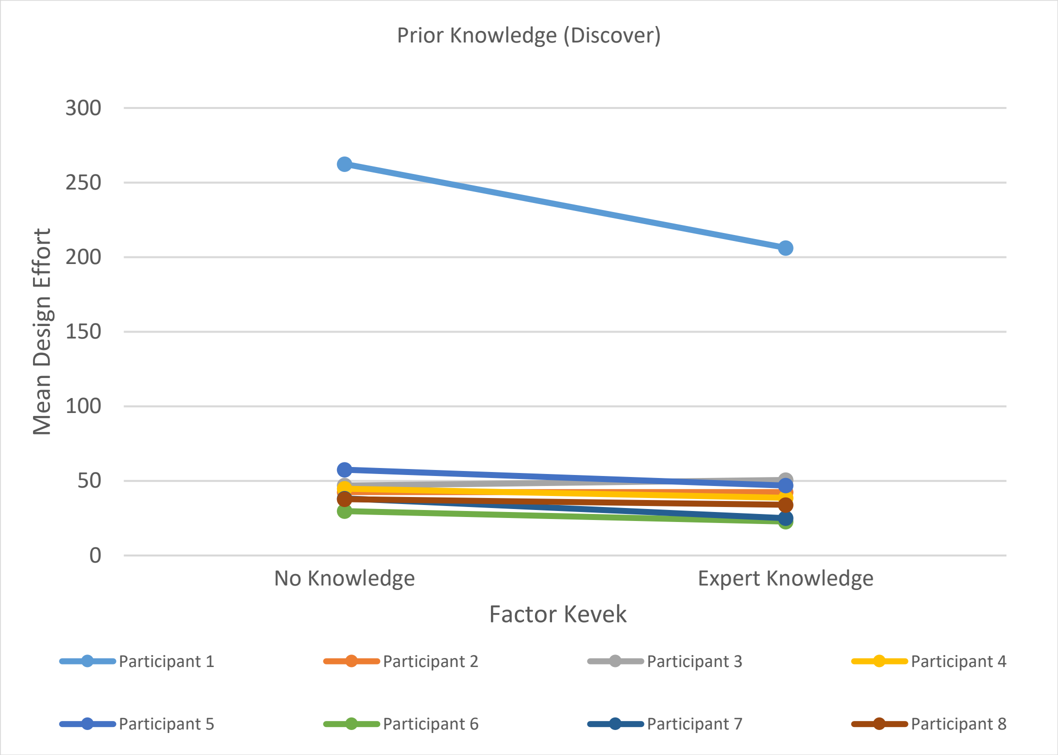
Mean Effect Plot of Project Scope Factor

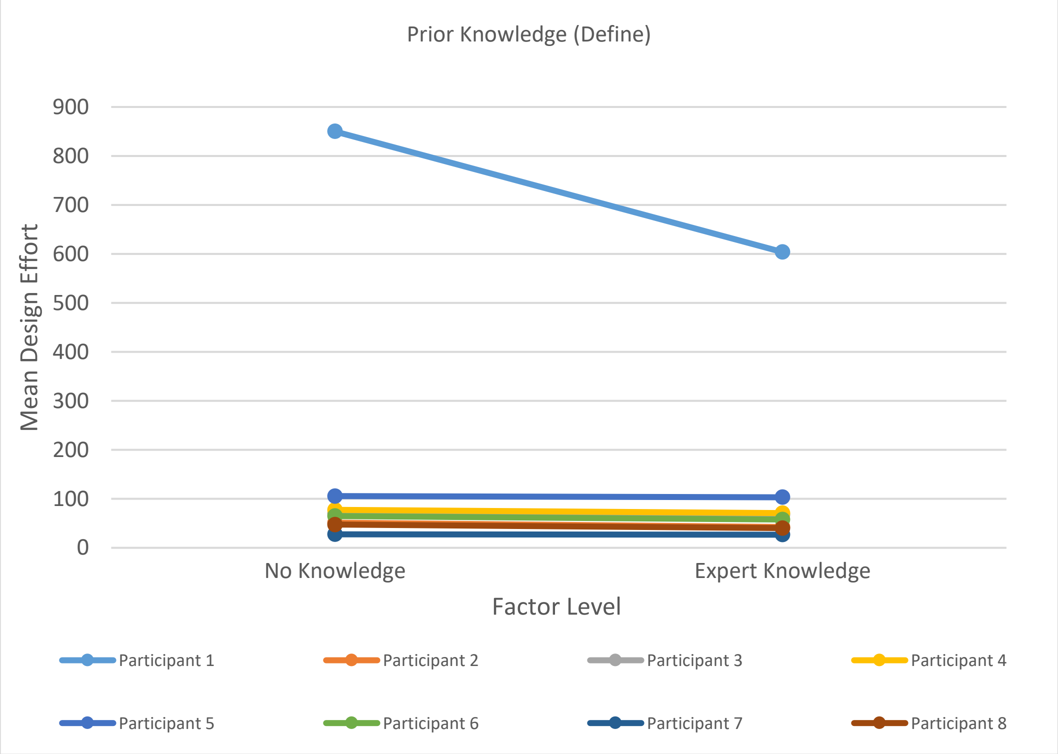

Regulatory Complexity (Discover)
Mean Design Effort
300
250
200
150
100
50
0
Highly Regulatory
No Regulations
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8

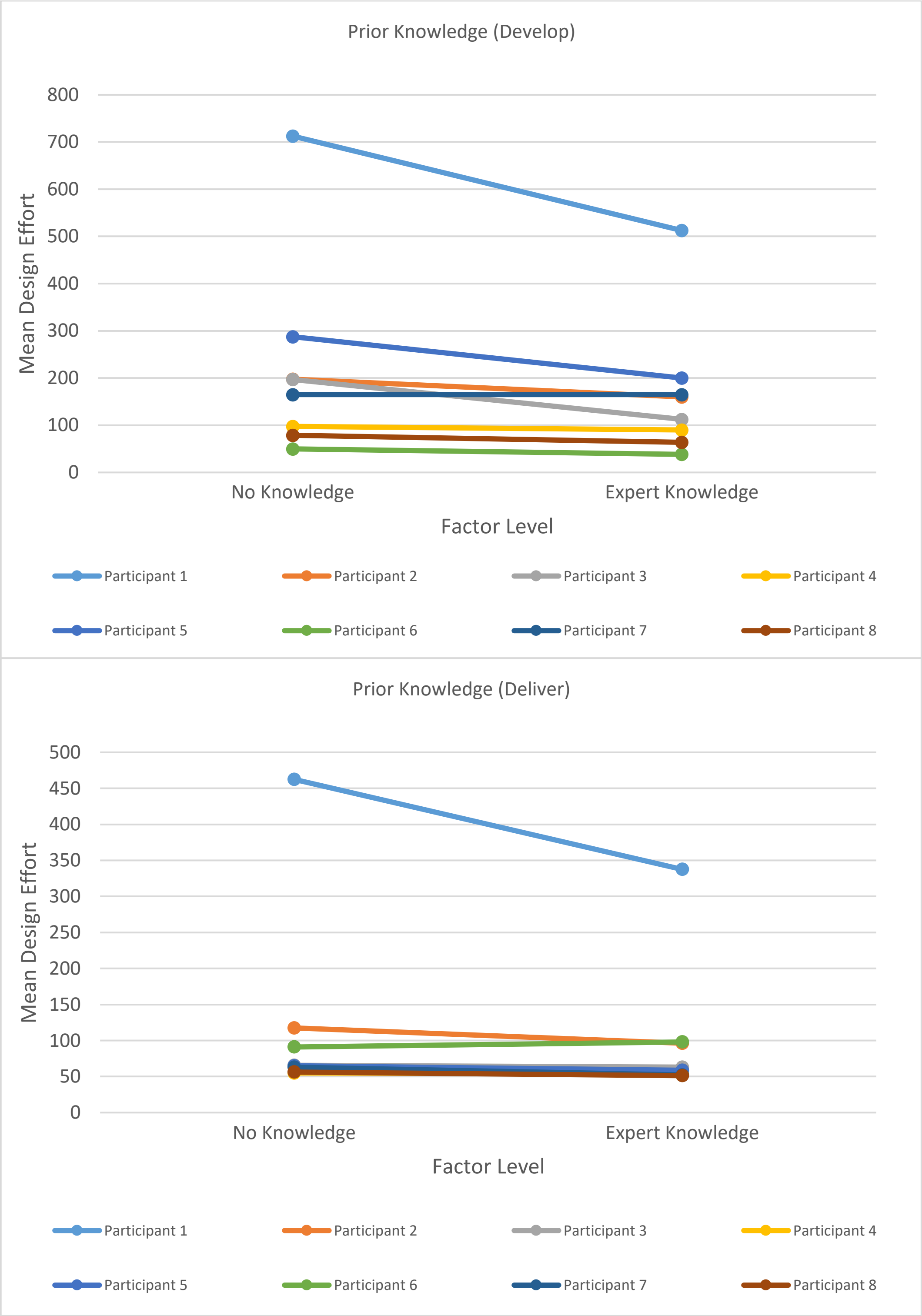

Regulatory Complexity (Define)
Mean Design Effort
900
800
700
600
500
400
300
200
100
0
Highly Regulatory
No Regulations
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8



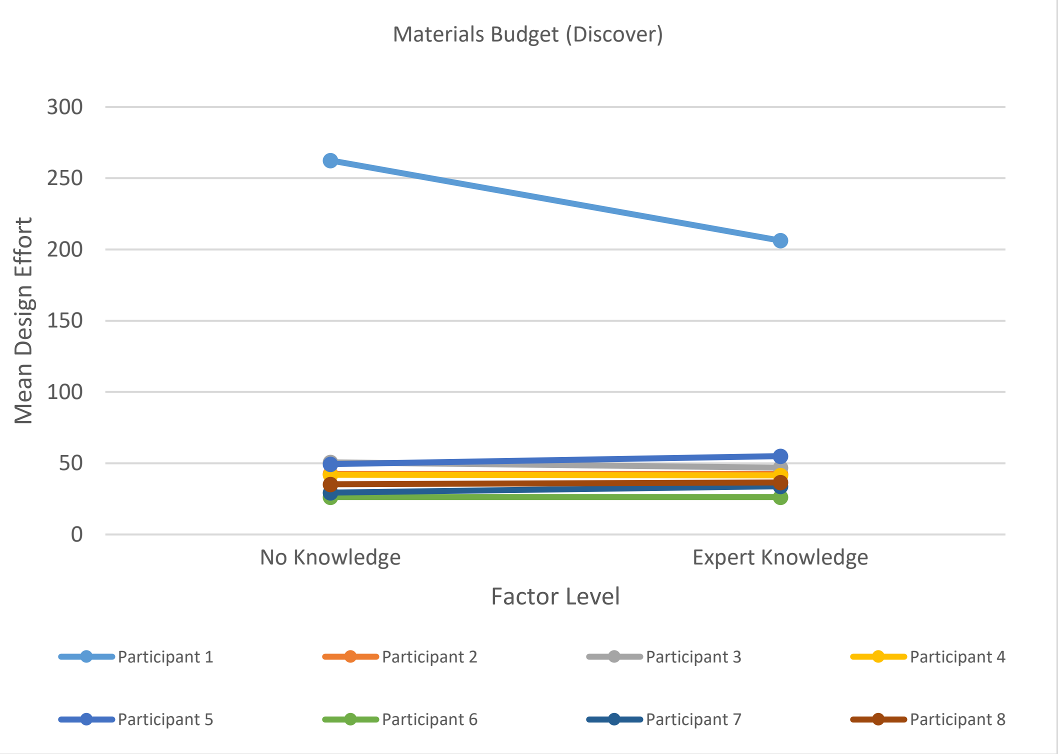
Mean Effect Plot of Regulatory Complexity Factor

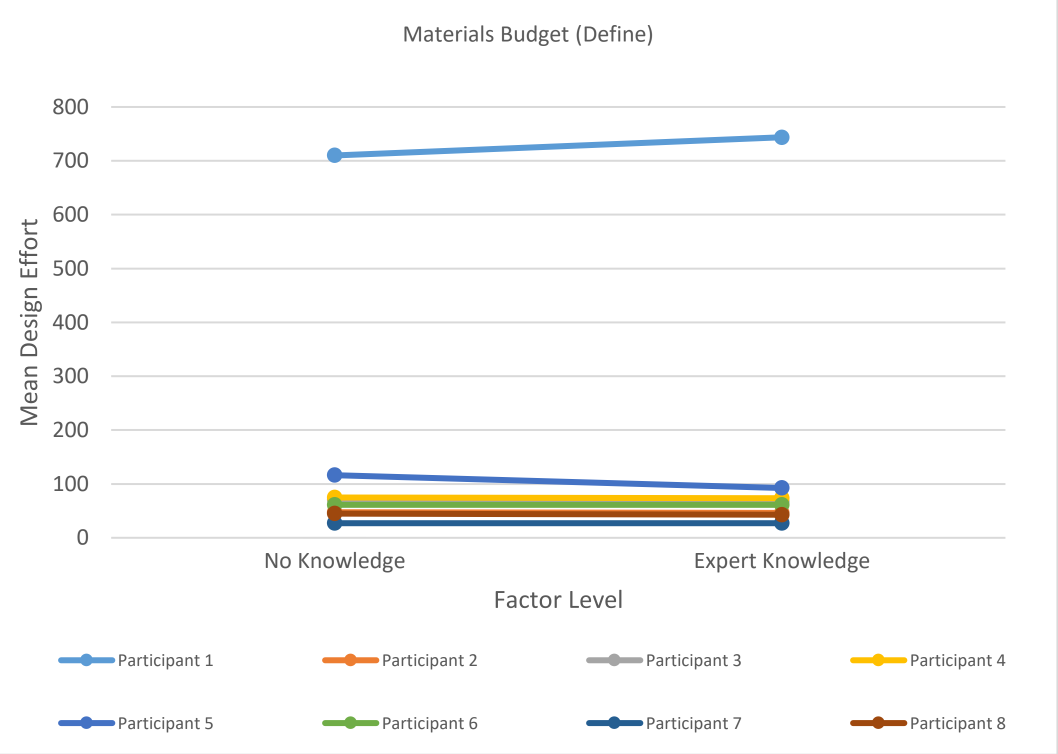

Prior Knowledge (Discover)
Mean Design Effort
300
250
200
150
100
50
0
No Knowledge
Expert Knowledge
Factor Kevek
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8

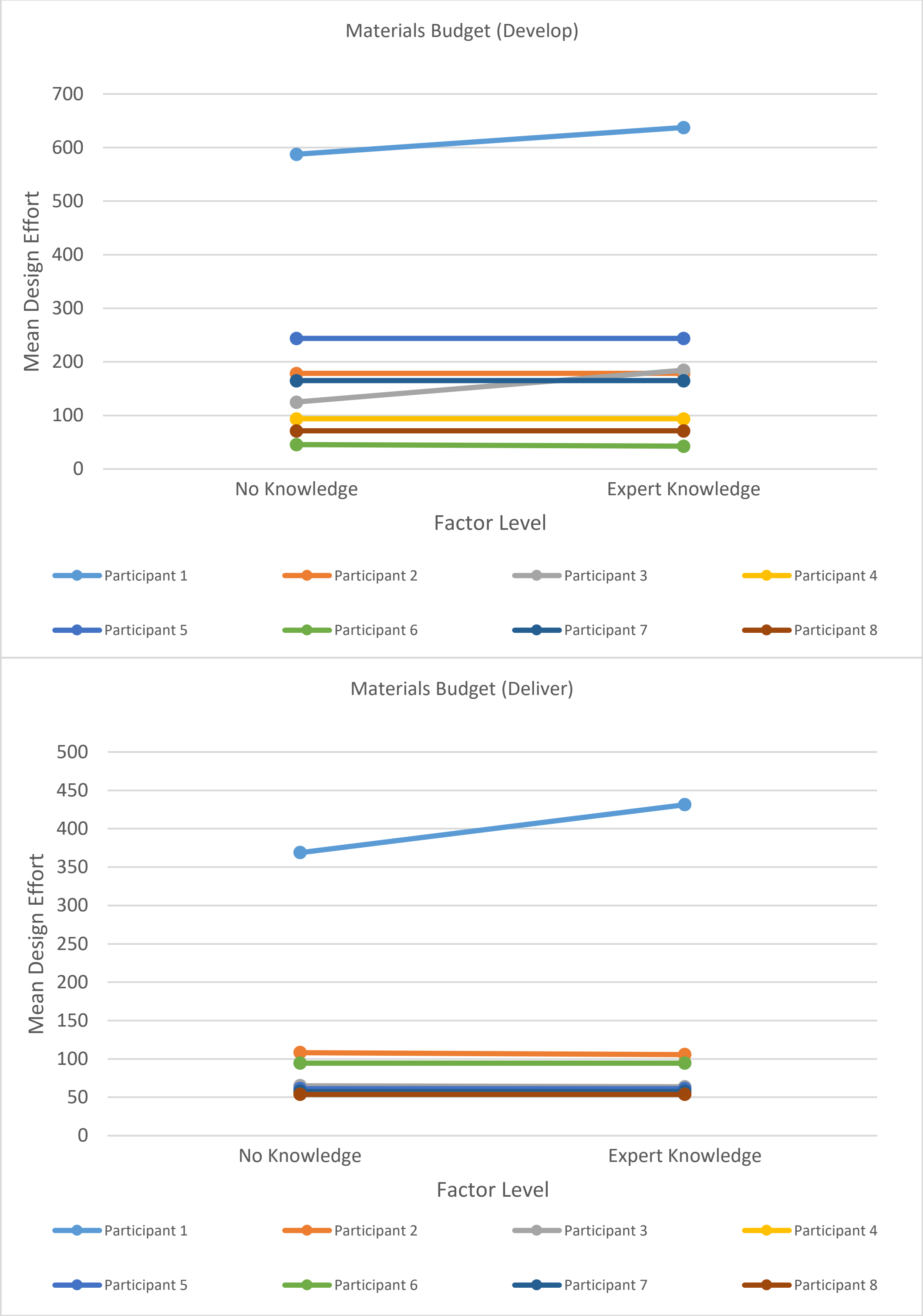

Prior Knowledge (Define)
Mean Design Effort
900
800
700
600
500
400
300
200
100
0
No Knowledge
Expert Knowledge
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8



Mean Effect Plot of Prior Knowledge Factor


Materials Budget (Discover)
300
250
200
150
100
50
0
Mean Design Effort
No Knowledge
Expert Knowledge
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8


Materials Budget (Define)
800
700
600
500
400
300
200
100
0
Mean Design Effort
No Knowledge
Expert Knowledge
Factor Level
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8



Mean Effect Plot of Materials Budget Factor

Appendix 4.13 - Participant Estimations (Taguchi)

Participant	Exp. Run	Discover	Define	Develop	Deliver	TOTAL	Participant	Exp. Run	Discover	Define	Develop	Deliver	TOTAL
1	**1**	40	60	40	40	180	**4**	**1**	1	12	10	20	72
	2	20	30	20	10	80		**2**	8	8	10	20	58
	3	60	80	60	60	260		**3**	18	18	20	40	118
	4	30	40	30	20	120		**4**	10	10	20	40	100
	5	50	60	60	30	200		**5**	40	40	50	50	180
	6	80	80	80	80	320		**6**	30	30	60	60	210
	7	50	80	80	70	250		**7**	50	50	70	70	290
	8	100	140	140	120	500		**8**	45	45	60	80	305
2	**1**	20	30	40	60	150	**5**	**1**	10	25	30	15	80
	2	10	30	40	60	140		**2**	60	15	15	10	46
	3	20	40	60	80	200		**3**	20	40	65	25	150
	4	15	40	60	80	195		**4**	20	40	60	20	140
	5	25	60	80	120	285		**5**	45	60	100	30	235
	6	25	80	80	140	325		**6**	35	60	120	40	255
	7	80	160	140	180	650		**7**	60	75	160	60	355
	8	180	160	140	200	680		**8**	65	85	180	80	410
3	**1**	50	75	250	150	525	**6**	**1**	85	170	340	85	680
	2	10	25	50	35	120		**2**	25	40	85	25	175
	3	40	60	220	120	440		**3**	40	85	85	40	335
	4	25	30	60	40	1550		**4**	85	170	170	85	680
	5	50	70	225	120	465		**5**	40	85	340	40	335
	6	15	30	75	50	170		**6**	40	85	170	40	335
	7	35	50	175	100	360		**7**	25	40	170	25	175
	8	20	40	125	100	285		**8**	85	170	85	85	680

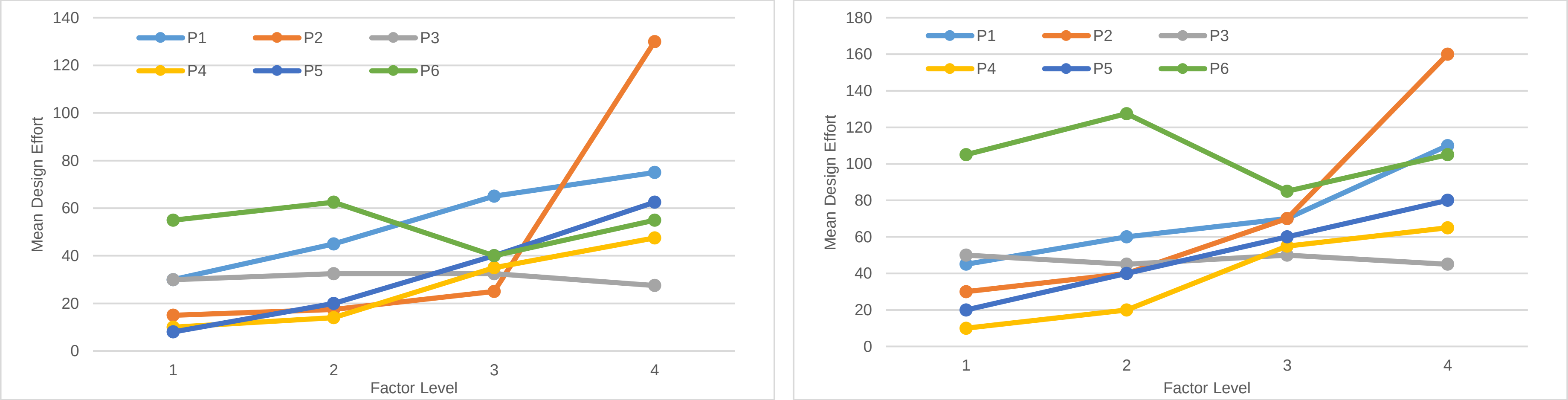
Appendix 4.14 - Regression Values (Taguchi)

	Discover	Define	Develop	Deliver	Discover	Define	Develop	Deliver	Discover	Define	Develop	Deliver
Participant	**2.1**				**2.2**				**2.3**			
Coefft.	53.13	105.63	211.17	53.13	46.88	75.00	80.00	115.00	32.63	50.00	91.25	35.00
Product Complexity 1 @ 1	1.88	-0.62	1.33	1.88	-31.88	-45.00	-40.00	-55.00	-24.63	-30.00	-68.75	-22.50
Product Complexity 2 @ 2	9.37	21.88	-62.42	9.37	-29.38	-35.00	-20.00	-35.00	-12.63	-10.00	-28.75	-12.50
Product Complexity 3 @ 3	-13.13	-20.63	22.58	-13.13	-21.88	-5.00	0.00	15.00	7.38	10.00	18.75	0.00
Product Complexity 4 @ 4	1.88	-0.63	38.52	1.88	83.13	85.00	60.00	75.00	29.88	30.00	78.75	35.00
Project Scope @ -	-5.63	-10.63	3.98	-5.63	-10.63	-2.50	0.00	-5.00	1.13	0.00	-2.50	-2.50
Project Scope @ +	5.63	10.63	-3.98	5.63	10.63	2.50	0.00	5.00	-1.13	0.00	2.50	2.50
Regulatory Complexity @ -	9.38	21.88	-1.33	9.38	14.38	2.50	0.00	5.00	-0.13	2.50	7.50	5.00
Regulatory Complexity @ +	-9.38	-21.88	1.33	-9.38	-14.38	-2.50	0.00	-5.00	0.13	-2.50	-7.50	-5.00
Prior Knowledge @ -	20.63	43.13	33.20	20.63	13.13	-2.50	0.00	0.00	2.38	2.50	1.25	1.25
Prior Knowledge @ +	-20.63	-43.13	-33.20	-20.63	-13.13	2.50	0.00	0.00	-2.38	-2.50	-1.25	-1.25
Participant	**2.4**				**2.5**				**2.6**			
Coefft.	26.63	37.50	47.50	55.00	53.75	71.25	63.75	50.00	30.63	47.50	147.50	89.38
Product Complexity 1 @ 1	-16.63	-27.50	-27.50	-30.00	-23.75	-26.25	-33.75	-25.00	-0.63	2.50	2.50	3.13
Product Complexity 2 @ 2	-12.63	-17.50	-7.50	-20.00	-8.75	-11.25	-18.75	-10.00	1.88	-2.50	-7.50	-9.38
Product Complexity 3 @ 3	8.38	17.50	7.50	-5.00	11.25	-1.25	6.25	5.00	1.88	2.50	2.50	-4.38
Product Complexity 4 @ 4	20.88	27.50	27.50	55.00	21.25	38.75	46.25	30.00	-3.13	-2.50	2.50	10.63
Project Scope @ -	3.38	0.00	-2.50	-2.50	-3.75	-1.25	-3.75	-7.50	13.13	16.25	70.00	33.13
Project Scope @ +	-3.38	0.00	2.50	2.50	3.75	1.25	3.75	7.50	-13.13	-16.25	-70.00	-33.13
Regulatory Complexity @ -	-0.38	0.00	2.50	7.50	16.25	18.75	16.25	25.00	0.63	3.75	20.00	15.63
Regulatory Complexity @ +	0.38	0.00	-2.50	-7.50	-16.25	-18.75	-16.25	-25.00	-0.63	-3.75	-20.00	-15.63
Prior Knowledge @ -	0.13	-2.50	0.00	0.00	1.25	3.75	3.75	2.50	5.63	6.25	17.50	13.13
Prior Knowledge @ +	-0.13	2.50	0.00	0.00	-1.25	-3.75	-3.75	-2.50	-5.63	-6.25	-17.50	-13.13

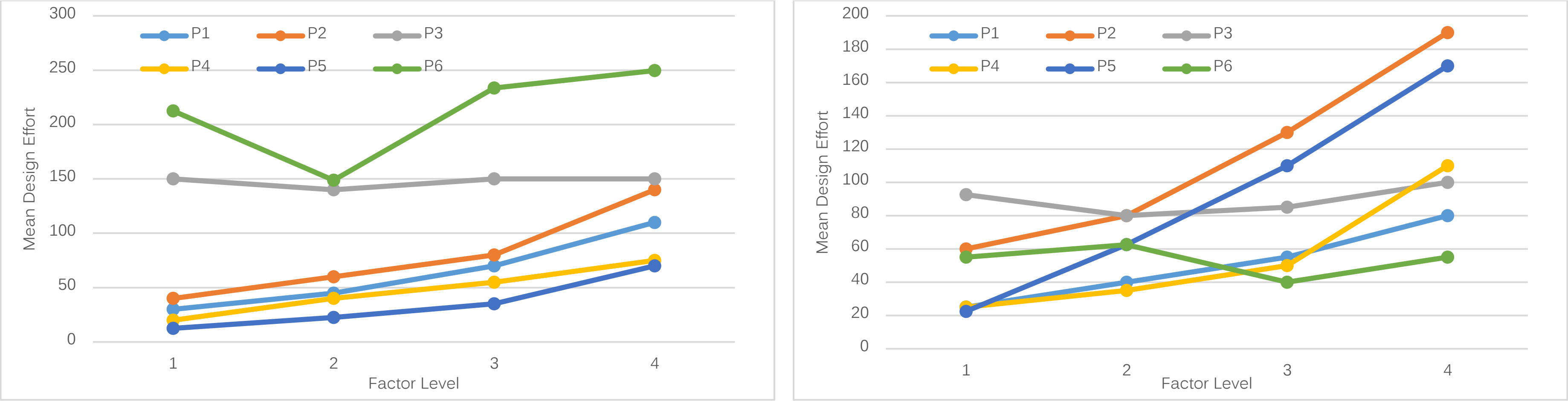
Appendix 4.15 - Mean Effects Plot Values (Taguchi)

		Product Complexity				**Project Scope**		**Regulatory Complexity**		**Prior Knowledge**	
		I	**II**	**III**	**IV**	**Ambiguous**	**Defined**	**Highly Regulated**	**Not Regulated**	**No Knowledge**	**Expert**
Discover	1	30	45	65	75	50	57.5	70	37.5	55	52.5
	2	15	17.5	25	130	36.25	57.5	61.25	32.5	60	33.75
	3	30	32.5	32.5	27.5	43.75	17.5	31.25	30	36.25	25
	4	10	14	35	47.5	30	23.25	26.25	27	26.75	26.5
	5	8	20	40	62.5	33.75	31.5	32.5	32.75	35	30.25
	6	55	62.5	40	55	47.5	58.75	62.5	43.75	73.75	32.5
Define	1	45	60	70	110	70	72.5	90	52.5	75	67.5
	2	30	40	70	160	72.5	77.5	77.5	72.5	72.5	77.5
	3	50	45	50	45	63.75	31.25	51.25	43.75	53.75	41.25
	4	10	20	55	65	37.5	37.5	37.5	37.5	35	40
	5	20	40	60	80	50	50	52.5	47.5	52.5	47.5
	6	105	127.5	85	105	95	116.25	127.5	83.75	148.75	62.5
Develop	1	30	45	70	110	60	67.5	80	47.5	67.5	60
	2	40	60	80	140	80	80	80	80	80	80
	3	150	140	150	150	217.5	77.5	167.5	127.5	165	130
	4	20	40	55	75	45	50	50	45	47.5	47.5
	5	12.5	22.5	35	70	32.5	37.5	40	30	36.25	33.75
	6	212.5	148.75	233.75	249.69	215.156	207.188	209.844	212.5	244.375	199.969
Deliver	1	25	40	55	80	42.5	57.5	75	25	52.5	47.5
	2	60	80	130	190	110	120	120	110	115	115
	3	92.5	80	85	100	122.5	56.25	105	73.75	102.5	76.25
	4	25	35	50	110	52.5	57.5	62.5	47.5	55	55
	5	22.5	62.5	110	170	88.75	93.75	98.75	83.75	92.5	90
	6	55	62.5	40	55	47.5	58.75	62.5	43.75	73.75	32.5

Appendix 4.16 - Mean Effects Plot Graphs for Product Complexity (Taguchi)



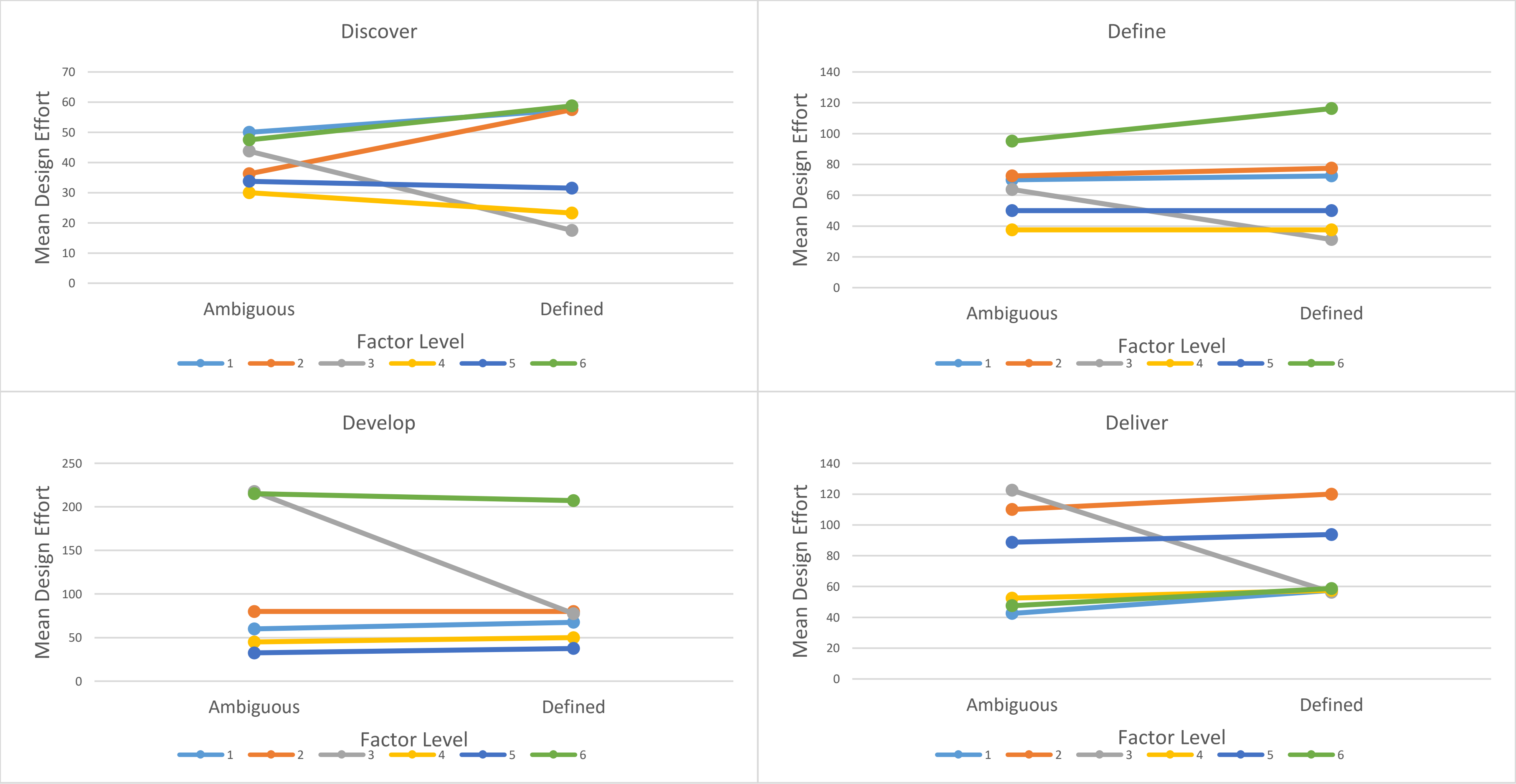
Discover (L), Define (R)



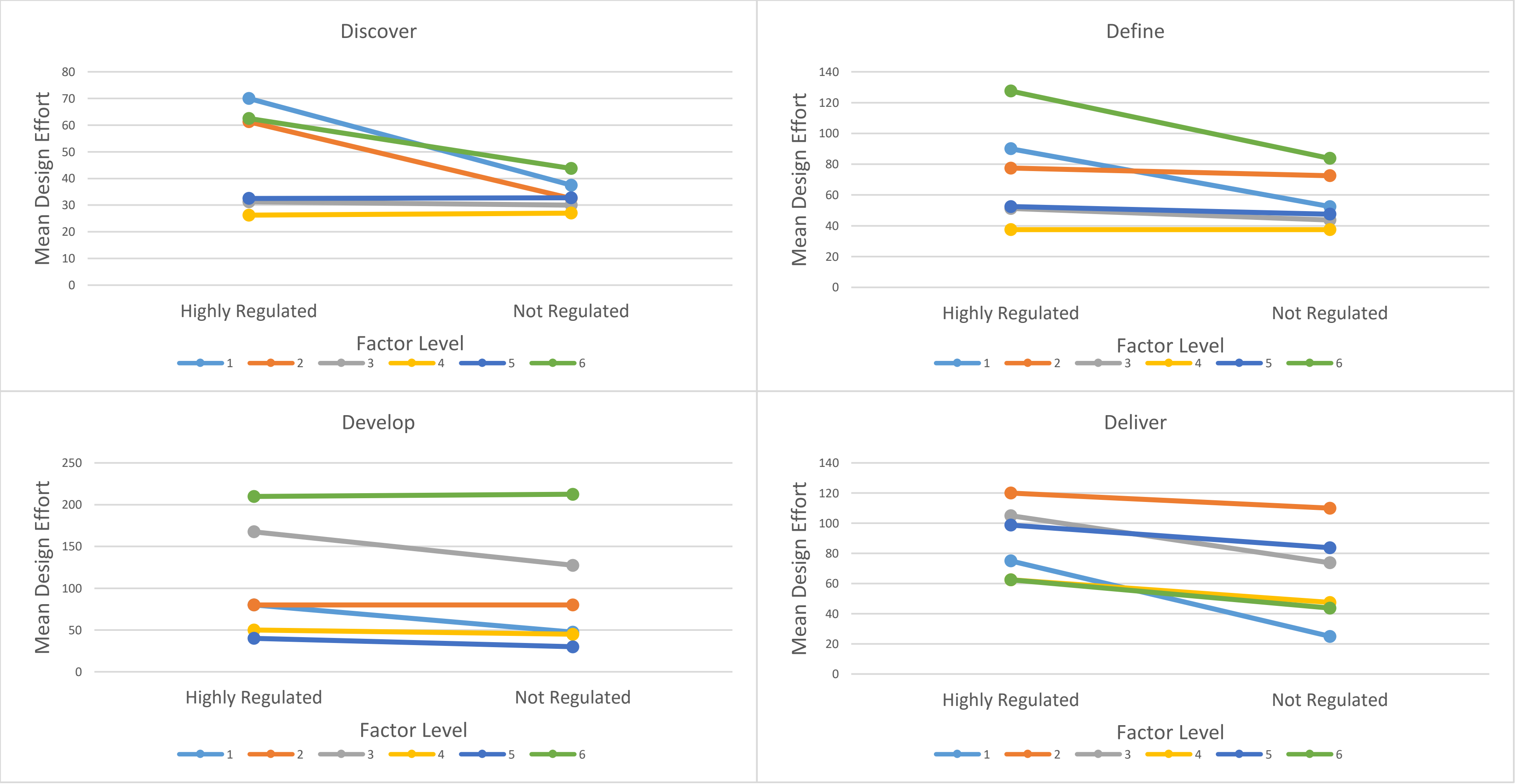
Develop (3) Deliver (R)

Appendix 4.17 - Mean Effects Plots Graphs (Taguchi)

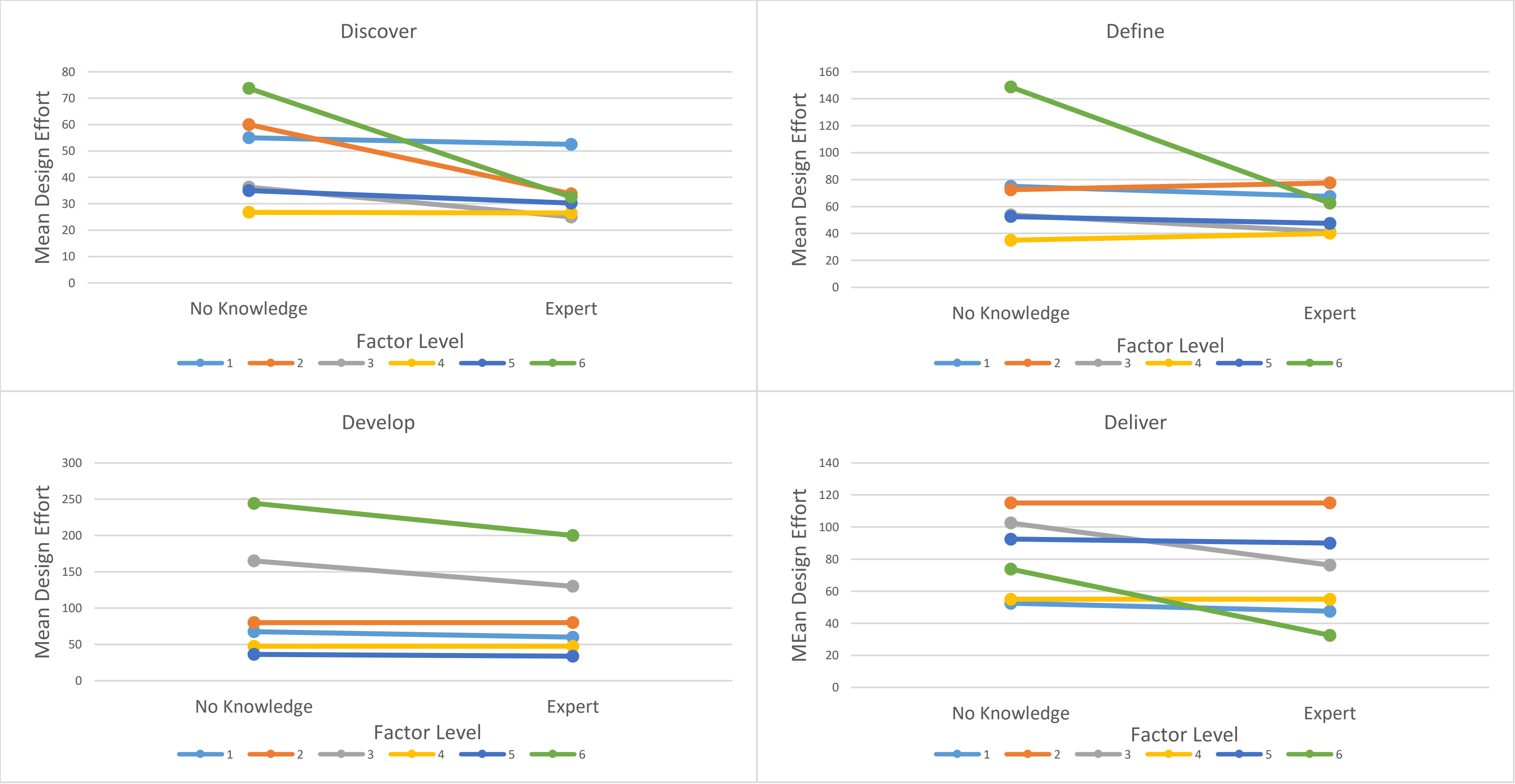
Project Scope



Regulatory Complexity

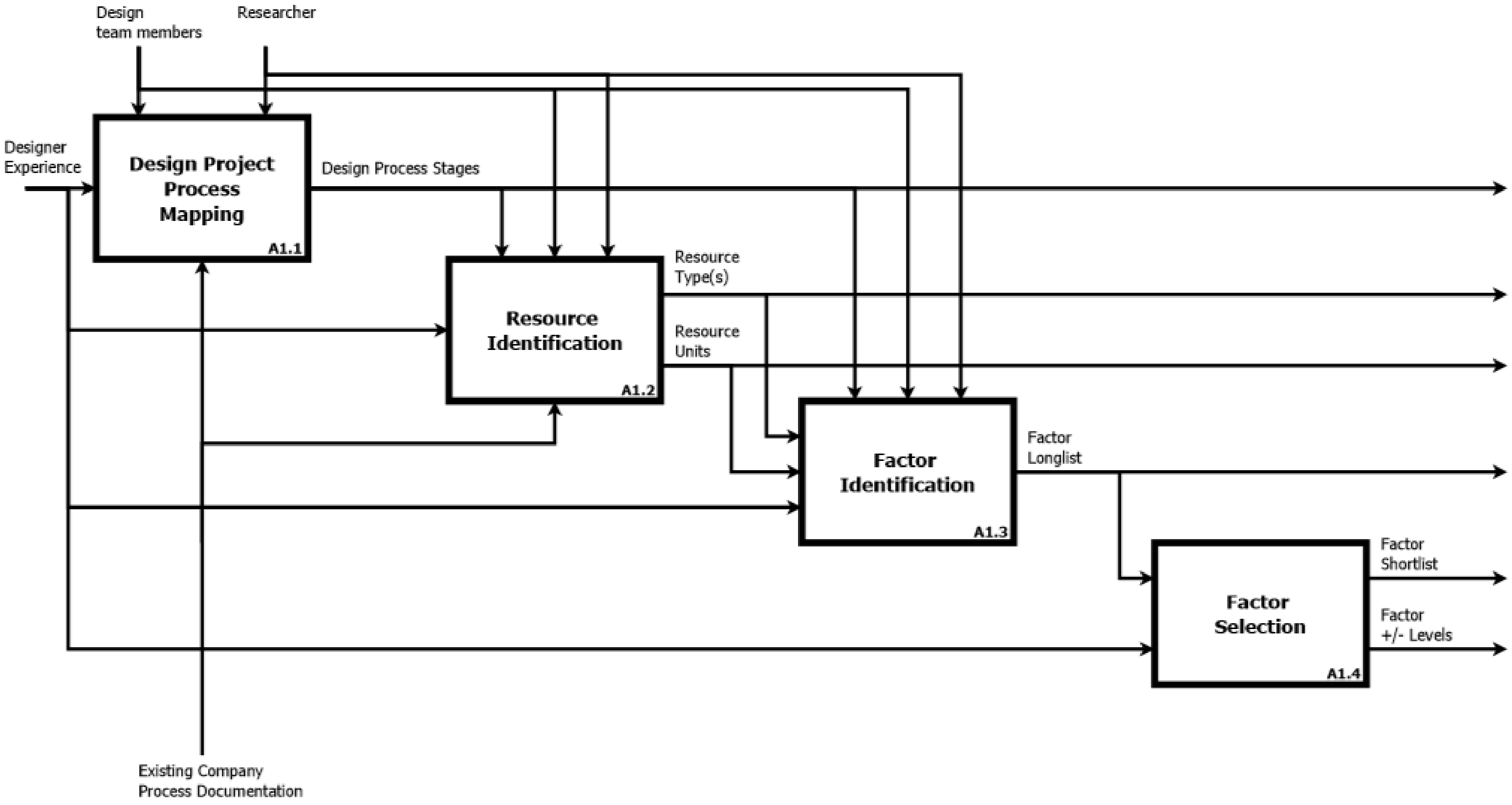


Prior Knowledge

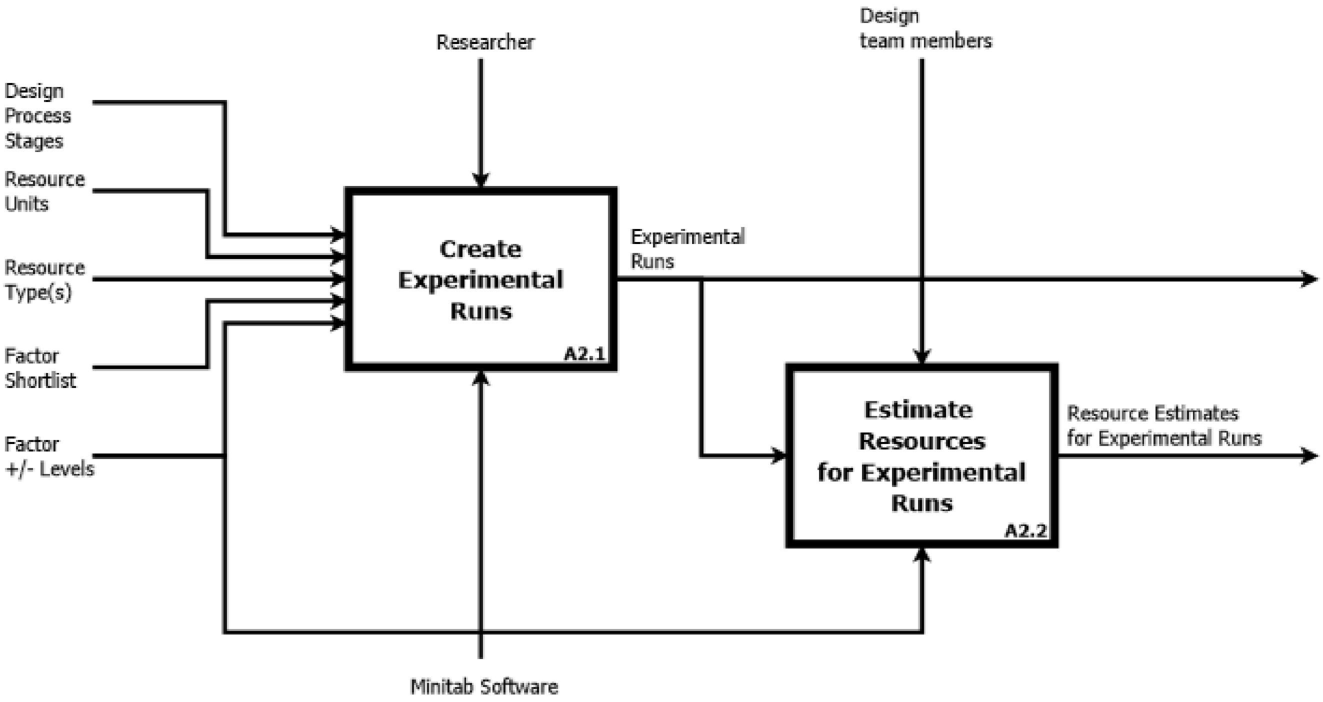


Case Study 2 Appendices

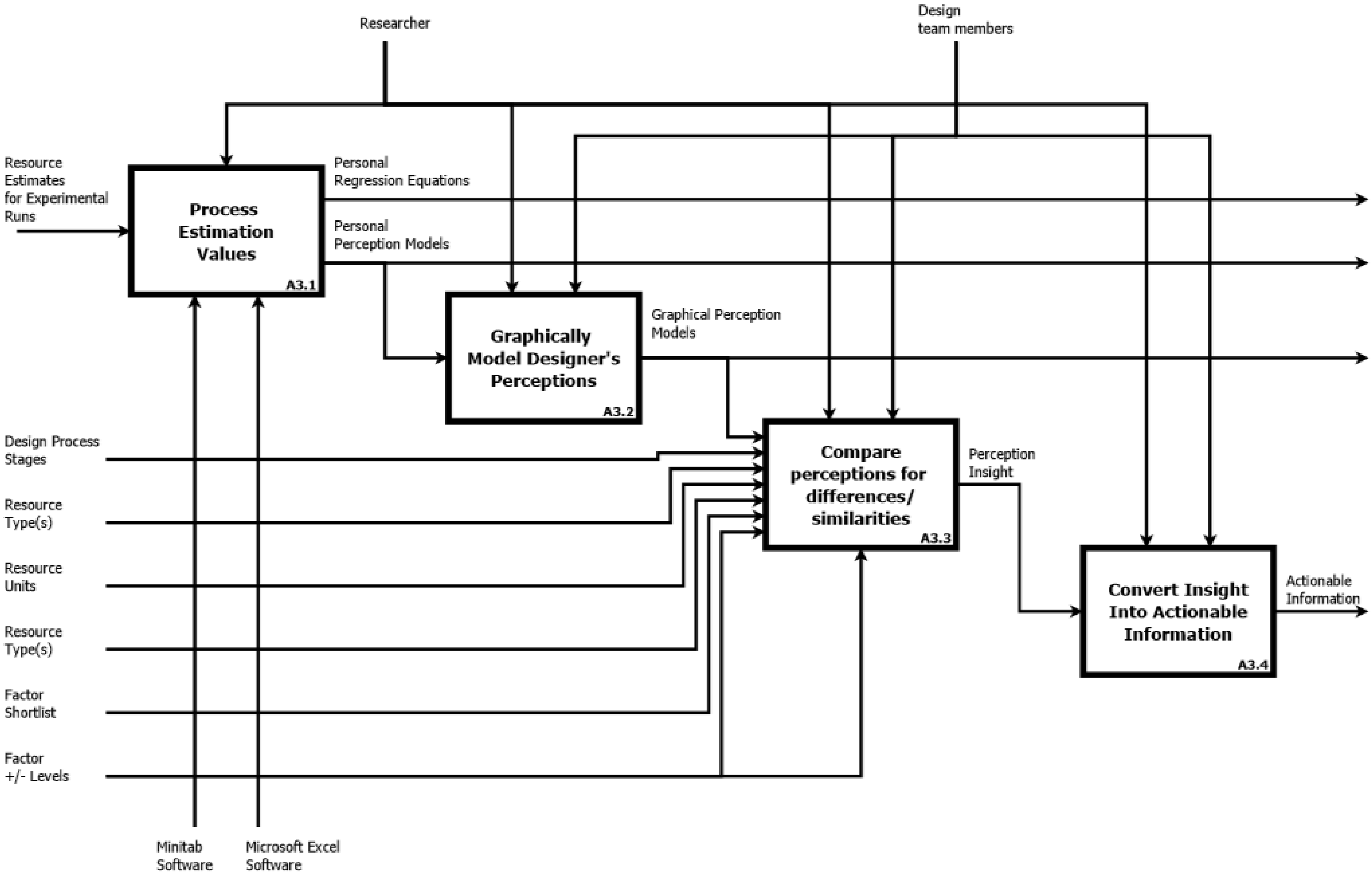
Appendix 5.1 - Case Study 2 Approach: Design Process and Factor Identification IDEF0



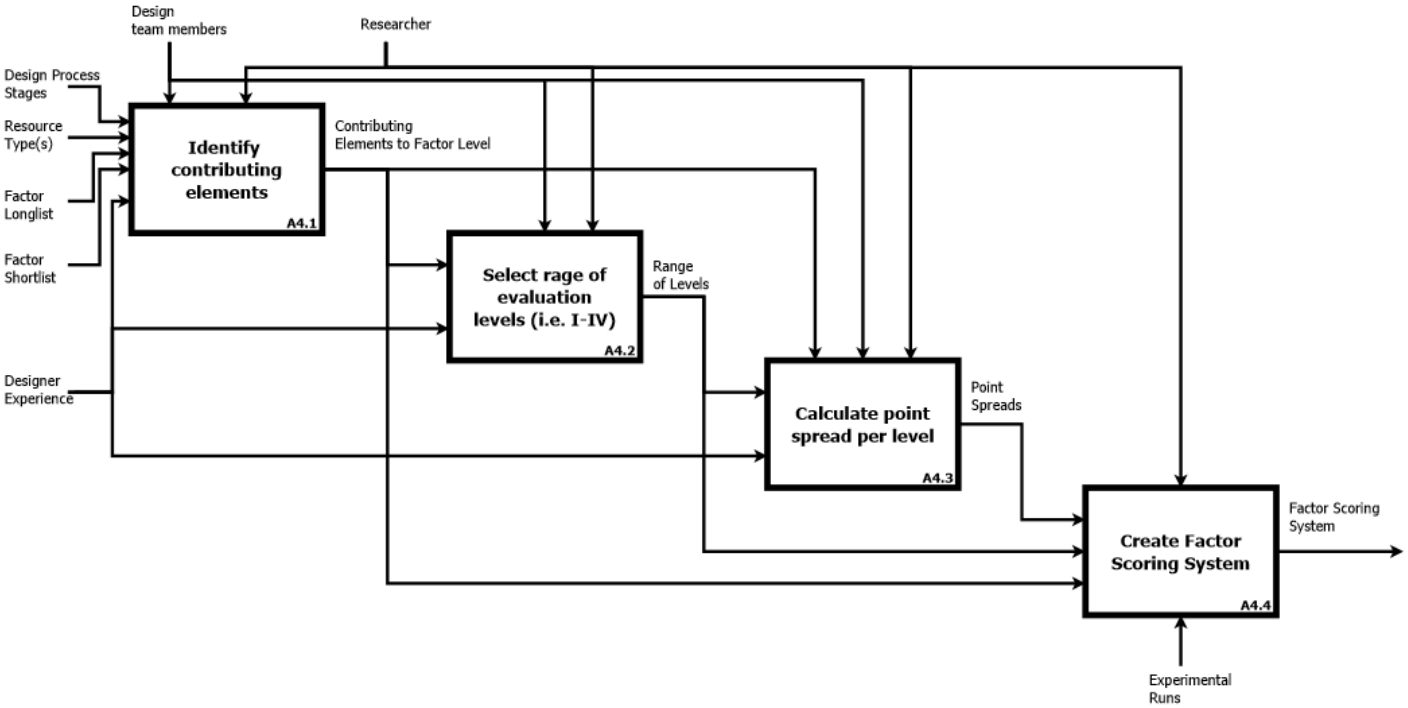
Appendix 5.2 - Case Study 2 Approach: Estimation Collection Phase IDEF0 Model



Appendix 5.3 - Case Study 2 Approach: Data Analysis & Perception Modelling IDEF0



Appendix 5.4 - Case Study 2 Approach: Influential Factor Identification IDEF0



Appendix 5.5 Participant Estimations (1 – 4) [Case Study 2]

		Participant 1						Participant 2						Participant 3						Participant 4						Participant 5					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
	Run	Pre-sign off	Discover	Define	Design	Detail	Deliver	Pre-sign off	Discover	Define	Design	Detail	Deliver	Pre-sign off	Discover	Define	Design	Detail	Deliver	Pre-sign off	Discover	Define	Design	Detail	Deliver	Pre-sign off	Discover	Define	Design	Detail	Deliver
Management	1	7	5	5	5	5	5	5	3	3	4	2	1	6	10	8	15	18	20	8	16	12	16	10	10	10	4	4	8	8	14
	2	7	10	10	10	10	10	7	2.5	5	15	20	20	16	8	8	15	18	30	16	16	16	24	16	24	10	6	16	16	24	48
	3	7	2	5	10	10	15	7	5	12.5	20	25	25	12	10	8	15	18	40	16	8	12	16	16	32	20	12	24	30	48	56
	4	7	1	5	10	10	10	3	2.5	2.5	2.5	2.5	2.5	4	4	4	5	6	7	8	8	8	16	16	16	7	2	4	8	8	12
	5	7	10	10	20	20	20	15	100	50	90	90	120	32	80	50	80	80	120	16	24	36	32	32	32	24	20	28	30	30	60
	6	7	10	10	15	15	20	21	40	15	40	22.5	20	24	50	30	60	60	60	8	16	24	16	16	16	18	15	20	30	30	30
	7	7	5	5	15	15	15	21	25	22.5	45	45	25	32	40	30	80	80	80	12	8	16	16	16	16	20	10	15	30	20	30
	8	7	10	10	20	20	20	9	30	45	80	100	120	24	32	20	60	80	80	16	8	8	12	12	16	12	6	20	38	40	40
Design	1	1	30	30	30	30	30	2	27	27	36	13	9	3	20	10	35	40	32	4	40	40	72	48	48	2	10	18	16	18	12
	2	1	60	60	60	60	60	2	40	40	70	50	50	3	40	20	70	80	80	8	80	80	120	80	160	2	24	32	48	80	24
	3	1	12	30	60	60	90	3	20	50	80	100	100	2	4	8	70	80	80	6	60	80	120	80	120	8	24	24	48	80	24
	4	1	7	30	60	60	60	1	10	12.5	30	30	30	1	4	4	35	40	32	2	40	40	80	48	80	2	8	16	16	18	8
	5	1	60	60	120	120	120	6	400	200	360	360	480	8	80	80	120	200	120	8	32	120	320	160	200	5	36	48	80	50	60
	6	1	60	60	90	90	120	6	360	135	360	203	180	8	60	30	120	160	60	4	24	120	240	80	80	8	30	40	90	100	40
	7	1	30	30	90	90	90	9	225	203	405	405	225	4	24	20	120	160	60	8	16	80	160	120	80	8	20	30	80	70	40
	8	1	60	60	120	120	120	2	120	180	320	400	480	4	32	30	150	200	120	**8**	16	80	240	120	200	8	20	38	90	90	80

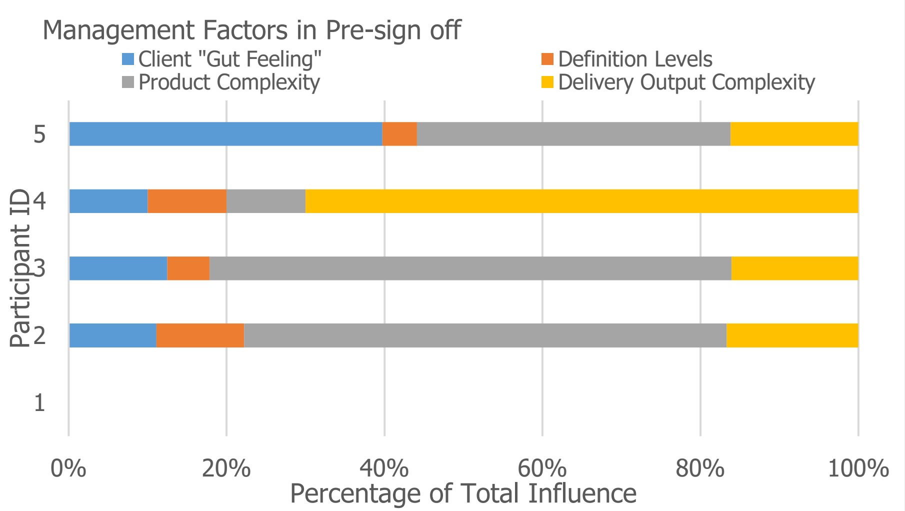
Appendix 5.6 Regression Equation Values [Case Study 2]

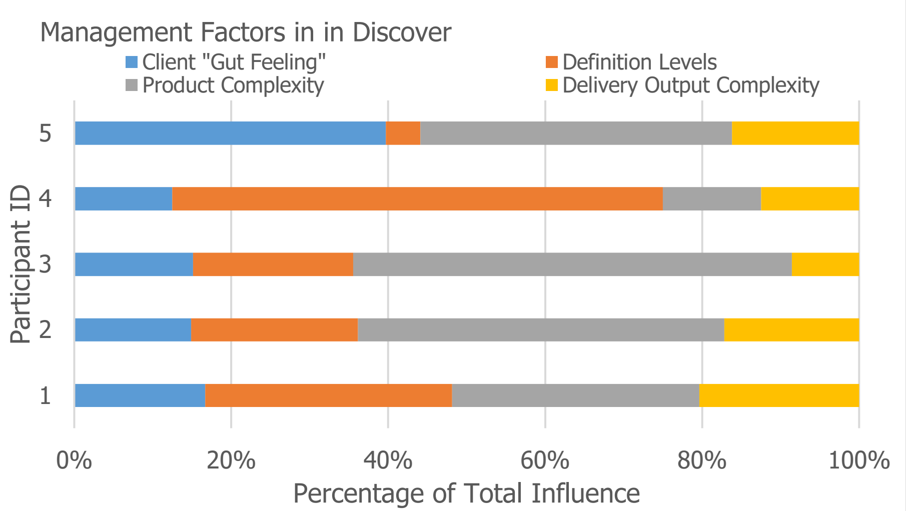
		Regression Coefficient										
	Phase	**Cft**	**A**	**B**	**C**	**D**	**AB**	**AC**	**AD**	**BC**	**BD**	**CD**
Participant 1	**1**	1	0	0	0	0	0	0	0	0	0	0
	2	39.875	6.875	-12.625	12.625	8.125	-0.625	0.625	5.125	0	0	0
	3	45	7.5	-7.5	7.5	7.5	6.20E-16	-6.20E-16	-2.00E-16	0	0	0
	4	78.75	3.75	3.75	26.25	11.25	3.75	-3.75	-3.75	0	0	0
	5	78.75	3.75	3.75	26.25	11.25	3.75	-3.75	-3.75	0	0	0
	6	86.25	3.75	3.75	26.25	11.25	-3.75	3.75	-11.25	0	0	0
Participant 2	**1**	3.875	-1.125	-0.125	1.875	-0.625	-1.125	-0.625	-0.125	0	0	0
	2	150.25	-17.75	-56.5	126	-5.25	-11	-18.5	-47.25	0	0	0
	3	106.25	-14.375	5.75	73.875	11.25	-1.375	-8.25	6.875	0	0	0
	4	207.625	-12.625	1.125	153.625	-0.125	-21.125	-8.625	0.125	0	0	0
	5	195.063	-24.438	38.687	146.813	32.438	5.688	-16.188	21.938	0	0	0
	6	194.25	-9.25	14.5	147	83.25	55.5	-2	-3.25	0	0	0
Participant 3	**1**	4.125	-0.125	-1.375	1.875	0.125	-0.125	0.125	-0.625	0	0	0
	2	33	1	-17	16	6	1	-4	-4	0	0	0
	3	25.25	-4.25	-9.75	14.75	9.25	5.75	-5.75	-5.25	0	0	0
	4	90	3.75	3.75	37.5	12.5	-5	3.75	3.75	0	0	0
	5	120	-7.40E-16	6.10E-15	60	20	2.10E-15	2.10E-15	-4.80E-15	0	0	0
	6	73	-8.30E-16	2.10E-15	17	27	3	-5.10E-16	-4.80E-16	0	0	0
Participant 4	**1**	6	-0.5	0	1	1.5	-0.5	-0.5	1	0	0	0
	2	38.5	1.5	-5.5	-16.5	8.5	-6.5	-3.5	-0.5	0	0	0
	3	80	8.00E-16	-10	20	10	-10	8.50E-16	-10	0	0	0
	4	169	1	-19	71	31	9	-1	-21	0	0	0
	5	92	-10	-3.50E-16	28	18	2	-10	2.00E-15	0	0	0
	6	121	9	-1	19	49	11	-9	1	0	0	0
Participant 5	**1**	5.375	-0.375	1.125	1.875	0.375	-1.125	1.125	-0.375	0	0	0
	2	21.5	-1	-3.5	5	4.5	-3	-0.5	-3	0	0	0
	3	30.75	0.75	-3.75	8.25	4.75	-0.75	-0.75	-1.25	0	0	0
	4	58.5	2.5	8.00E-17	26.5	8	-8	2.5	-2.60E-15	0	0	0
	5	63.25	8.75	1.25	14.25	11.75	-19.25	8.75	1.25	0	0	0
	6	36	2	2	19	11	4	3	3	0	0	0

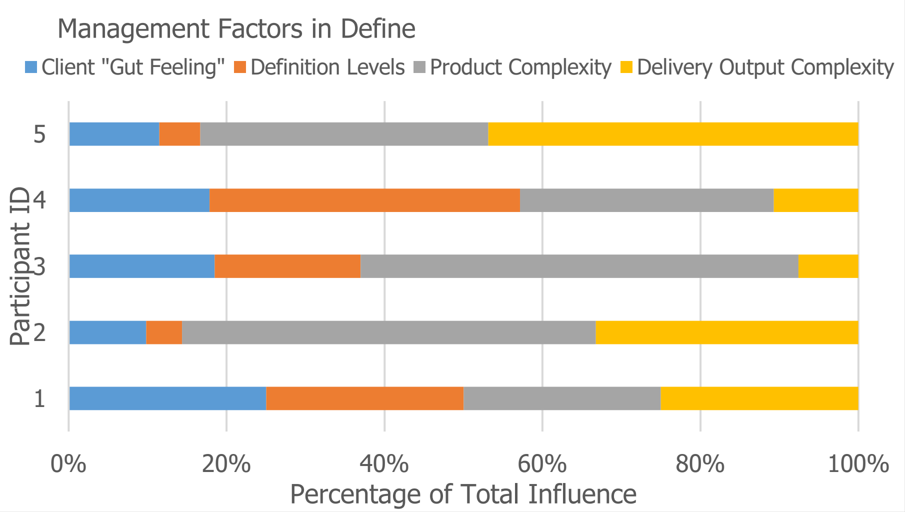
Note:

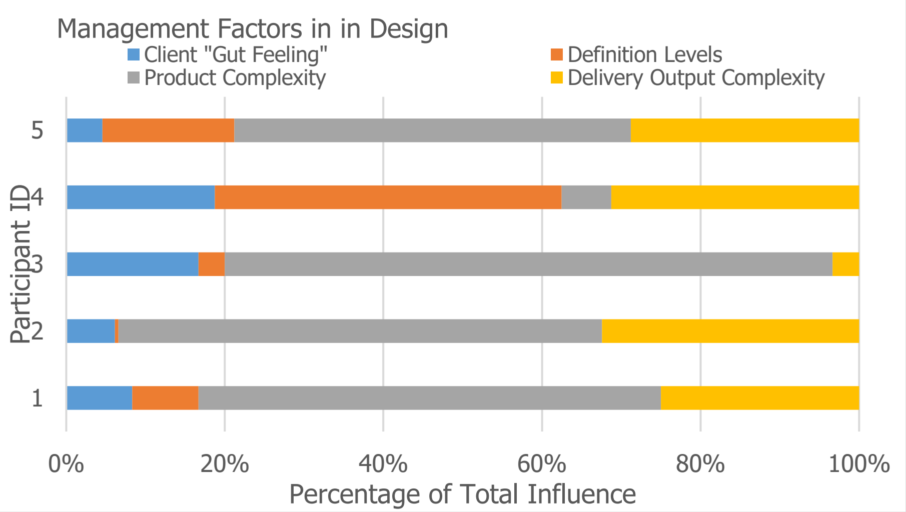
Project Phases are numbered:	1. Pre-Sign Off; 2. Discover; 3. Define; 4. Design; 5. Detail; 6. Deliver
Factors are labelled:	A. Client "Gut Feeling"; B. Definition Level (Inputs); C. Product Complexity; D. Delivery Output Complexity

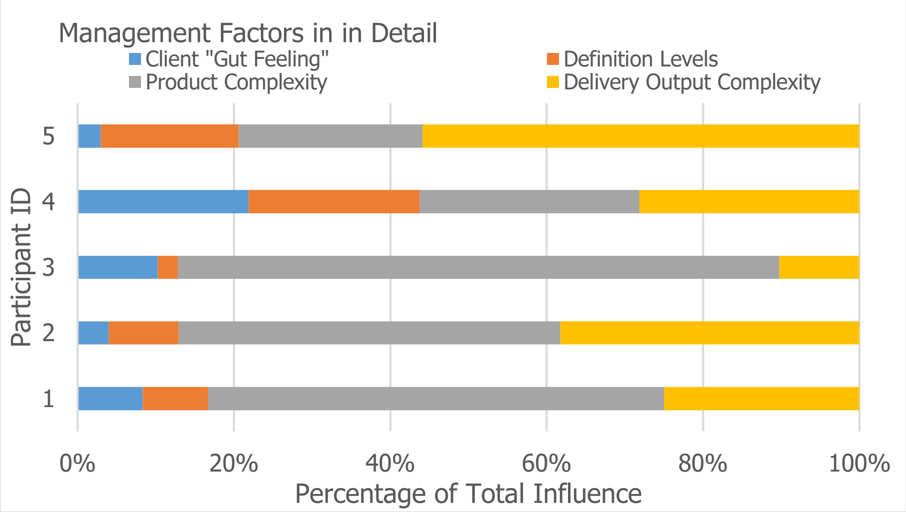
Appendix 5.7 Percentage Influence Graphs (Management & Design Factors) [Case Study 2]

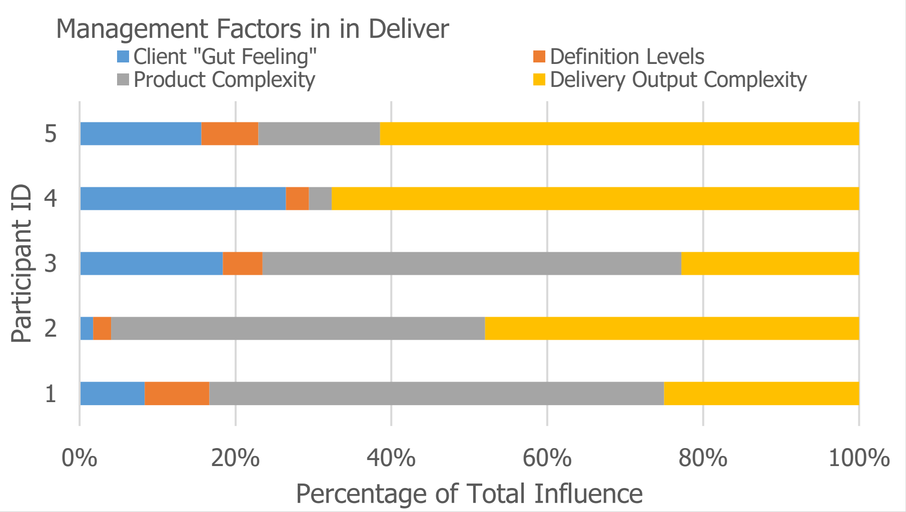


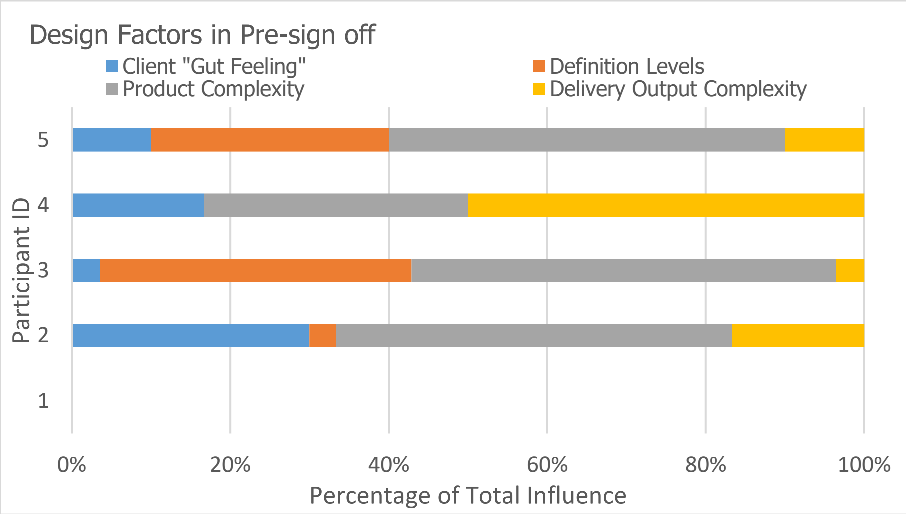




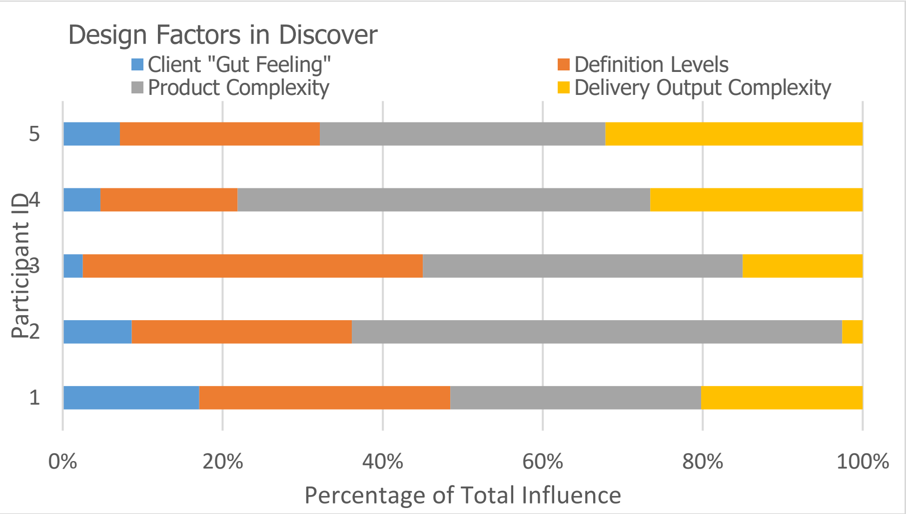



Management Factors in in Detail
Client "Gut Feeling"
Definition Levels
Product Complexity
Delivery Output Complexity
Participant ID
5
4
3
2
1
0%
20%
40%
60%
80%
100%
Percentage of Total Influence

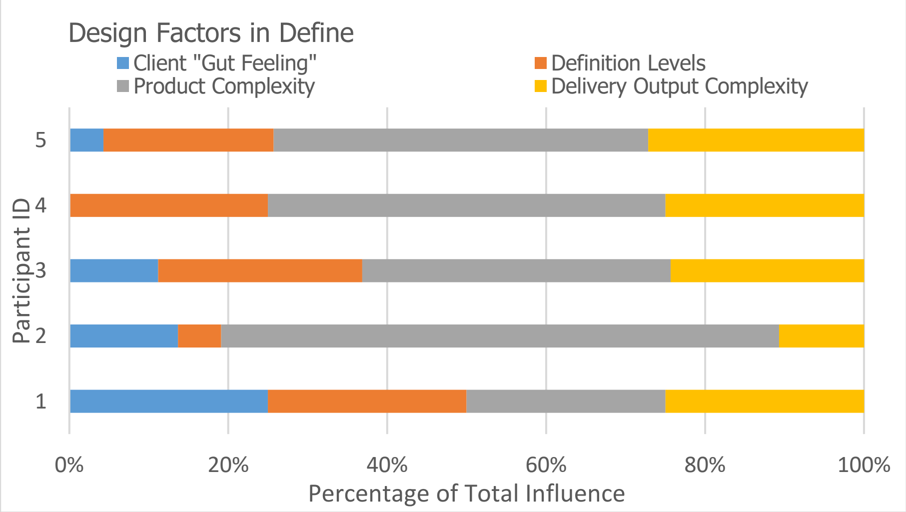

Management Factors in in Deliver
Client "Gut Feeling"
Definition Levels
Product Complexity
Delivery Output Complexity
Participant ID
5
4
3
2
1
0%
20%
40%
60%
80%
100%
Percentage of Total Influence



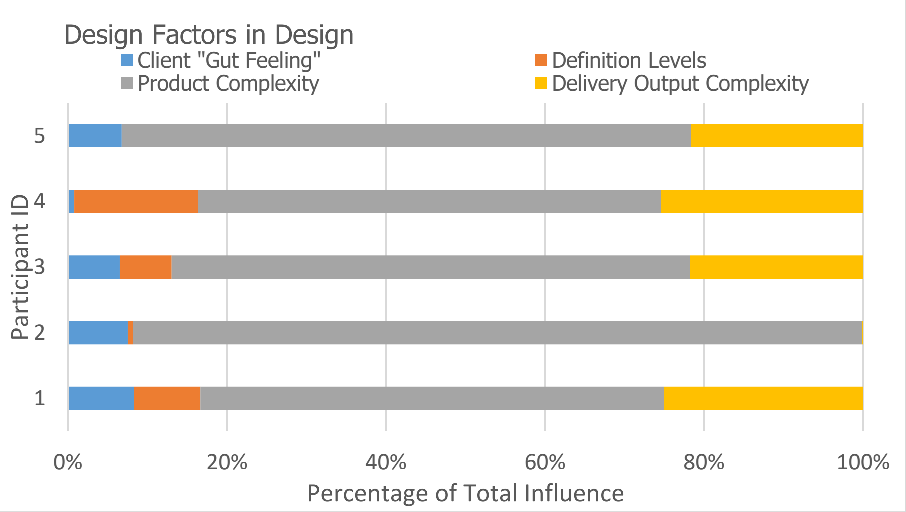
Design Factors in Pre-sign off



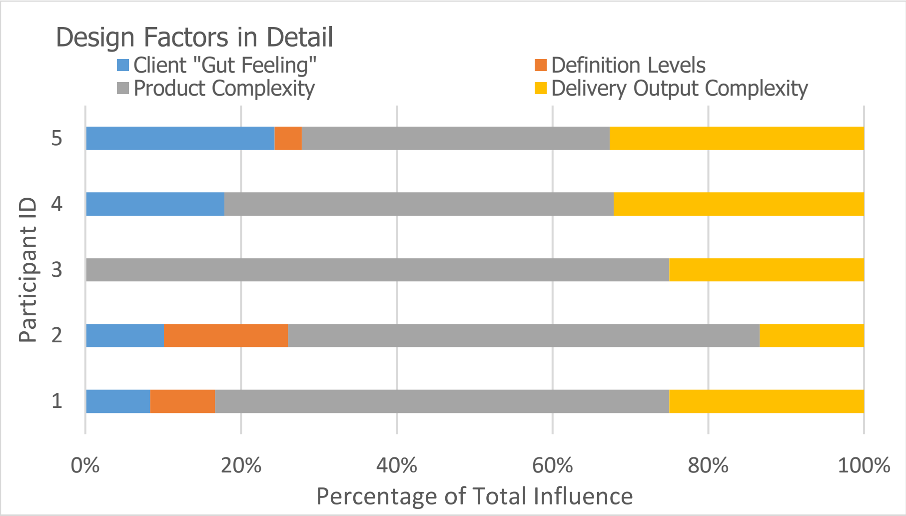
Design Factors in Discover

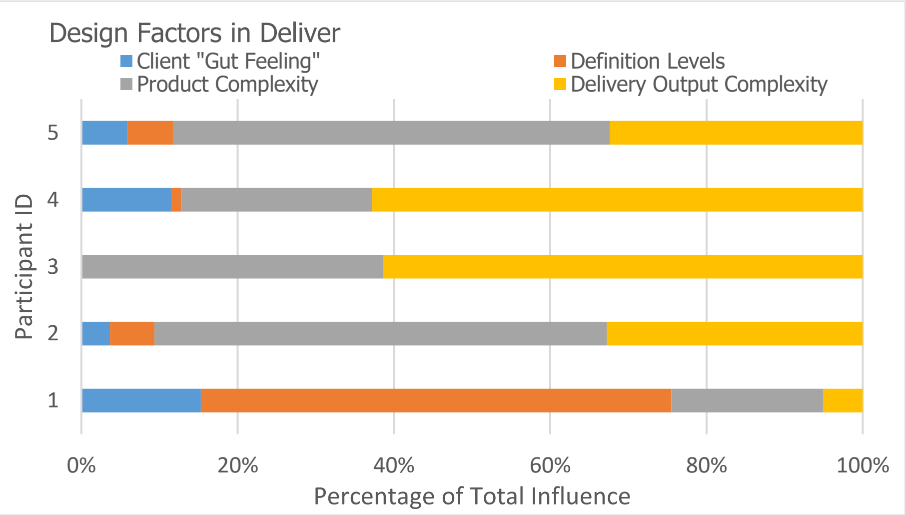


Design Factors in Define



Design Factors in Design

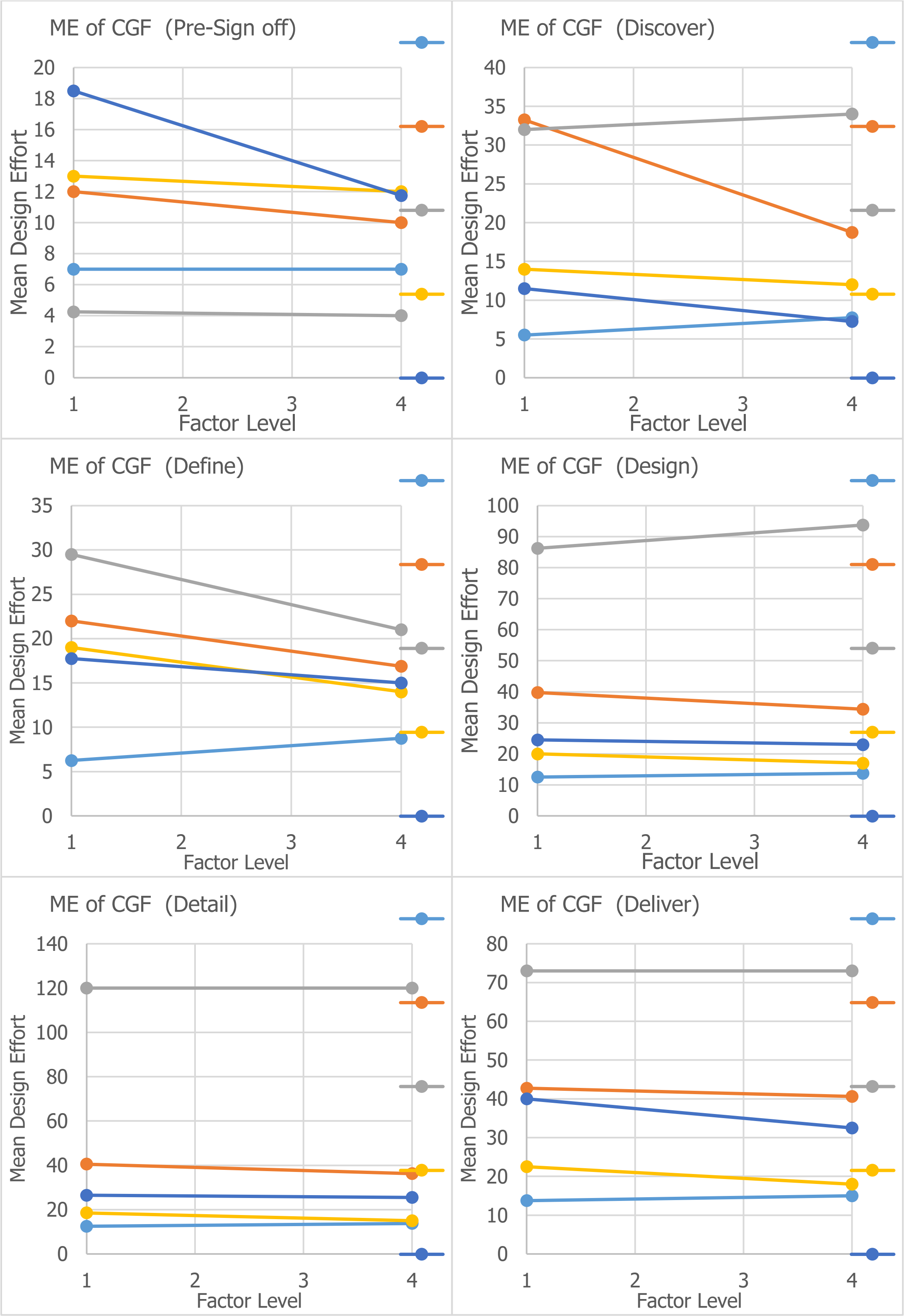

Design Factors in Detail
Client "Gut Feeling"
Definition Levels
Product Complexity
Delivery Output Complexity
Participant ID
5
4
3
2
1
0%
20%
40%
60%
80%
100%
Percentage of Total Influence


Design Factors in Deliver
Client "Gut Feeling"
Definition Levels
Product Complexity
Delivery Output Complexity
Participant ID
5
4
3
2
1
0%
20%
40%
60%
80%
100%
Percentage of Total Influence

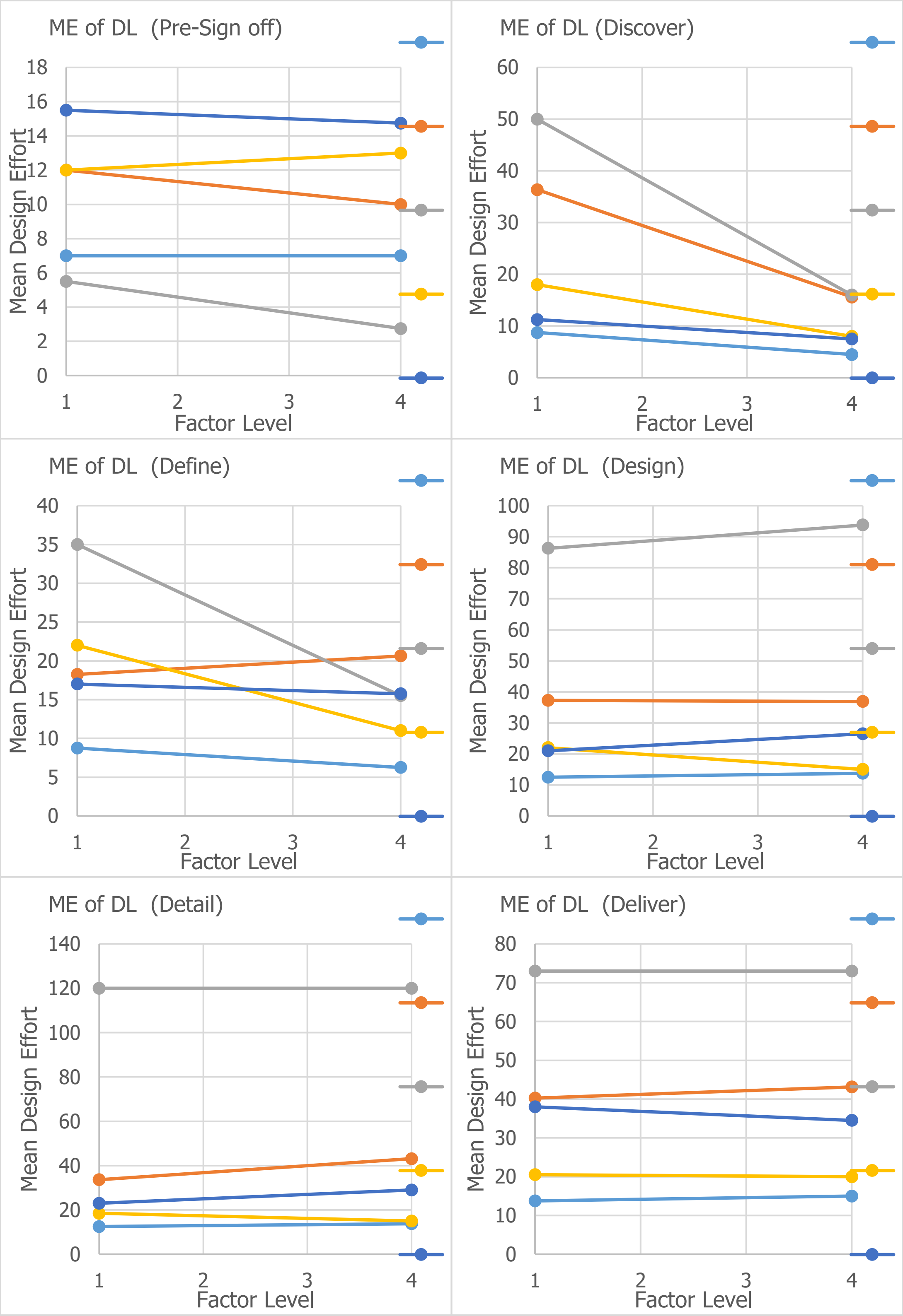
Appendix 5.8 Mean Effect Plot Values [Case Study 2]

		Factor								Participant
		Client "Gut Feeling"		Definition Level (Inputs)		Product Complexity		Delivery Output Complexity		
		1	4	1	4	Simple	Complex	Low	High	
Stage	Pre-Sign Off	1	1	1	1	1	1	1	1	1
		5	2.75	4	3.75	2	5.75	4.5	3.25	2
		4.25	4	5.5	2.75	2.25	6	4	4.25	3
		6.5	5.5	6	6	5	7	4.5	7.5	4
		5.75	5	4.25	6.5	3.5	7.25	5	5.75	5
	Discover	33	46.75	52.5	27.25	27.25	52.5	31.75	48	1
		168	132.5	206.75	93.75	24.25	276.25	155.5	145	2
		32	34	50	16	17	49	27	39	3
		37	40	44	33	55	22	30	47	4
		22.5	20.5	25	18	16.5	26.5	17	26	5
	Define	37.5	52.5	52.5	37.5	37.5	52.5	37.5	52.5	1
		119.875	91.875	100.5	111.25	32.375	179.375	94.25	117.5	2
		29.5	21	35	15.5	10.5	40	16	34.5	3
		80	80	90	70	60	100	70	90	4
		30	31.5	34.5	27	22.5	39	26	35.5	5
	Design	75	82.5	75	82.5	52.5	105	67.5	90	1
		220.25	195	206.5	208.75	54	361.25	207.25	207.25	2
		86.25	93.75	86.25	93.75	52.5	127.5	77.5	102.5	3
		168	170	188	150	98	240	138	200	4
		56	61	58.5	58.5	32	85	50.5	66.5	5
	Detail	75	82.5	75	82.5	52.5	105	67.5	90	1
		219.5	170.625	156.375	233.75	48.25	341.875	162.625	227.5	2
		120	120	120	120	60	180	100	140	3
		102	82	92	92	64	120	74	110	4
		54.5	72	62	64.5	49	77.5	51.5	75	5
	Deliver	82.5	90	82.5	90	60	112.5	75	97.5	1
		203.5	185	179.75	208.75	47.25	341.25	111	277.5	2
		73	73	73	73	56	90	46	100	3
		112	130	122	120	102	140	72	170	4
		34	38	34	38	17	55	25	47	5

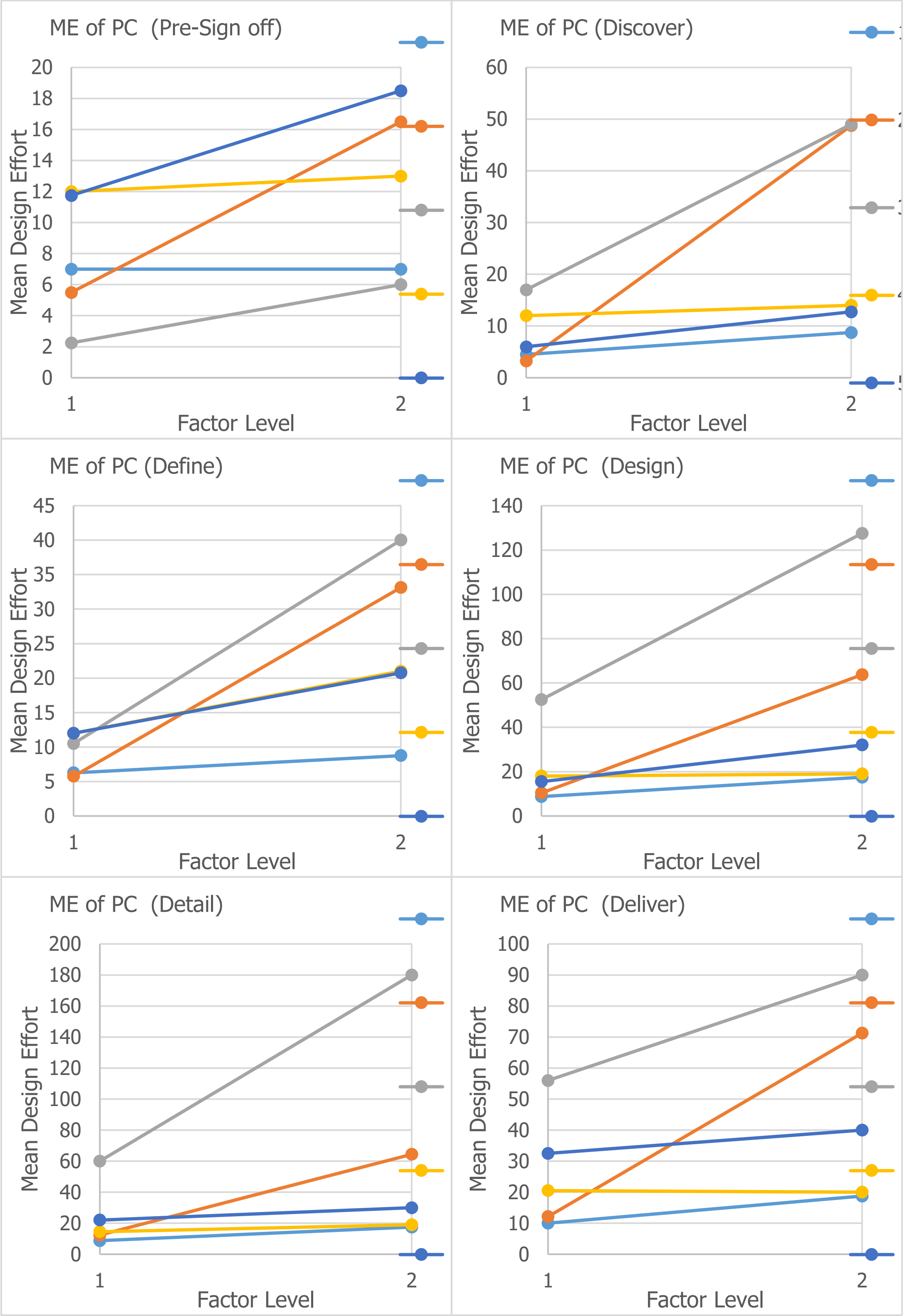
Management Design Effort influenced by Client “Gut Feel” Factor



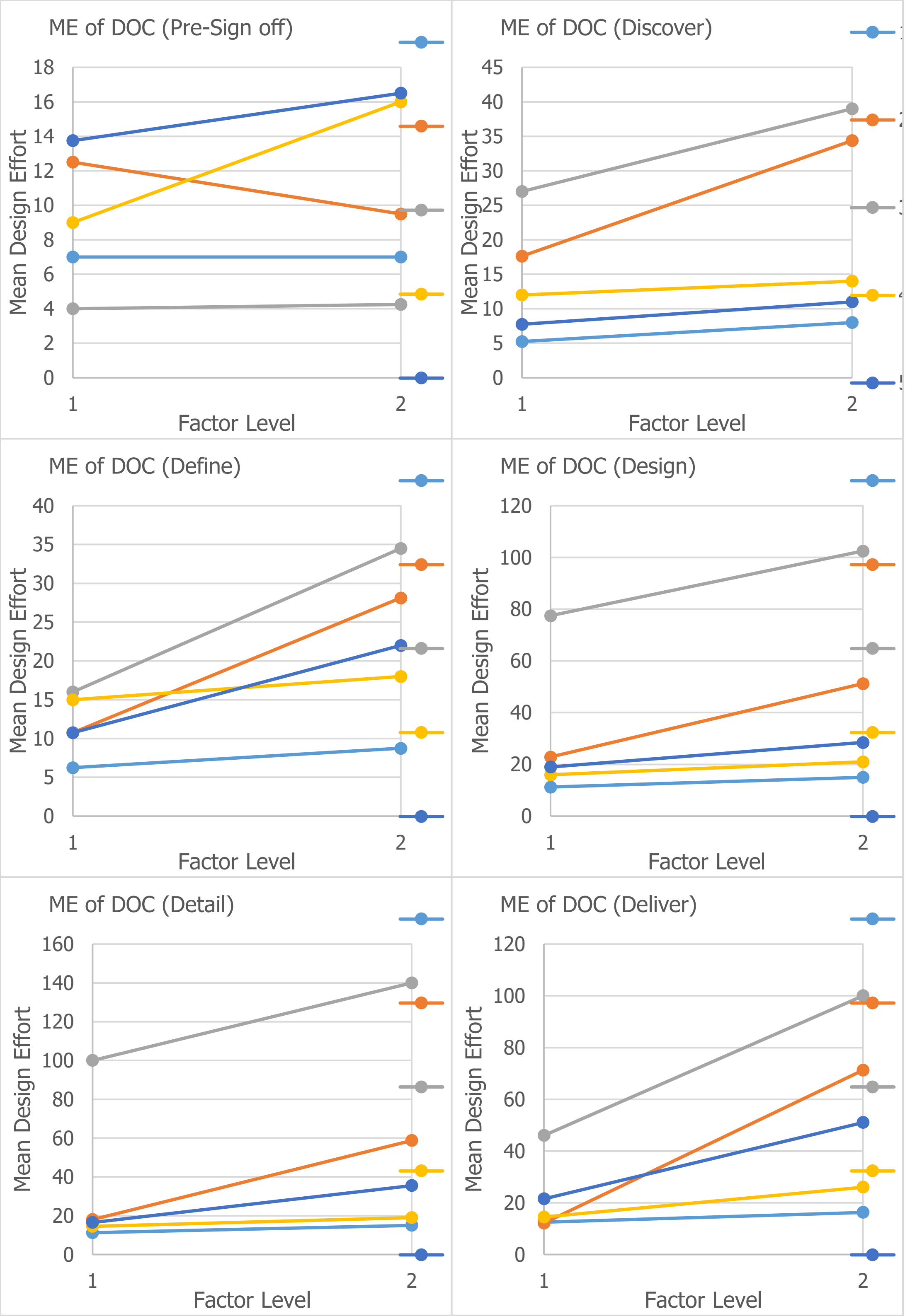
Management Design Effort influenced by Definition Levels Factor



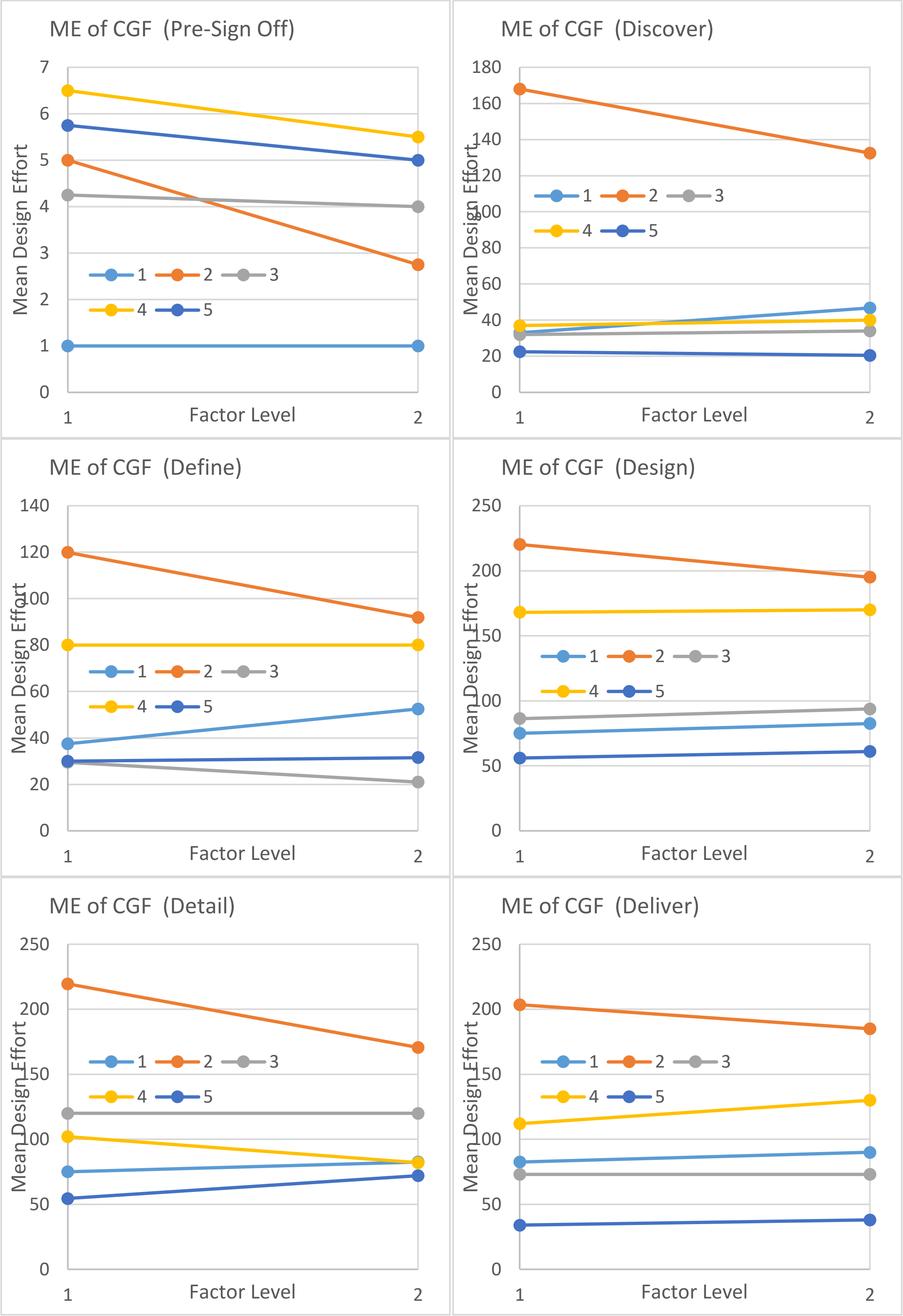
Management Design Effort influenced by Product Complexity Factor



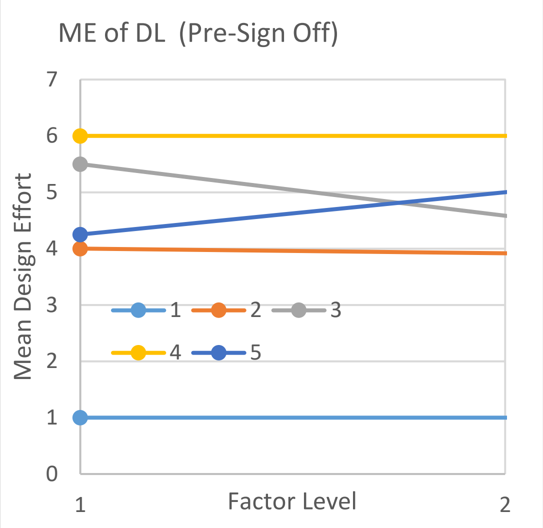
Management Design Effort influenced by Delivery Output Complexity Factor

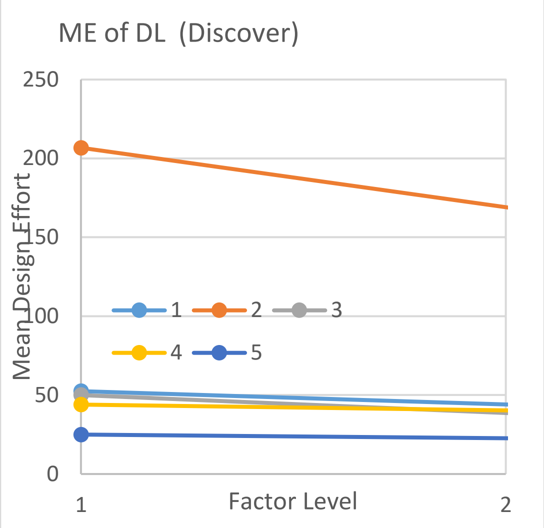


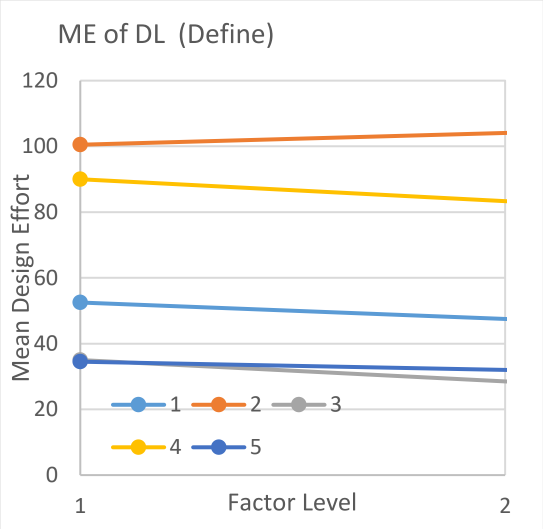
Design Activity Design Effort influenced by Client “Gut Feel” Factor



Design Activity Design Effort influenced by Definition Level (Inputs) Factor


ME of DL (Pre-Sign Off)


ME of DL (Discover)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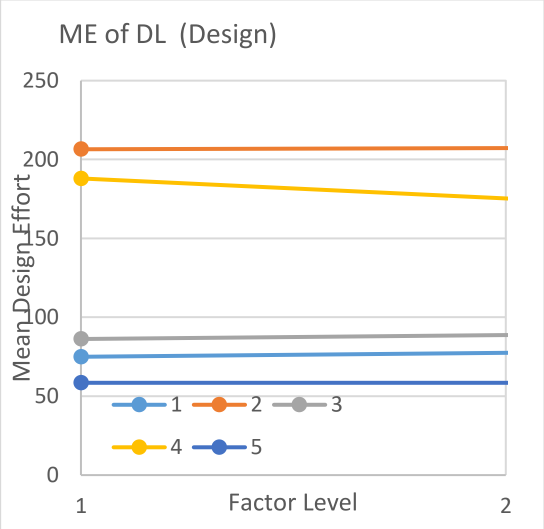
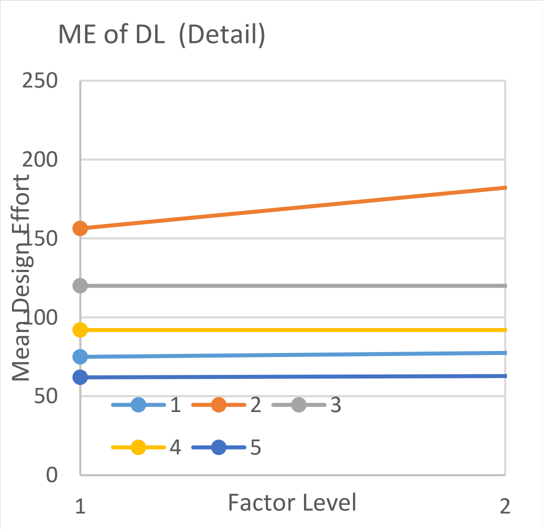
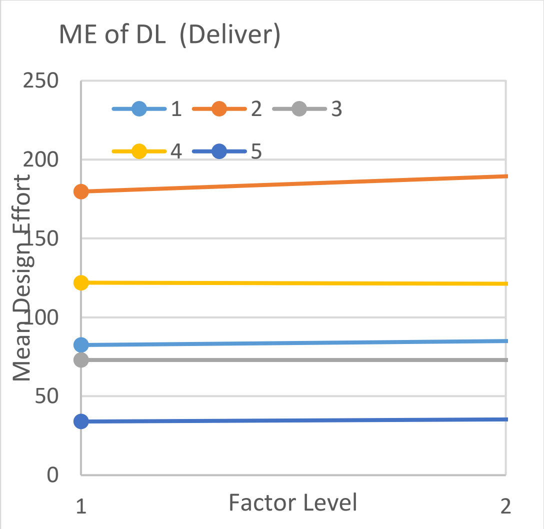
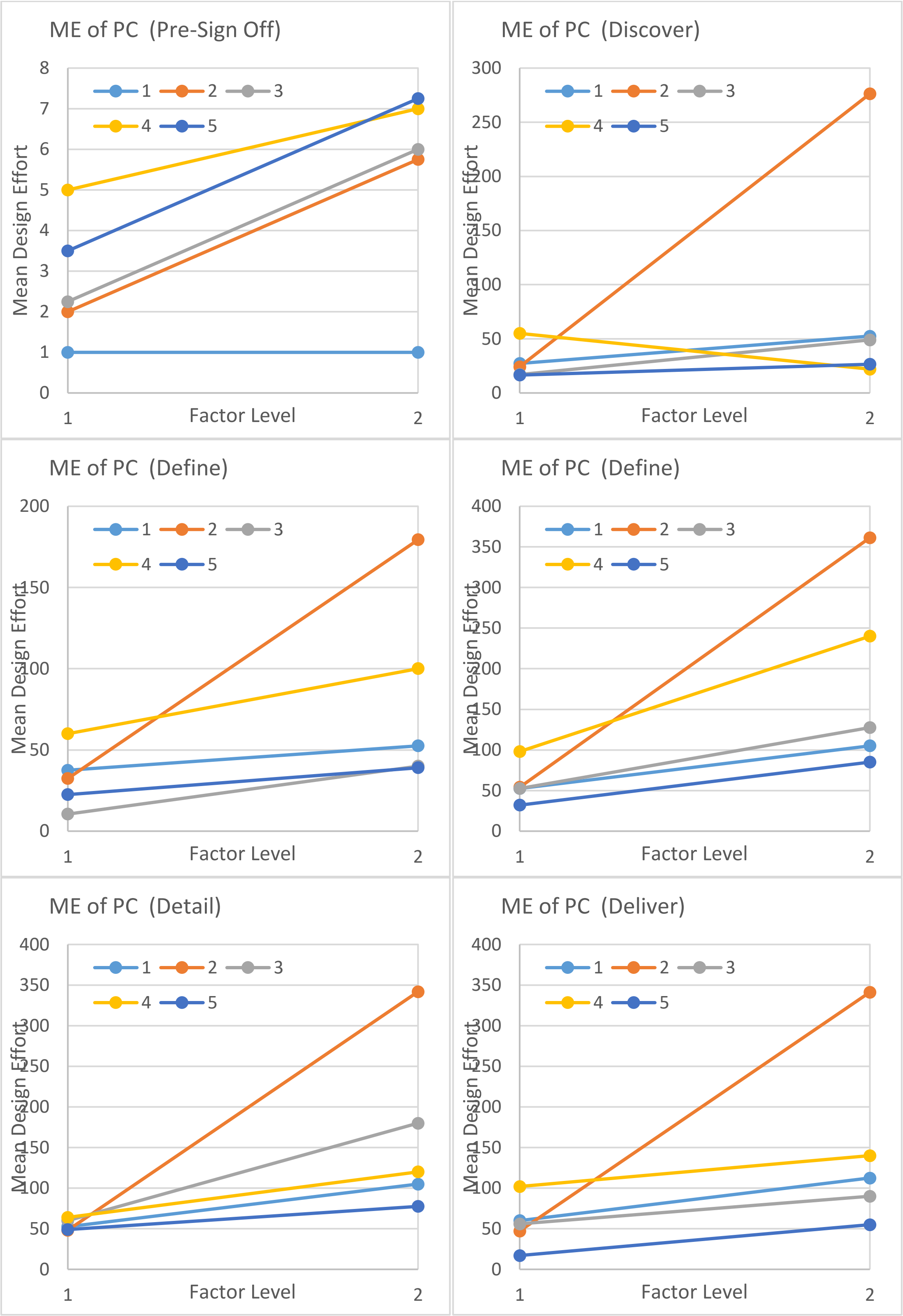

ME of DL (Design)

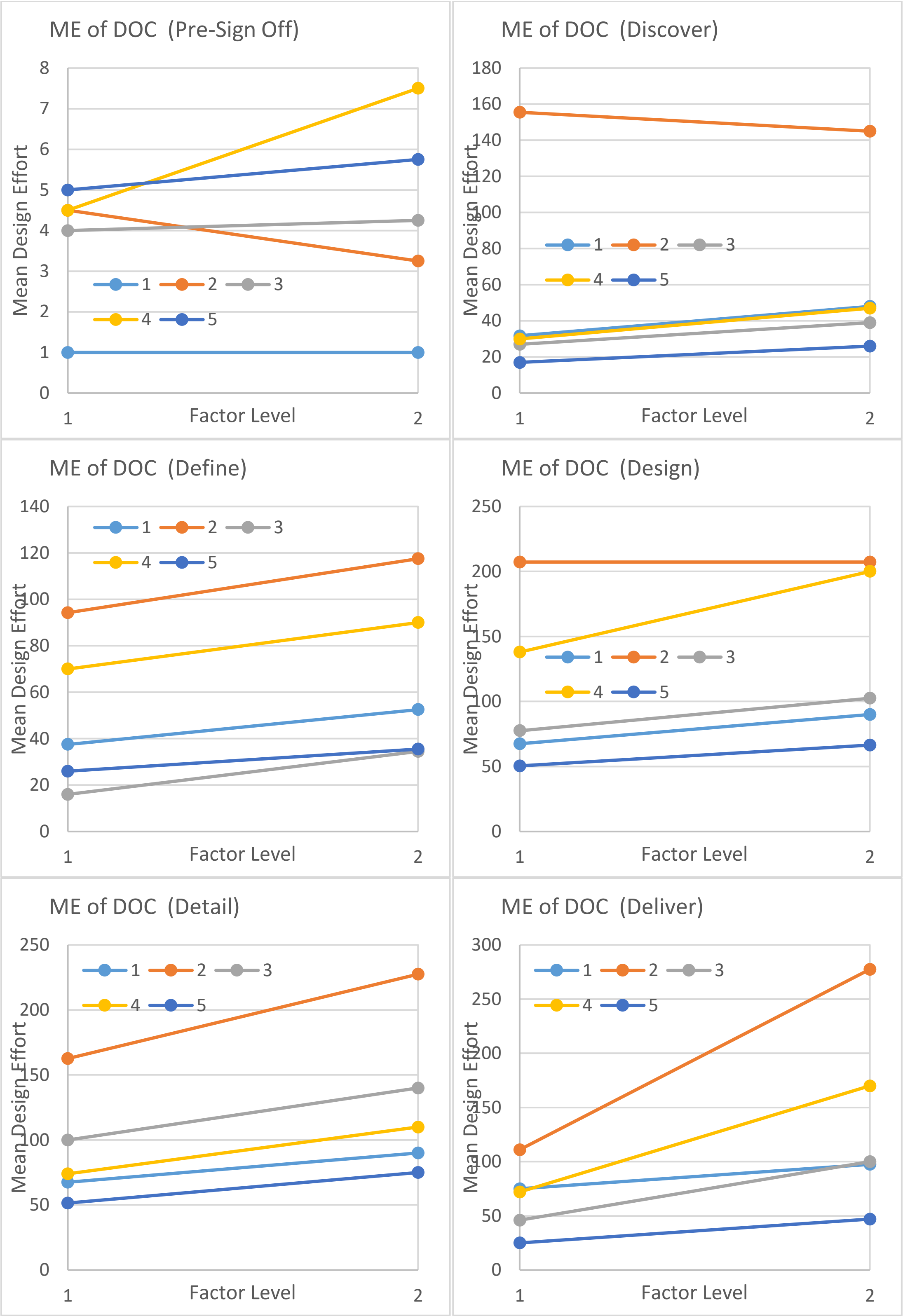

ME of DL (Detail)


ME of DL (Deliver)

Design Activity Design Effort influenced by Product Complexity Factor

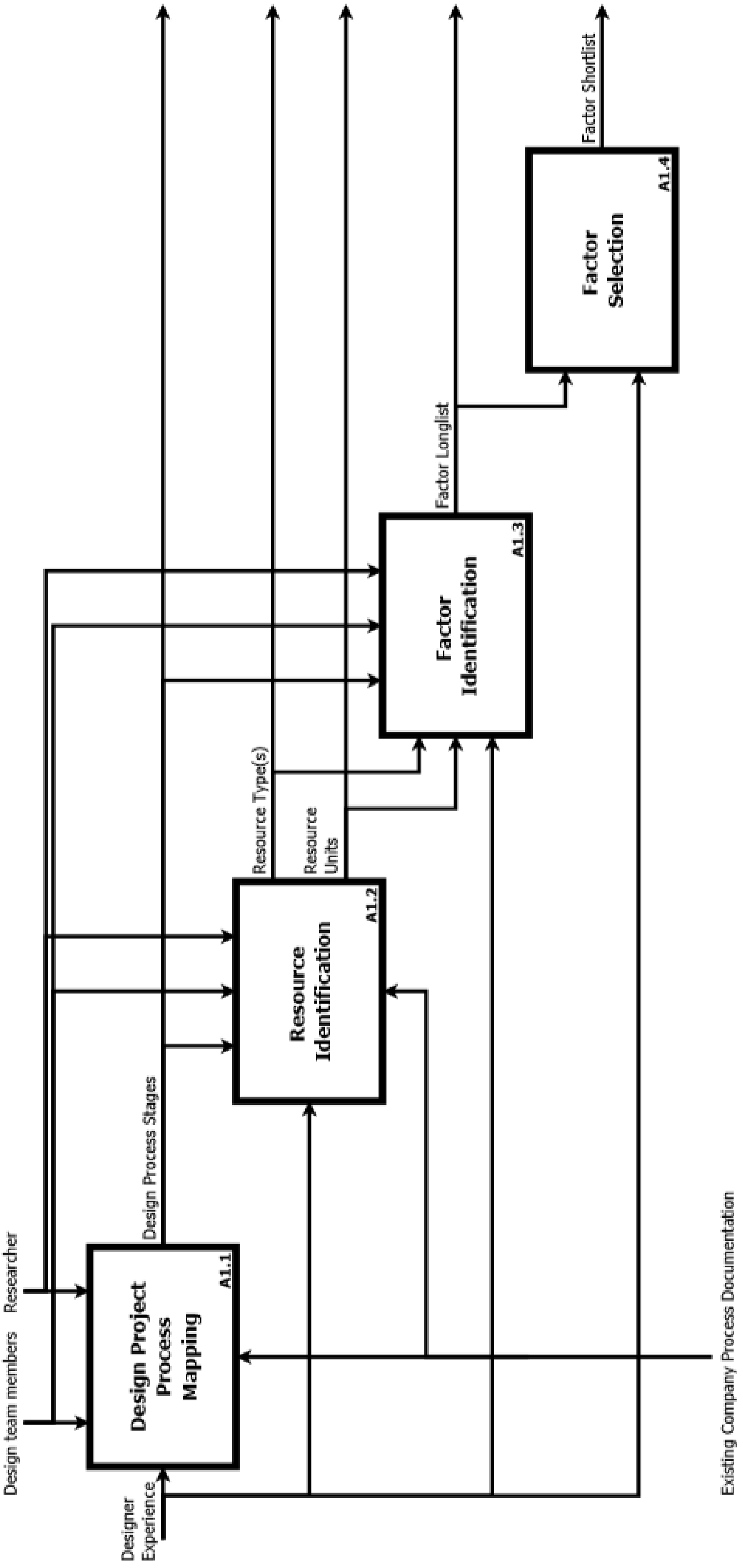


Design Activity Design Effort influenced by Delivery Output Complexity Factor

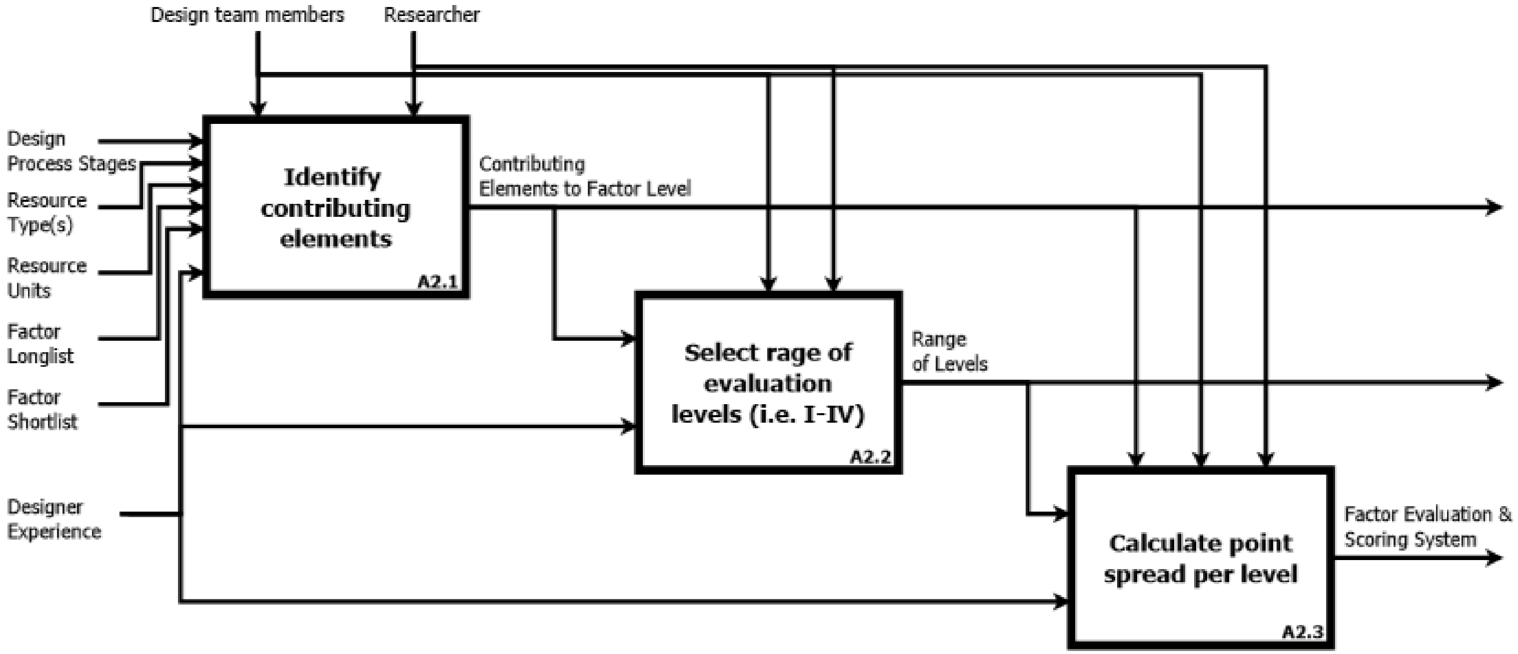


Case Study 3 Appendices

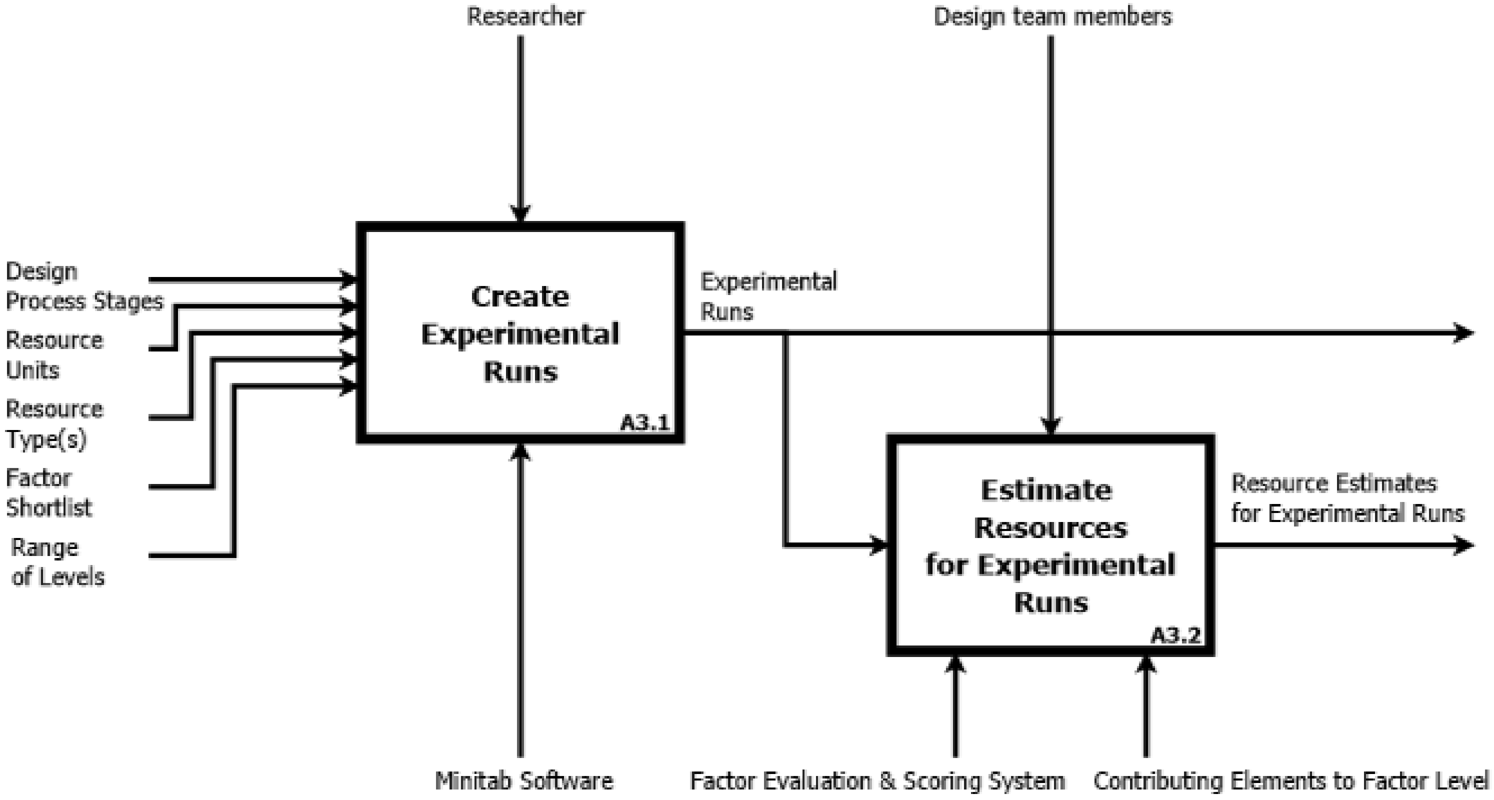
Appendix 6.1 Case Study 3: Approach - Design Process & Factor Identification IDEF0 Model



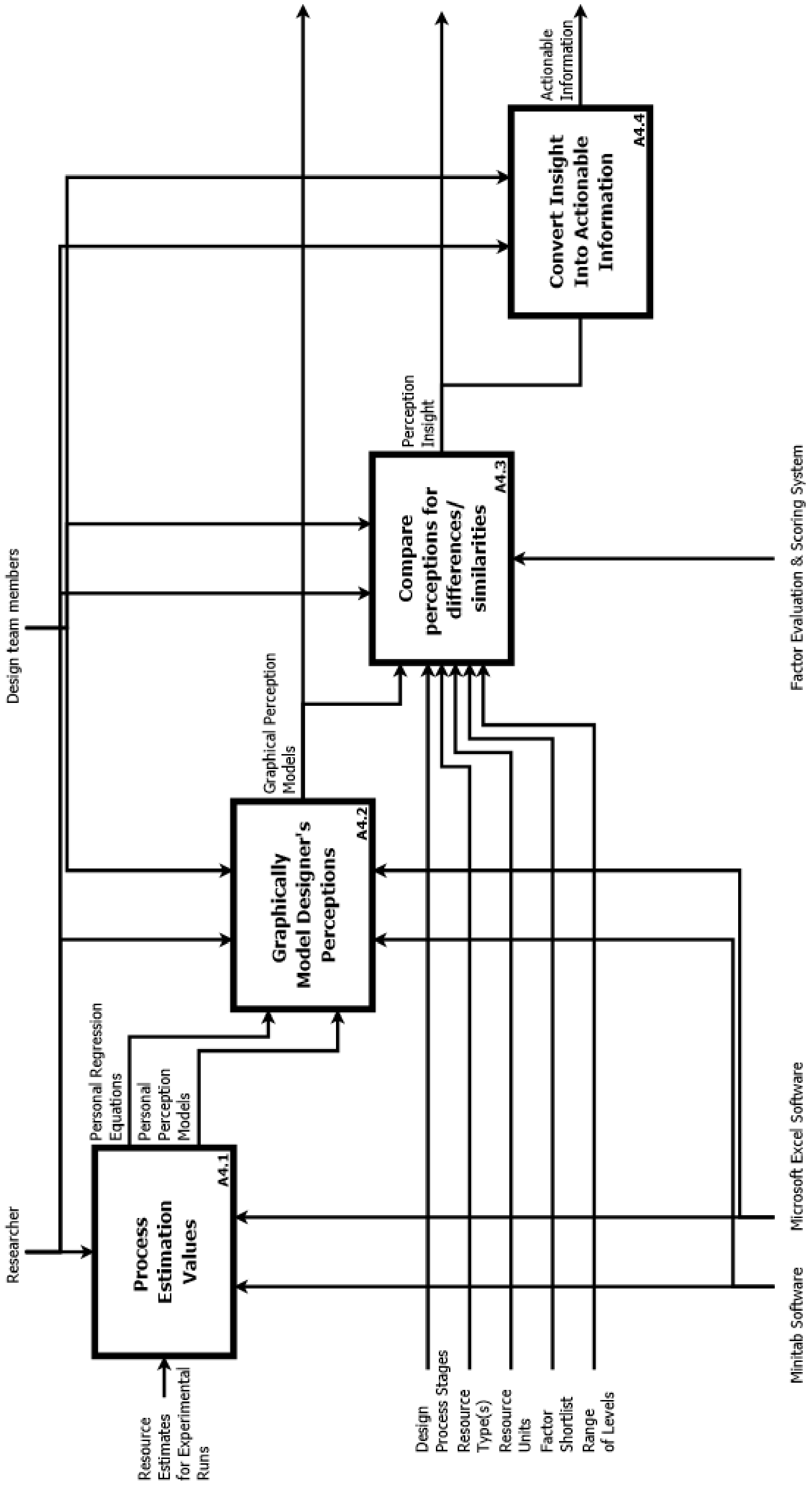
Appendix 6.2 Case Study 3: Approach - Create Factor Evaluation Scoring System IDEF0 Model



Appendix 6.3 Case Study 3: Approach - Collect Estimates IDEF0 Model



Appendix 6.4 - Case Study 3: Approach - Compare Perceptions for Difference / Similarities IDEF0 Model



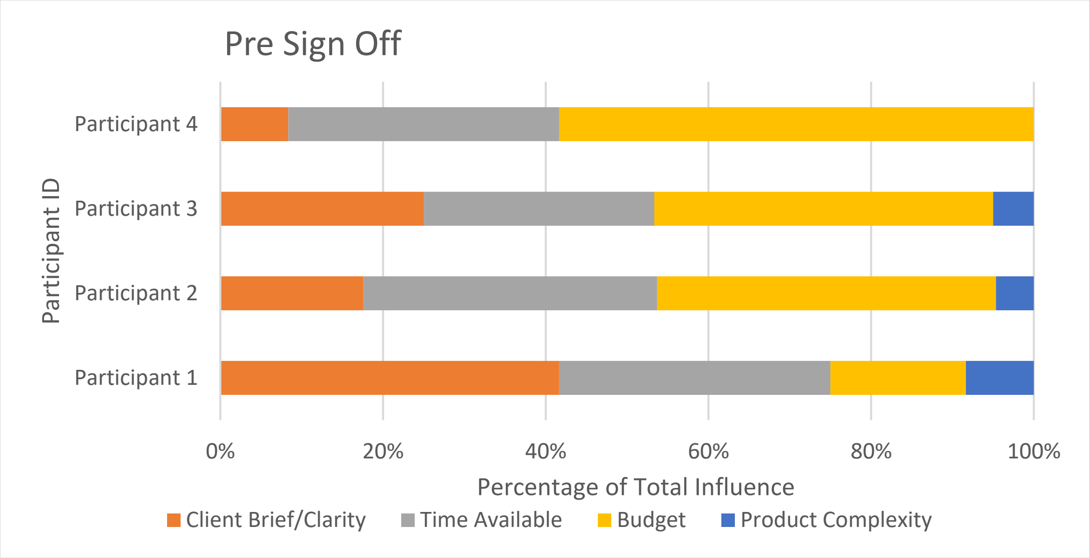
Appendix 6.5 Workshop 2 Estimation Values [Case Study 3]

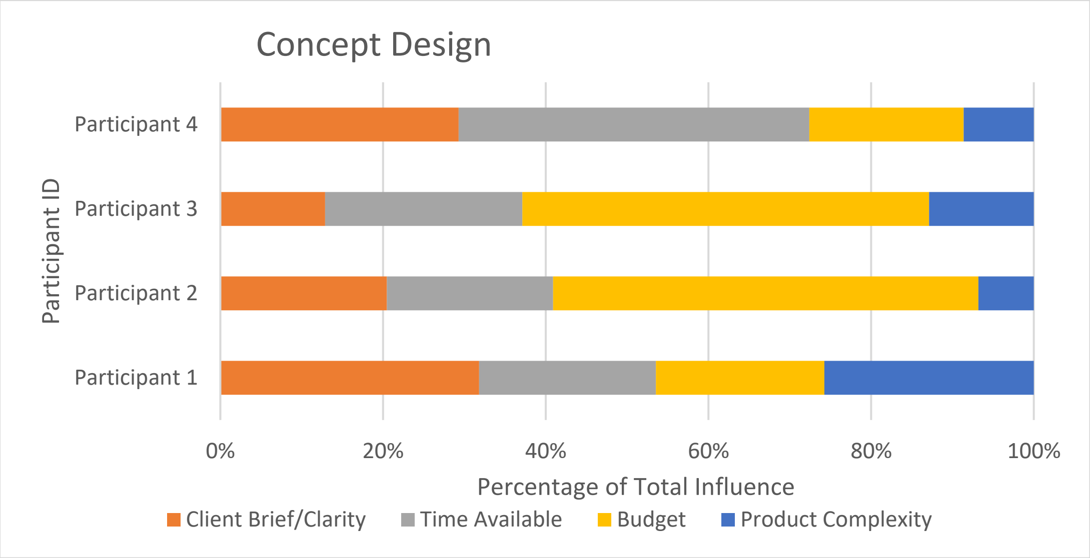
Participant	**Run**	**Pre Sign Off**	**Concept Design**	**Technical Draft**	**Prototyping**	**Final Build**	**Participant**	**Run**	**Pre Sign Off**	**Concept Design**	**Technical Draft**	**Prototyping**	**Final Build**
1	1	2	15	5	10	30	3	1	0.5	0	0	0	1
	2	2	15	5	8	15		2	3	5	3	3	40
	3	0.5	1	1	0	2		3	0	0.5	1	1	3.5
	4	0.5	3	1	0	8		4	0.5	0.5	1	1	12
	5	1	1	0.5	0	8		5	0.5	0.5	1	1	10
	6	3	15	5	5	70		6	8	7	4	4	68
	7	1	10	5	3	30		7	3	7	7	7	12
	8	0	0.5	1	0	10		8	0	0	0.5	0.5	6
2	1	1	0	0	1	0	4	1	0	5	0	5	0
	2	3	7	6	4	14		2	3	3	3	2	15
	3	0.5	0.5	0.5	1	1		3	0.5	0	0	0	3
	4	0.5	0.5	0.5	0	2		4	2	1	2	1	10
	5	0.5	0.5	0.5	0	2		5	2	2	2	0.5	7
	6	14	10	14	4	30		6	5	7	7	3	70
	7	8	7	5	0	19		7	3	3	4	3	50
	8	0	0.5	0	0	10		8	0.5	0.5	0.5	0	10

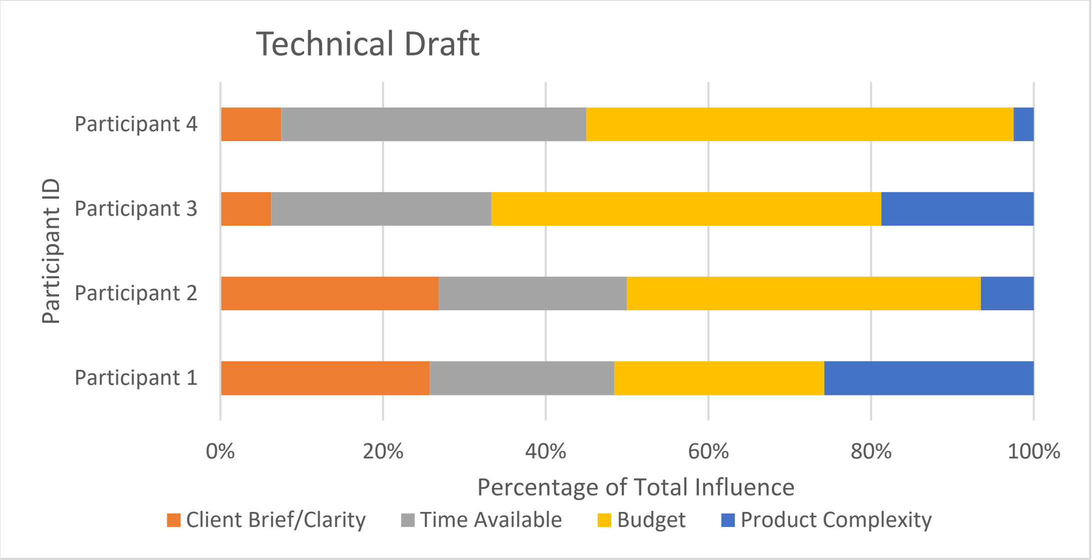
Appendix 6.6 Regression Values [Case Study 3]

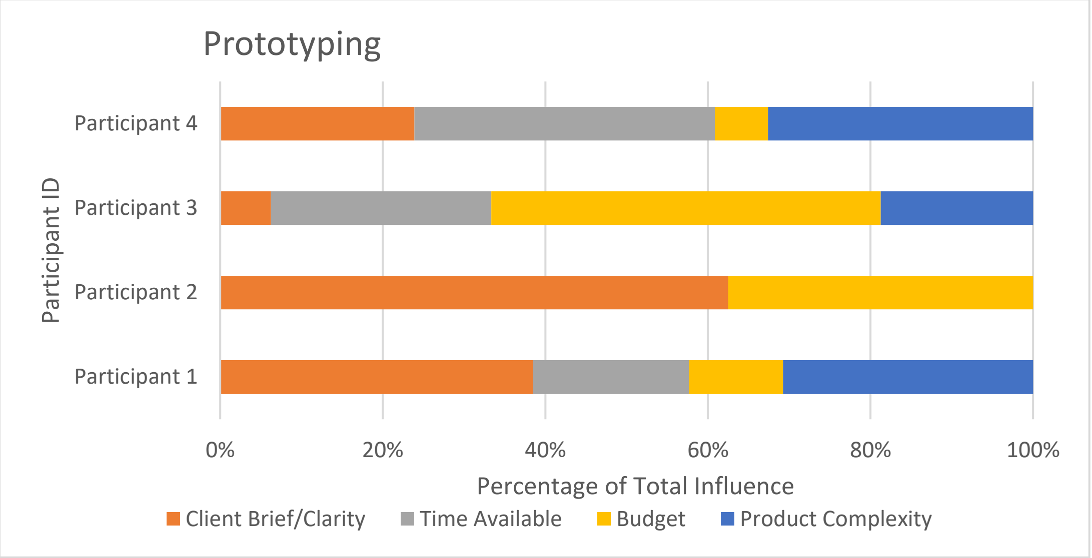
P	Value	Pre Sign Off	Concept Design	Technical Draft	Prototyping	Final Build
1	Coefft	1.25	7.5625	2.9375	3.25	21.625
	A	0.625	3.9375	1.0625	2.5	7.625
	B	0.5	2.6875	0.9375	1.25	12.875
	C	-0.25	-2.5625	-1.0625	-0.75	-9.625
	D	0.125	3.1875	1.0625	2	-0.875
	AB	0.125	0.8125	0.0625	0.5	7.875
	AC	-0.375	-0.9375	0.0625	3.4787E-16	-3.625
	AD	9.1793E-17	0.3125	-0.0625	1.25	-5.875
2	Coefft	3.4375	3.25	3.3125	1.25	9.75
	A	1.1875	1.125	1.8125	1.25	1.5
	B	2.4375	1.125	1.5625	-3.656E-17	3
	C	-2.8125	-2.875	-2.9375	-0.75	-8.5
	D	-0.3125	0.375	-0.4375	-1.288E-16	-1
	AB	0.4375	-0.5	0.3125	7.7922E-17	0.75
	AC	-1.0625	-1.25	-1.9375	-0.75	-2.25
	AD	-2.3125	-1.25	-1.6875	-9.652E-17	-3.25
3	Coefft	1.9375	2.5625	2.1875	2.1875	19.0625
	A	0.9375	0.5625	-0.1875	-0.1875	9.0625
	B	1.0625	1.0625	0.8125	0.8125	3.6875
	C	-1.5625	-2.1875	-1.4375	-1.4375	-12.4375
	D	-0.1875	0.5625	0.5625	0.5625	-2.8125
	AB	0.3125	-0.6875	-0.8125	-0.8125	2.6875
	AC	-1.0625	-0.6875	-0.0625	-0.0625	-13.4375
	AD	-0.9375	-1.1875	-1.0625	-1.0625	-4.8125
4	Coefft	2	2.6875	2.3125	1.8125	20.625
	A	0.125	1.0625	0.1875	0.6875	1.375
	B	0.5	1.5625	0.9375	1.0625	11.125
	C	-0.875	-0.6875	-1.3125	-0.1875	-15.625
	D	0	0.3125	-0.0625	0.9375	-1.875
	AB	-0.125	0.6875	0.0625	0.4375	1.875
	AC	-1	-0.5625	-1.1875	0.1875	-4.875
	AD	-0.625	-0.0625	-0.9375	0.0625	-12.625

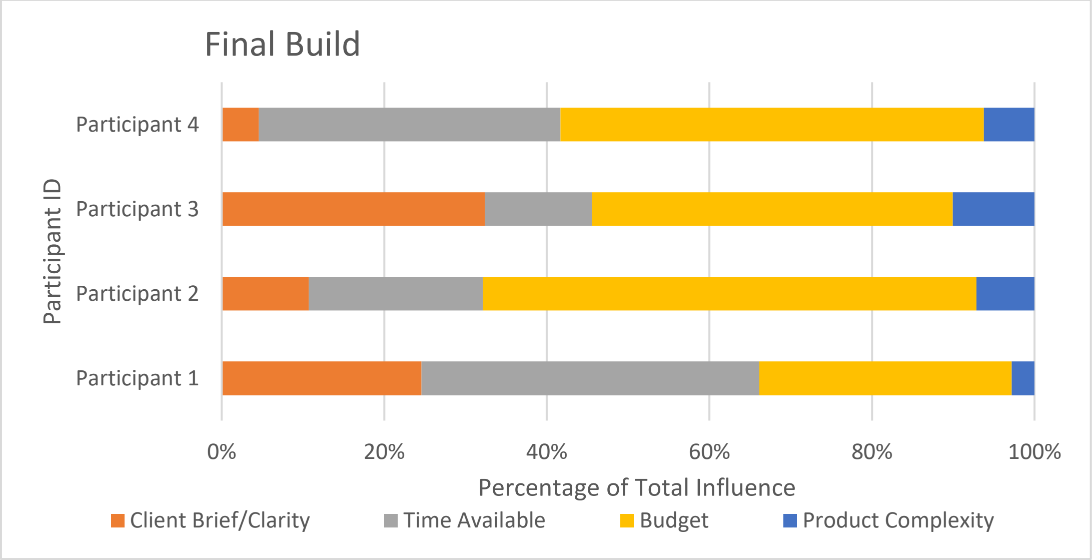
Appendix 6.7 Percentage Influence Graphs [Case Study 3]






Technical Draft
Participant 4
Participant 3
Participant 2
Participant 1
Participant ID
0%
20%
40%
60%
80%
100%
Percentage of Total Influence
Client Brief/Clarity
Time Available
Budget
Product Complexity

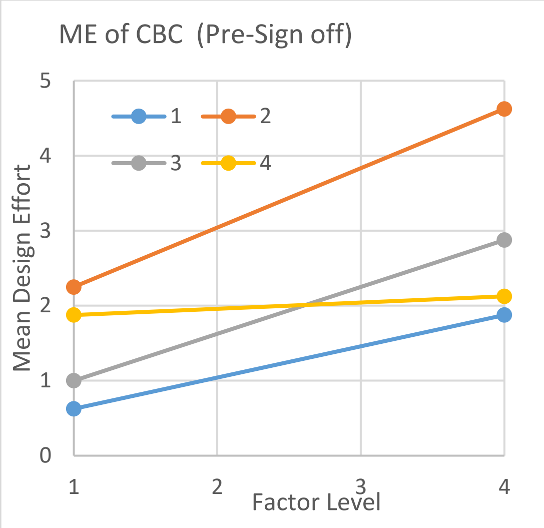

Prototyping
Participant 4
Participant 3
Participant 2
Participant 1
Participant ID
0%
20%
40%
60%
80%
100%
Percentage of Total Influence
Client Brief/Clarity
Time Available
Budget
Product Complexity

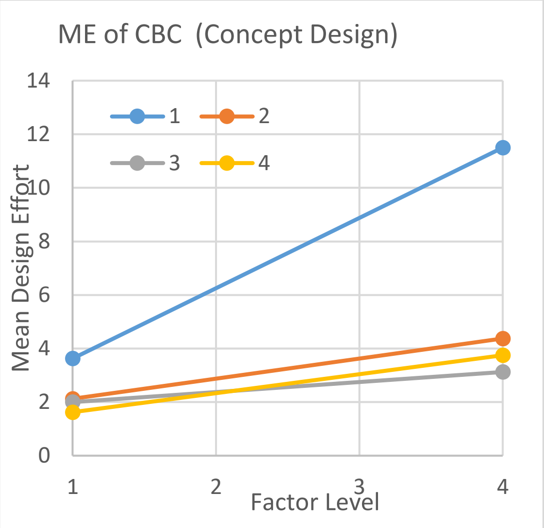

Final Build
Participant 4
Participant 3
Participant 2
Participant 1
Participant ID
0%
20%
40%
60%
80%
100%
Percentage of Total Influence
Client Brief/Clarity
Time Available
Budget
Product Complexity

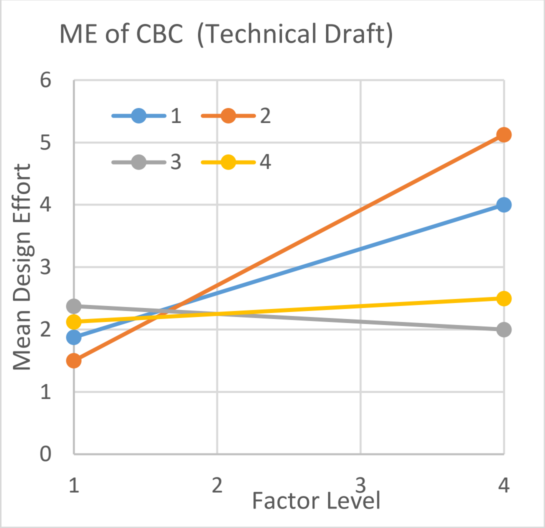
Appendix 6.8 Workshop 4 Mean Effect Values [Case Study 3]

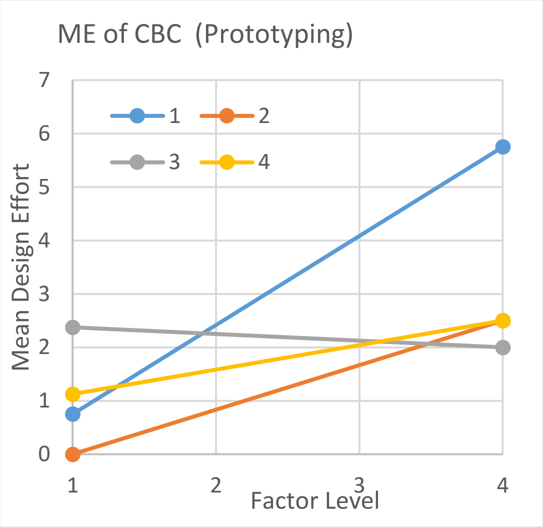
	Client Brief/Clarity		**Time Available**		**Budget**		**Product Complexity**		**P**
Stage	**1**	**4**	**1**	**4**	**1**	**4**	**1**	**4**	
Pre Sign-Off	0.625	1.875	0.75	1.75	1.5	1	1.125	1.375	**1**
	2.25	4.625	1	5.875	6.25	0.625	3.75	3.125	**2**
	1	2.875	0.875	3	3.5	0.375	2.125	1.75	**3**
	1.875	2.125	1.5	2.5	2.875	1.125	2	2	**4**
Concept Design	3.625	11.5	4.875	10.25	10.13	5	4.375	10.75	**1**
	2.125	4.375	2.125	4.375	6.125	0.375	2.875	3.625	**2**
	2	3.125	1.5	3.625	4.75	0.375	2	3.125	**3**
	1.625	3.75	1.125	4.25	3.375	2	2.375	3	**4**
Technical Draft	1.875	4	2	3.875	4	1.875	1.875	4	**1**
	1.5	5.125	1.75	4.875	6.25	0.375	3.75	2.875	**2**
	2.375	2	1.375	3	3.625	0.75	1.625	2.75	**3**
	2.125	2.5	1.375	3.25	3.625	1	2.375	2.25	**4**
Prototyping	0.75	5.75	2	4.5	4	2.5	1.25	5.25	**1**
	0	2.5	1.25	1.25	2	0.5	1.25	1.25	**2**
	2.375	2	1.375	3	3.625	0.75	1.625	2.75	**3**
	1.125	2.5	0.75	2.875	2	1.625	0.875	2.75	**4**
Final Build	14	29.25	8.75	34.5	31.25	12	22.5	20.75	**1**
	8.25	11.25	6.75	12.75	18.25	1.25	10.75	8.75	**2**
	10	28.13	15.38	22.75	31.5	6.625	21.88	16.25	**3**
	19.25	22	9.5	31.75	36.25	5	22.5	18.75	**4**

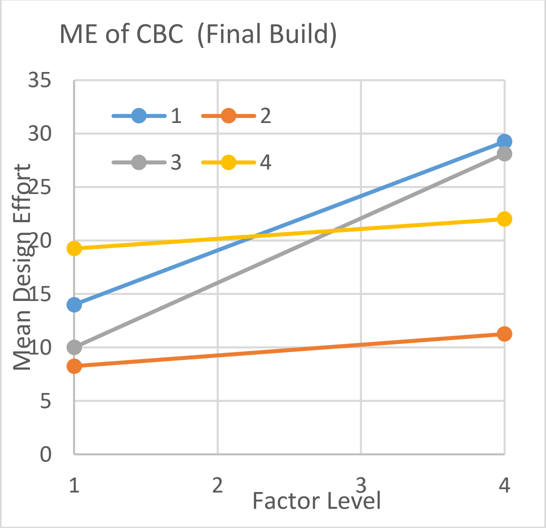
Client / Brief Clarity Mean Effect Plots



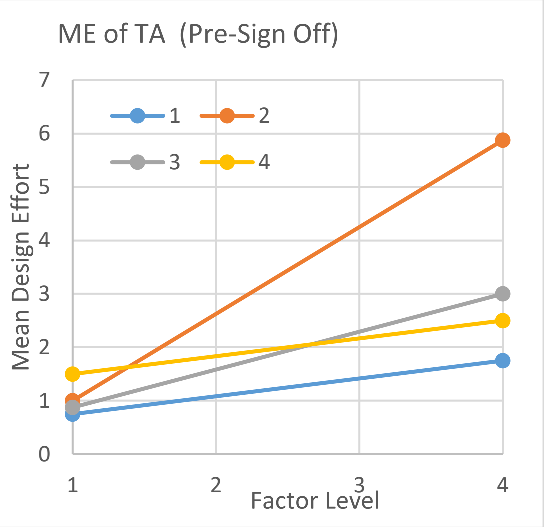


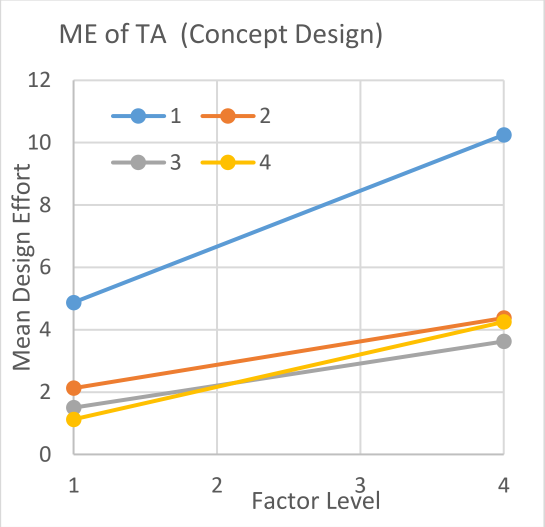






Time Available Mean Effect Plots


ME of TA (Pre-Sign Off)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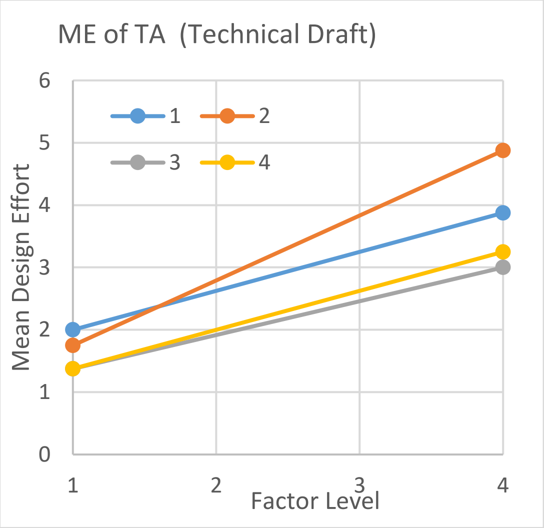
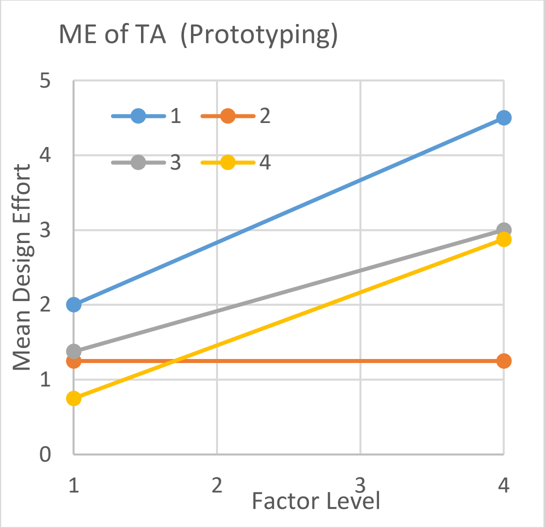
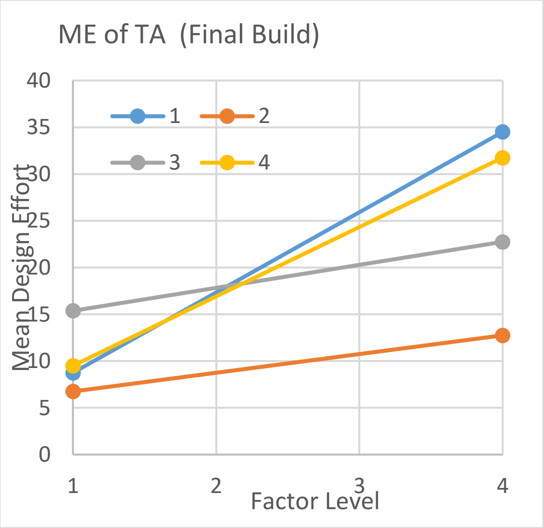
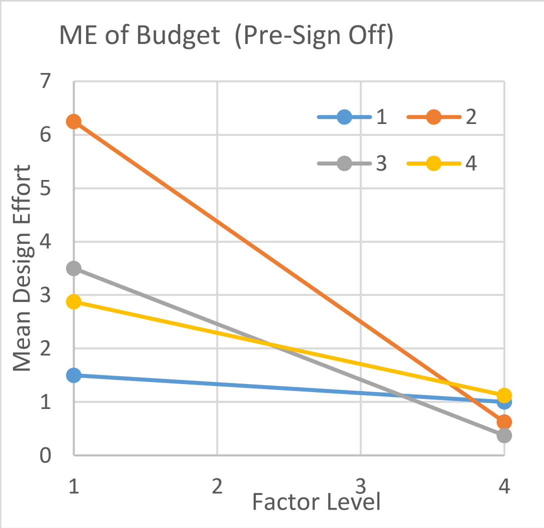
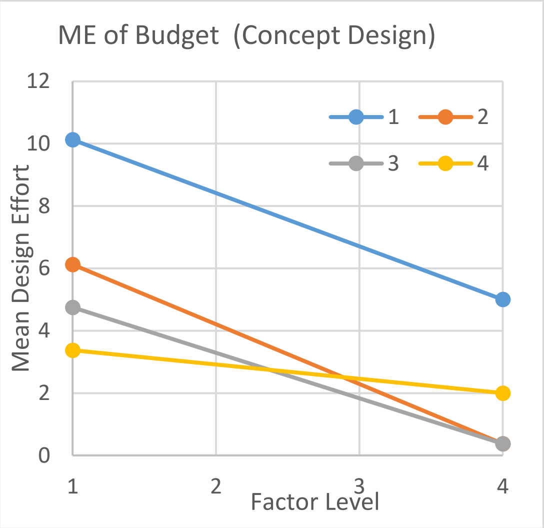

ME of TA (Technical Draft)

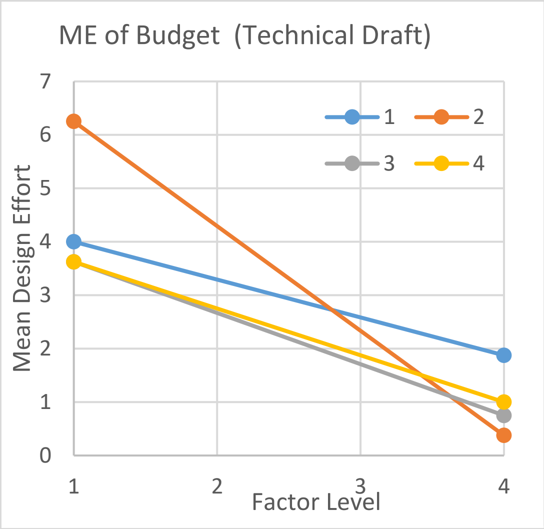

ME of TA (Prototyping)

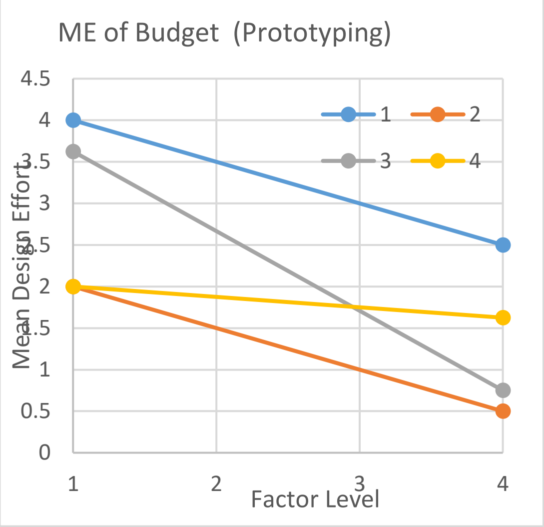

ME of TA (Final Build)

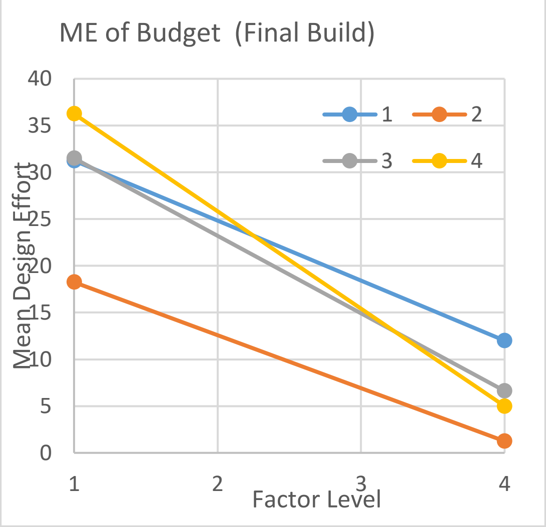
Budget Mean Effect Plots



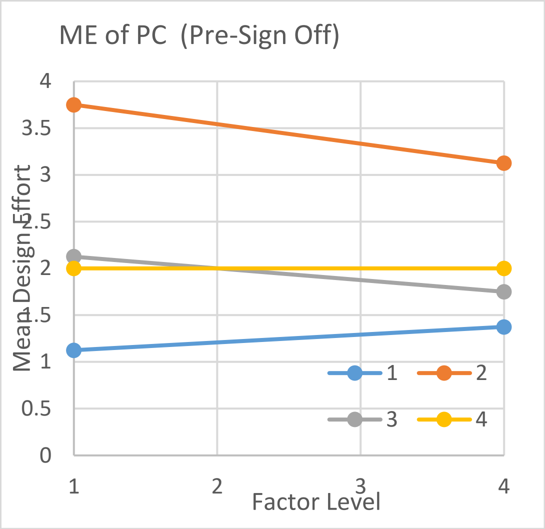


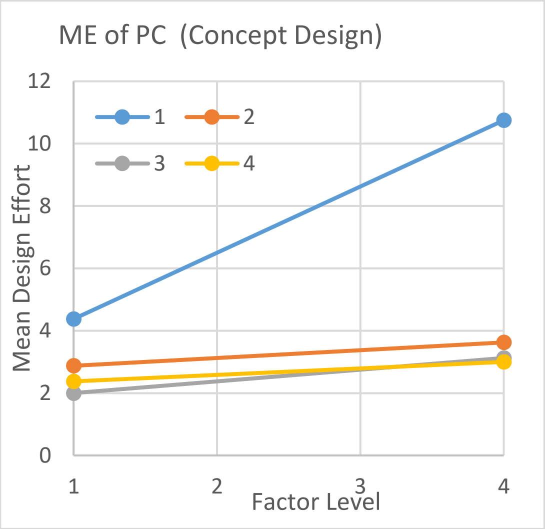


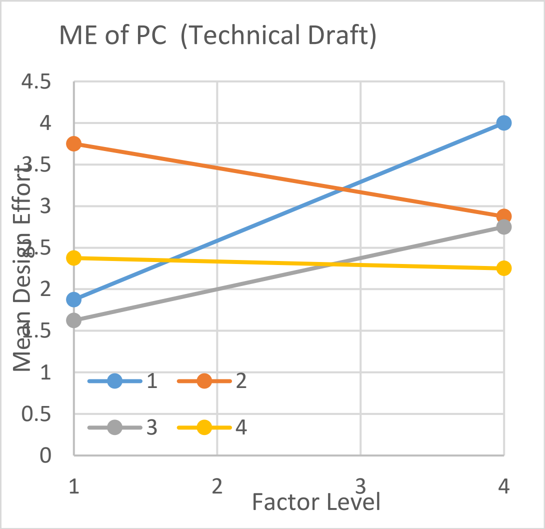


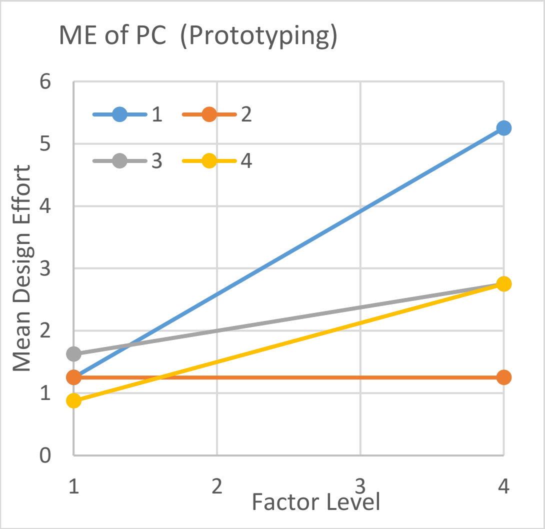


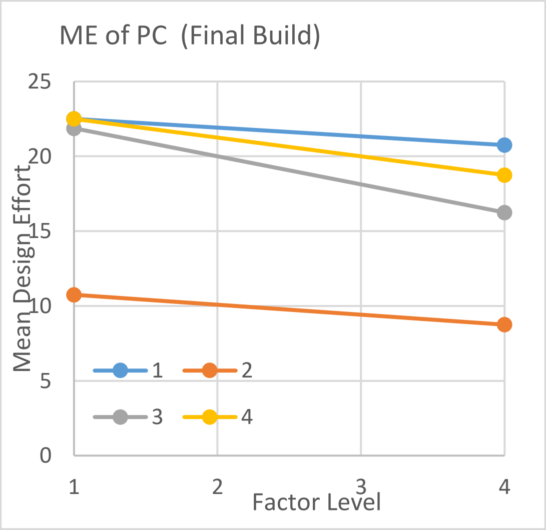
Product Complexity Mean Effect Plots











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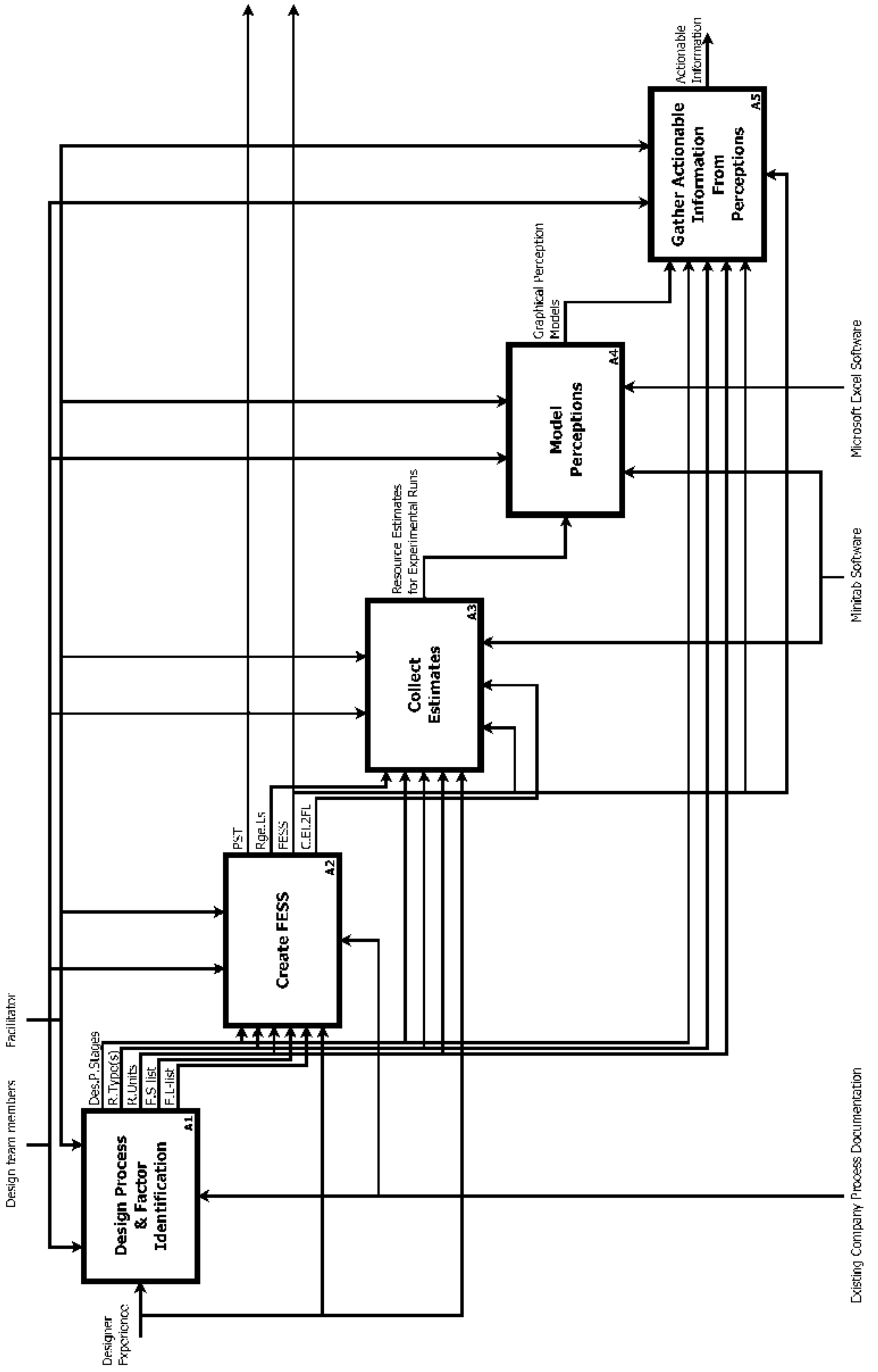
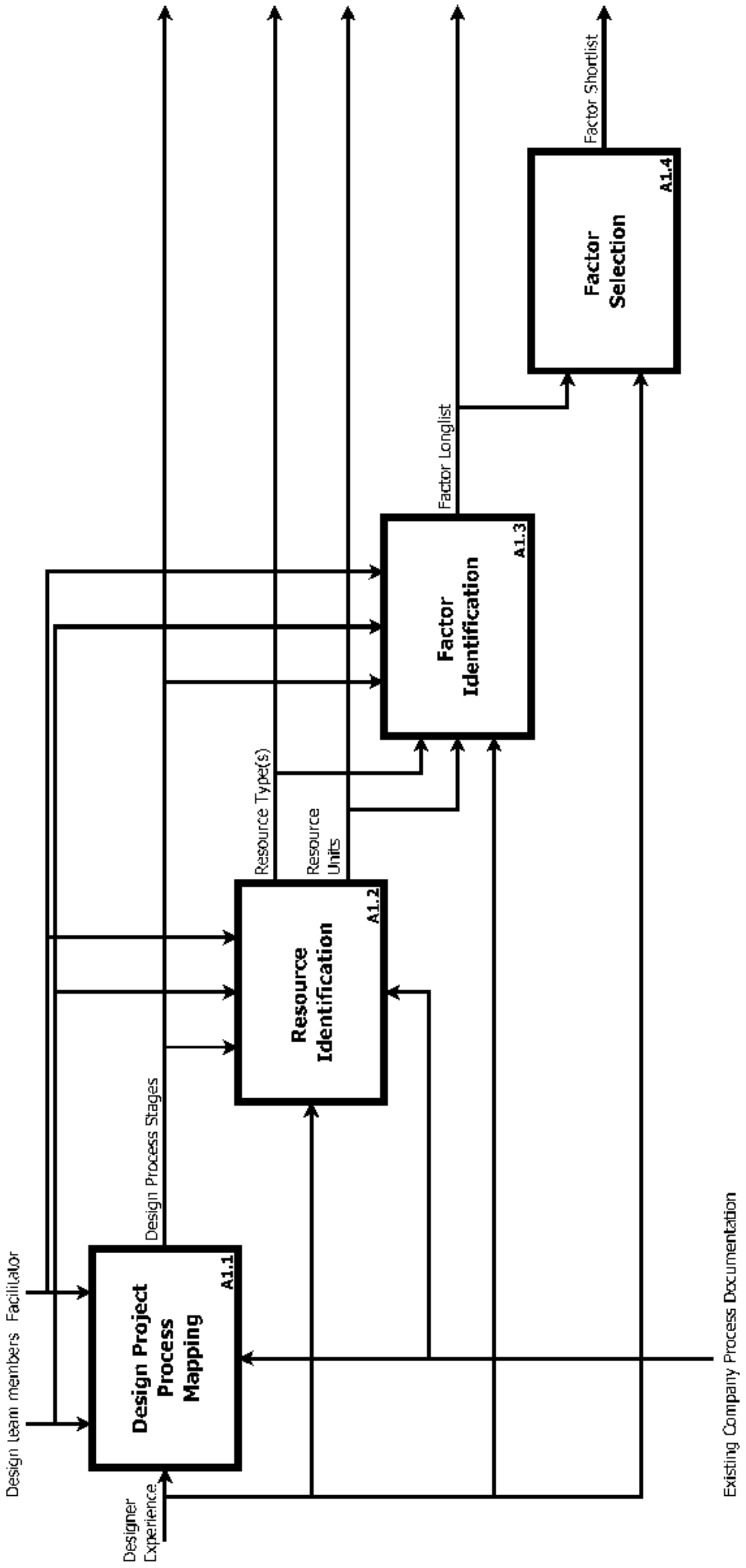
CoFIDE: Appendices

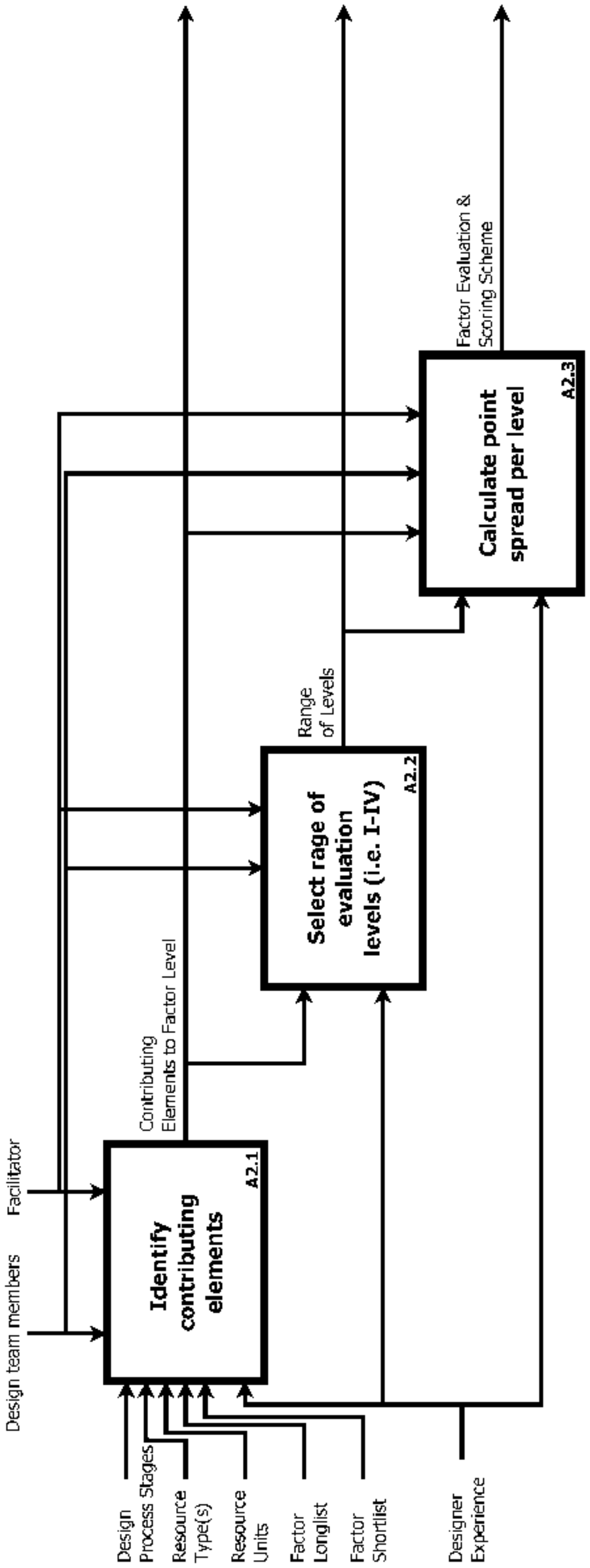
Appendix 10.1 CoFIDE Method IDEF0 Model



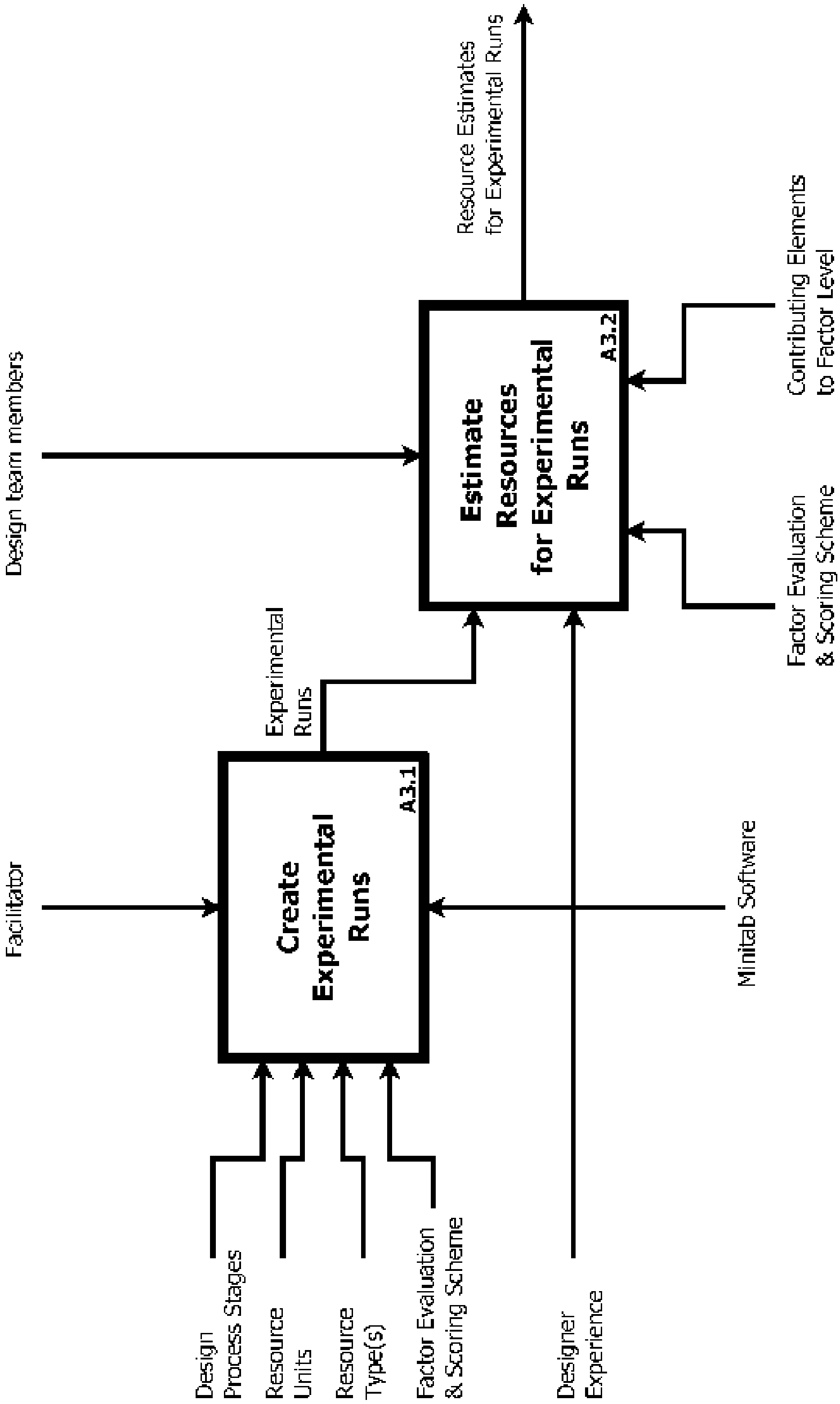
[1] Collaborative Factor Identification for Design Effort (CoFIDE) Method IDEF0 Diagram



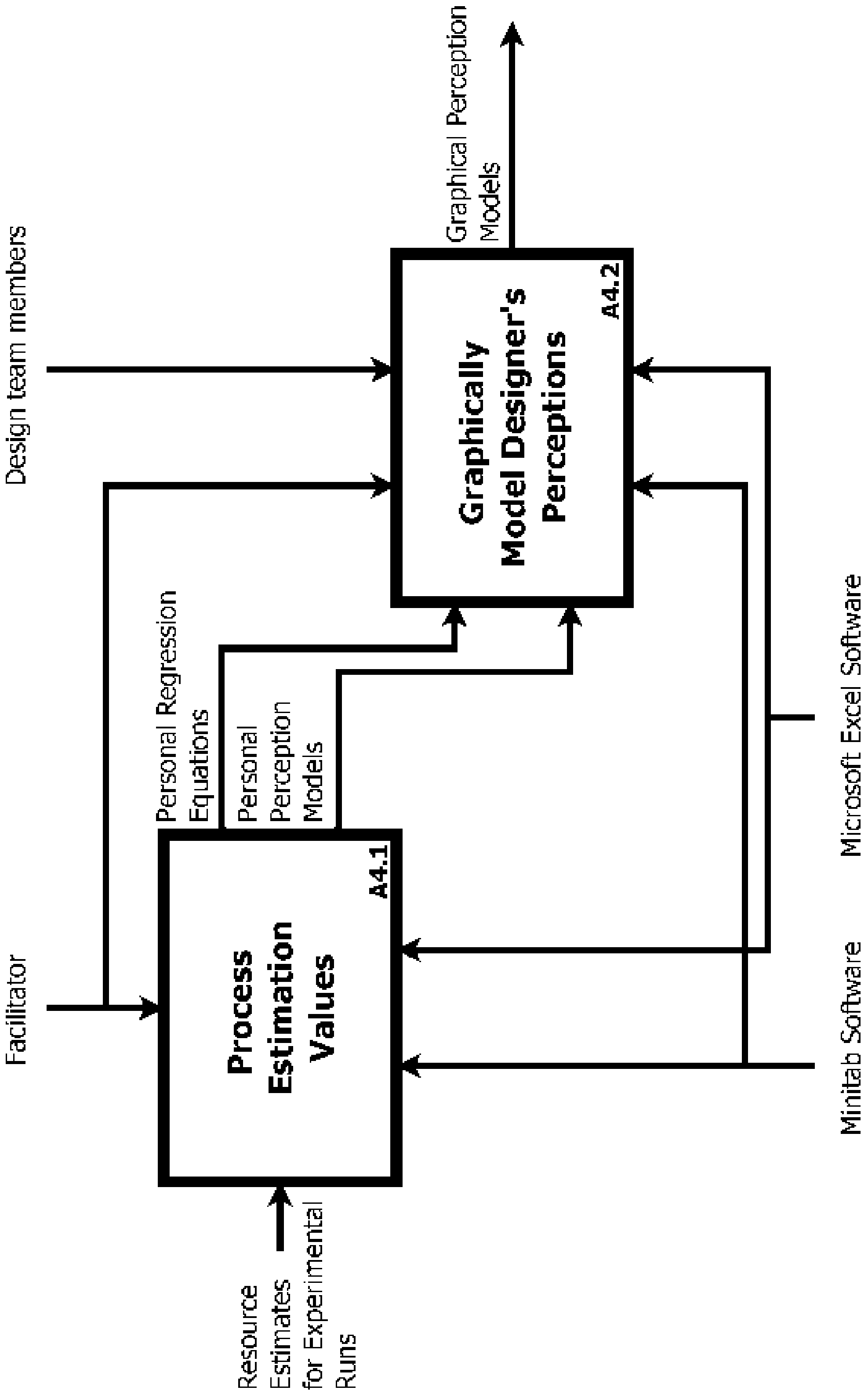
[2] CoFIDE Method - Design Process and Factor Identification IDEF0 Diagram



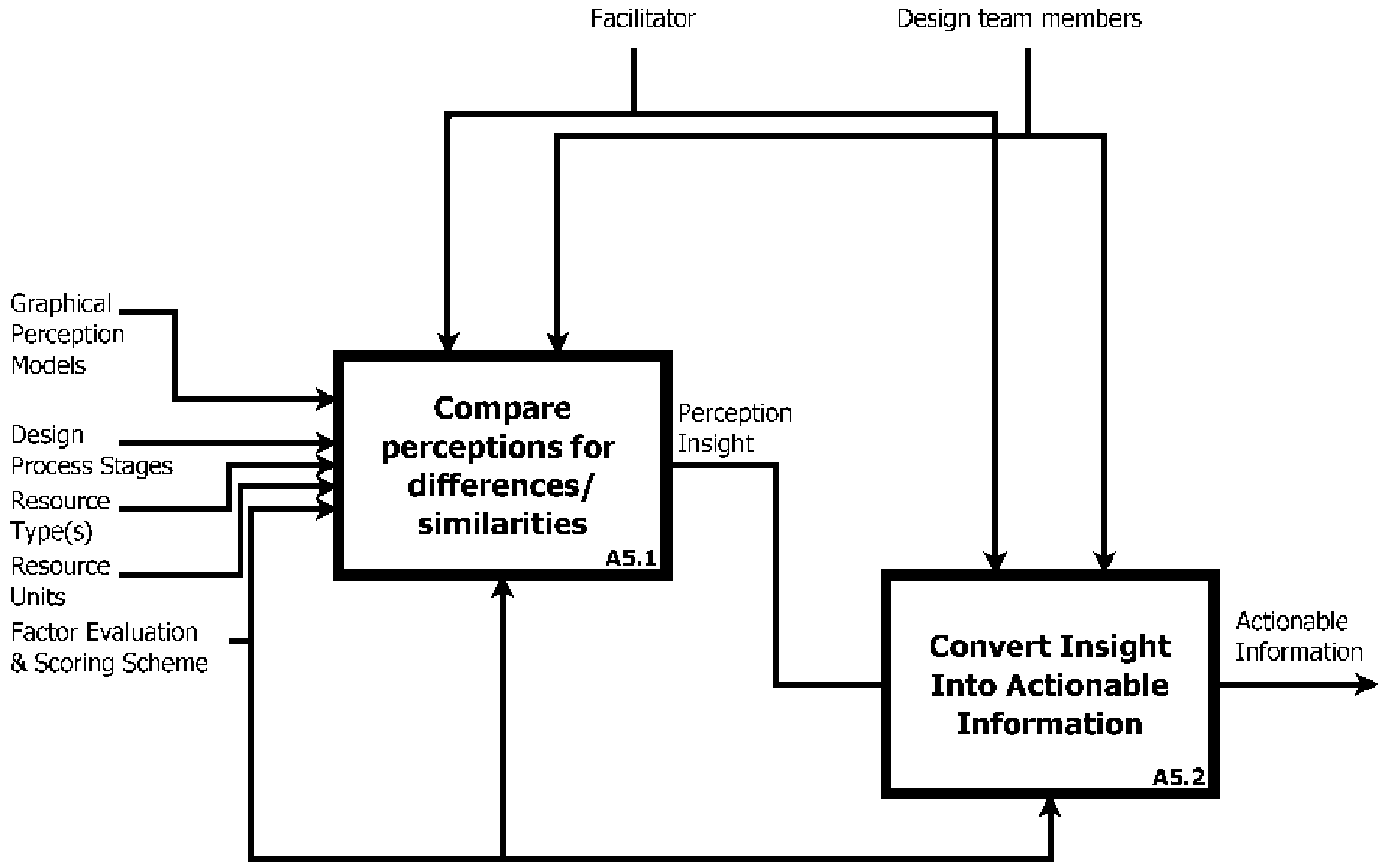
[3] CoFIDE Method - Create Factor Evaluation Scoring Scheme IDEF0 Diagram



[4] CoFIDE Method – Collect Estimates IDEF0 Diagram



[5] CoFIDE Method Model Perceptions IDEF0 Diagram



[6] CoFIDE Method Gather Actionable Information from Perceptions IDEF0 Diagram