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A Decision Support System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts

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LIST OF PUBLICATIONS RELATED TO THIS RESEARCH

Journal Paper I – (Serugga et al., 2020e) – Serugga, J., Kagioglou, M., & Tzortzopoulos, P. (2020d). Value Generation in Front-End Design of Social Housing with QFD and Multiattribute Utility Theory. *Journal of Construction Engineering and Management, 146*(4), 04020019.

Journal Paper-II – Journal of Engineering Management (Submitted/Under Review) – (Benefits Realisation: A Novel and impactful Model for Front End Design Decision Making Using Dempster-Shafer Theory and QFD)

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Conference Papers

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ABSTRACT

There is an increasing interest in the performance of construction projects, focussing on measurable value delivery. This research proposes a novel decision support system to support Front End Design (FED) decision making in addressing continuing value constraints in the delivery of project benefits. Stakeholder involvement and interests in projects that impact on project requirements understanding and management often means competing and sometimes conflicting requirements. However, projects now face increasing expectations to cope with emergent needs, which adds to uncertainty in the design process. As a result, there are continuing challenges in understanding and measuring project performance in terms of derived benefits.

Increasingly, research points to the need for new understanding of FED processes on account of their vital contribution to value generation throughout the project life cycle. Much of current design practice however relies on qualitative explanatory/rationalistic methods to model uncertainty and predict changes in use cases in projects. The reliability of the approaches in the face of myriad, often conflicting and competing stakeholder interests in AEC design is increasingly under focus. This research adopts a mixed-methods approach in developing, validating and evaluating the proposed system in two case study project contexts for comparative assessment of the modelling results. The research formalises a new decision system (DESIDE), in exploring mathematical modelling based on Bayesian probabilistic models and proposes a new system focussed on the utility of decision making in the realisation of project benefits. The research explores the use of probability theory and appropriate mathematical approaches in the management and modelling of requirements and uncertainty during design decision making. The research also explores the use of complementary requirements forecasting modelling in a holistic integrated modelling approach.

The research contributes to knowledge through 1) the new decision system that presents new frontiers in empirical evaluation of FED Benefits Realisation, 2) presenting an integrated analytical modelling approach of project requirements modelling in FED with a focus on the full project lifecycle performance based on analytical utility assessments and cause-effect modelling and 3) presenting a new integrated forecast and uncertainty probabilistic modelling approach of requirements in FED to support benefits realisation in projects.

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LIST OF ACRONYMS

AEC – Architecture, Engineering and Construction

BR - Benefits Realisation

BRM - Benefits Realisation Management

BRP - Benefits Realisation Plan

BIM – Building Information Modelling

AHP - analytic hierarchy process

ANP – Analytical Network Process

QFD – Quality Function Deployment

HOQ – House of Quality

CBA – Choosing by Advantages

DS-T – Dempster Shafer Theoretic

LPS – Last Planner System

HMM – Hidden Markov Model

FED – Front End Design

URs – User Requirements

DRs – Design Requirements

UT – Utility Theory

UF – Utility Function

MCDM – Multi-Criteria Decision Making

MOORA - multi-objective optimisation on the basis of ratio analysis

COPRAS - Complex proportional assessment

PROMETHEE - preference ranking organisation method for enriched evaluation

MAUT – Multi-Attribute Utility Theory

MCDM – Multi-Criteria Decision Making

MMR – Mixed Methods Research

DSR – Design Science Research

SBD – Set-Based Design

PBD – Point-Based Design

LPS – Last Planner System

DQI – Design Quality Indicator

NPD – New Product Development

PSS – Product Service Systems

FoD – Frame of Discernment

bpa – basic probability assignment

DS – Dempster Shafer Theoretic

BoE – Body of Evidence

1 INTRODUCTION

1.1 Introduction

Chapter one introduces the significance of Front-End Design (FED) decision making in Benefits Realisation in projects with a focus on Requirements Management in dynamic environments. The broader discussion in the chapter is to support the subsequent mathematical modelling based on Bayesian probabilistic models. More generally, the chapter sets the research background, problem and need. The remainder of the chapter delineates the research aim and objectives, and a discussion of the key contribution to knowledge of this research. It concludes with the structure of the thesis.

1.2 Research Overview

Increasing research is seeking to highlight the vital role of FED in the Benefits Realisation cycle (Gibson et al., 2010; Fuentes & Smyth, 2016; Elzomor et al., 2018).

FED is the project delivery stage encompassing all project processes relating to project idea/purpose definition, scope and goals definition; and establishing the business case including any feasibility (Whelton & Ballard, 2002). In FED, processes, project processes also establish any funding mechanisms, stakeholder, risk, benefits, value and execution planning and finally project outline designs (Lawson, 2005; Sinclair, 2013; Scherer et al., 2016). The project context can impact on all these FED processes because of influences on decision making and project requirements; while they can, at the same time, be dynamic and uncertain (Locatelli et al., 2014; Locatelli et al., 2017). Uncertainty (explored in much more conceptual detail in section 5.5) in project processes, particularly in FED processes, ultimately impacts on Benefits Realisation.

According to Bradley (2016) Benefits Realisation is *'an outcome of change, which is perceived as positive by a stakeholder'.* Emergent research points to continuing underperformances in projects (lacking in the positive perceptions by stakeholders) as a result of the uncertainty that leads to waste in project processes and ultimately in Benefits Realisation (Um & Kim, 2018; Naeni & Salehipour, 2020). Insufficiencies in benefits realisation planning suggest that any outcome of change in such instances are correspondingly inadequate, perhaps owing to a lack of robust tools to support decision making in uncertain and dynamic project contexts (Serra &

Kunc, 2015; Bradley, 2016; Doherty, 2016). Insufficiency in project processes also appears to extend to predictive capabilities of FED processes as well as to empirical modelling of the dynamics in FED processes (Petit, 2012; Leon et al., 2017; Salam et al., 2019).

Research increasingly point to the need for understanding FED processes better on account of their vital contribution to value generation throughout the project life cycle (Collins et al., 2016; Samset & Volden, 2016; Almqvist, 2017; Elzomor et al., 2018). Much of current design practice, however, still relies on qualitative explanatory methods to understand and account for uncertainty and predicting changes in use cases in projects (see section 3.3 and analysis in 7.4). Rational/explanatory models or visual aid approaches can be unreliable with understanding project requirements owing to the myriad of stakeholders in the Architecture, Engineering and Construction (AEC) projects today.

The rising number of stakeholders in design means competing and sometimes conflicting requirements (Yu et al., 2019), that if design decision making does not fully account for them, waste within processes abounds. For instance, central and local governments continue to control both national and local policy and regulatory areas, respectively, that impact on design decision making (Petit & Hobbs, 2010; Gundersen et al., 2012). Authorities, in this case, can predicate variables and parameters in compliance regimes that constrain design decision making. Additionally, due to the contextual nature of design, the policies, and regulations at the national level may fail to account for local contextual issues that weighing on Benefits Realisation. Stakeholders like environmental and local interest groups will similarly likely constrain the same design decision making in ways again that impact on Benefits Realisation for the project.

While there are notable improvements in the broader AEC processes in terms of new project delivery systems; there are still notable underperformances among projects (Mustafa & Al-Bahar, 1991; Latham, 1994; Egan, 1998; Zou et al., 2007; Tezel et al., 2018; Burger et al., 2019). Recently, there has been an increasing focus on value delivery to the end-user away from the traditional constraints of time, scope and quality (Tillmann et al., 2010; Love et al., 2015; Laurent & Leicht, 2019). Despite this, the sector remains adversarial and fragmented (Khan et al., 2017), which impacts on value generation and Benefits Realisation. One vital element in value generation approaches is that design processes can embed capacity in understanding and accounting for emergent needs. Having the ability to integrate emergent needs means that it is possible that, as use changes emerge, designs can adapt even within dynamic contexts.

If design processes have to focus on value, i.e. both stated and derived user perceptions in use, projects have to explore the use of analytical techniques that support design decision making to improve project performance. The concept of 'value in use' and benefit has been discussed interchangeably in past research (Tillmann et al., 2010; Tillmann et al., 2012; Sweeney et al., 2018). Sweeney et al. (2018) postulate benefits as *'value-in-use'* as opposed to *'value in exchange'* another value proposition. There is, however, no agreement as to what value exactly means. This research explores the historical and philosophical value positions in section 2.3.1.

It however suffices that the level of value performance in the understanding of benefits realisation and requirements management in the wider AEC largely, remains understudied (Coolen & Hoekstra, 2001; Doherty et al., 2012; Coombs, 2015). A focus on value during design means understanding user requirements in the process of transforming them into design requirements.

1.3 Research Need

There is need to understand benefits realisation from a FED perspective (Fuentes & Smyth, 2016; Mastura et al., 2017; Breese et al., 2020) and accounting for elements of contextual influences (Locatelli et al., 2014; Collyer, 2015; Laurent & Leicht, 2019; Salam et al., 2019) that impact on this process both in terms of the uncertainty (Pérez et al., 2018) and influence on emergent needs (Leon et al., 2017). Research needs to extend understanding to the various preference structures influencing requirements management and uncertainty in design (Pérez et al., 2011; Collyer, 2015; Leon et al., 2017; Pérez et al., 2018). In regard to the latter, in a utilitarian understanding, the choices both implied and derived reflected in designs form part of a preference structure during trade-offs (Keeney & Raiffa, 1993; Keeney, 2002). The structures, however, are inherently dynamic, bringing uncertainty to design decision making perhaps in part owing to the imprecision in defining any pertinent factors (Fodor & Roubens, 1994).

Preference structures have been studied widely for their role in trade-offs during decision making (Zhang et al., 2019a). Yet, there is little evidence to suggest their application to AEC design decision making. Nonetheless, the application of utilitarian decision making that focuses decision-makers on the utility of outcomes (Dozzi et al., 1996; Malak Jr et al., 2009); appears important in the understanding of requirements and realisation of benefits. New tools are required that not only support value creation in design (Schöttle & Arroyo, 2016); but are also rigorous in modelling uncertainty (Navarro-Martinez et al., 2019; Naeni & Salehipour,

2020) in design processes and engage with emergent needs because of the users' dynamic preference structures (Collyer, 2015; Leon et al., 2017; Pérez et al., 2018; Salam et al., 2019).

FED processes are at the forefront of this vital process in Benefits Realisation (Fuentes & Smyth, 2016). As the evolution of support tools in decision making takes hold, new tools beyond those that currently rely on explanatory/rational approaches in modelling uncertainty in Requirements Management and prediction modelling are needed (Leon et al., 2017; Salam et al., 2019).. The suggestion here is that the successful realisation of any project, therefore, lends to how closely the intended and derived benefits match the user preferences even amidst change through use (Doherty et al., 2012; Coombs, 2015; Andrade et al., 2016; Badewi, 2016; Badewi & Shehab, 2016; Bradley, 2016).

According to Lawson (2005), design is a problem-solving endeavour, and therefore, design processes should continually assess the design problem, both current and emergent in devising design solutions. Designs similarly need the capacity to evolve with use changes (Luthra & Mussbacher, 2017). Often in practice, however, project and, therefore, designs have not only failed to deliver on intended benefits (Breese et al., 2015; ul Musawir et al., 2017; Breese et al., 2020), but there also appears to be difficulty in quantifying the derived benefits for end-users. Designs continue to fail to deliver on intended and derived benefits through underperformances, for instance when they fail to continually adapt to users' and stakeholders' needs (Lookman et al., 2017).

The need for designs to continually adapt to changing lifestyles rather than the other way round is essential to design performance today in what has sometimes been referred to as user-centred design (Woodcock, 2016). This approach, the authors argue, ensures that there is limited need to substantially alter the design in the future to meet any emergent needs or render them obsolete to be demolished. It also emerges that any changes as a result, ultimately lead to lost value and potentially a reflection of inefficiencies in the initial design process. Successfully realising planned/intended benefits, therefore, lends to an effective Requirements Management process in design while derived benefits (those that the project delivers throughout its lifecycle) are dependent on how the design in turn successfully engages with use change prediction and forecasting. Managing benefits is, therefore, an essential part of FED and new research is needed to understand these intricate dynamics to support new knowledge in benefits realisation practice.

1.4 Research Problem and Key Conceptualisations

There is limited knowledge and research into design decision making and its critical role on in supporting FED processes (Gibson et al., 2010; Gibson & Bosfield, 2012) for benefits realisation (Fuentes & Smyth, 2016; Breese et al., 2020). The main motivation for this research lies in the limited understanding presently in design practice of the particular role of dynamic contexts in influencing design decision making (Locatelli et al., 2014; Locatelli et al., 2017) and how the corresponding uncertainty influences design decision making in FED. Literature including Keeney and Raiffa (1993); Elmisalami et al. (2006); Charles-Cadogan (2018); Navarro-Martinez et al. (2019) illustrates how Requirements Management from a user perspective should reinforce a focus on the utility of benefit of decision-making, particularly during design. Yet, the studies highlight a gap in current practice and theory of utilitarian based Requirements Management and uncertainty management in FED particularly that based on mathematical modelling, ultimately contributing in part to prevalent waste during FED. Research by Thyssen et al. (2010); Haddadi et al. (2016); Boukhris et al. (2017); Kpamma et al. (2017); Smyth et al. (2018) highlights the need for due consideration for the end-user needs and desires; including any projection of use changes in the delivery of projects. Such authors point to underlying gaps design practice, where designers and professional teams often embark on the implementation of project objectives without user-input.

Similarly, there are notable differences among contexts in the perception of value from designs and design practice itself owing to *'structure and agency'* (Kagioglou & Tzortzopoulos, 2016; Laurian et al., 2017) as discussed in section 2.2.4. Local contexts constitute a significant influencing factor on AEC design decision making (Locatelli et al., 2014). A lack of full understanding, therefore, of the vital role contextual factors play in value generation in FED processes often leads to the reported gaps between intended and derived benefits. As a result of myriad stakeholders and changing user needs (Yu et al., 2019); and uncertainty in both design processes and contexts (Um & Kim, 2018; Naeni & Salehipour, 2020), design practice is characterised by the following:

- A limited understanding of the roles of participatory design (Schuler & Namioka, 1993; Kensing & Blomberg, 1998; Bratteteig & Wagner, 2016; Kpamma et al., 2017; Eleftheriadis et al., 2018) as a vital constituent of value co-creation (Thyssen et al., 2010; Martinez et al., 2016; Cohen et al., 2017; Smyth et al., 2018) in FED processes.

- Evidence that the limited participatory FED is hampering the general Requirements Management process hence impacting on Benefits Realisation in projects (see 3.2).
- The emergence of an increasing number of tools aimed at modelling integrated project delivery systems that appear to be insufficient for the dynamic and information-intensive front end (Arroyo & Long, 2018; Pérez et al., 2018).
- An emergent position that current tools remain largely explanatory (see sections 3.3 and 7.4) and are unable to model the dynamic processes in complex contexts (Liu, 2011).
- An understanding that use case changes in the course of the project life cycle can be fast and dynamic and therefore need analytical tools able to capture and integrate complex data in design decision making (Shieh & Wu, 2009; Lindhard et al., 2019)
- Finally, that as a result of the all the above, FED processes need new analytical tools to support uncertainty modelling (see 5.5), focus design decision making on the utility of benefit (see 3.4.3); and manage and predict competing and conflicting requirements (see section 5.2) concurrently (Pich et al., 2002; Hill, 2010; Dietrich, 2018).

New integrated project delivery systems and participatory design, according to Kpamma et al. (2017) are vital elements in FED processes in value generation. It is, however, noted by Tezel et al. (2018) and highlighted by Gomes et al. (2016) that there are low levels of collaboration and integration in FED in the still predominantly fragmented AEC set up in practice, a situation reinforced by authors like Saunders et al. (2017) and Ahmad et al. (2016).

Contextual influences and dynamics like the environment, geopolitics, technology, and sociocultural factors, among others, interact with process systems in AEC. The influencing elements as stakeholder needs and desires, competing expertise, and inherent subjectivity, among others within design can all work to impact on design decision making. The interaction of all the elements ultimately constrains design processes contributing to further uncertainty in project delivery (Sjödin et al., 2016). According to Chesbrough et al. (2018), however, sometimes the constraints arise out of deliberate *'conceptual ambiguity'*. Conceptual ambiguity, according to Turner and Cochrane (1993) can manifest as poorly defined goals and methods.

Increasing research including Kpamma et al. (2017), Sjödin et al. (2016) adding to earlier research by Austin et al. (2001) and Austin et al. (1999) among others is arguing for a renewed focus on participatory and collaborative design, particularly in FED to support Benefits Realisation planning processes. The authors similarly accept that FED is inherently dynamic and unstructured; adding that structure needs to be brought to the information and knowledge sharing processes e.g., in the management of requirements to improve value/benefit delivery.

Bringing structure to FED processes can also be in the form of integrated collaborative design practices that focusses on the needs of the end-user. Participatory, integrated and collaborative design processes that involve end-users and broader stakeholders (Gomes et al., 2016; Kpamma et al., 2017) at the centre of any value propositions will ultimately tackle information exchange deficits and value loss that leads to disbenefits i.e. the negative impacts on Benefits Realisation.

Regarding uncertainty, Zwikael et al. (2018) argue the successful realisation of project benefits depends on fully understanding the core purpose of the project through defining clearly the target goals. Zwikael et al. (2018) and Doherty (2016), highlight that vital link between such decision making and the realisation of intended benefits. For successful realisation of benefits, Zwikael et al. (2018) for example, argue that a specific, attainable and comprehensive benefits-based decision-making process is imperative.

This is an essential part of the design process role, according to Lawson (1983), yet there is limited evidence in research and practice to quantitatively and empirically model project benefits and its processes. Cardoso et al. (2016), therefore, argue for new design practices to engage with user requirements and cases and model perhaps analytically, such problems with new solutions something that is missing in current practice. In doing this, Lawson (1983) argued that the design process much depends on the rigour of the information at hand, and the completeness of the information is therefore essential.

Kpamma et al. (2017) and Boukhris et al. (2017), among others, therefore, argue for participatory and co-creative environments, respectively. Karni and Vierø (2017); Dietrich (2018) argue for increasing awareness of unawareness in processes; Navarro-Martinez et al. (2019) on a focus on the utility of decision making while Shieh and Wu (2009) highlight the need to engage with changing requirements. For processes to collectively deliver sufficient value propositions, Taghizade et al. (2019), Markou et al. (2017) and earlier Geum and Park (2011) adding to emerging research argue that such processes take a life-cycle approach. The authors argue that this is vital in building the necessary evidence base to support decision making processes suggesting the important role of FED decision making. Participatory and co-creative processes while increasingly important, can place particular burdens on decision making during design in dynamic contexts. Current practice and research are still, however, limited in addressing this gap.

1.4.1 Front End Design

FED represents all the processes leading up to detailed design (see section 1.2). Participatory FED design process (see section 2.2.2) represents its most significant opportunities in FED processes. Participatory design integrates stakeholder needs into decision making early in the project life cycle, including aspects as the needs of end-users and the community. FED, however, remains understudied in research (Hedges et al., 1993; Hwang & Ho Jia, 2012; Samset & Volden, 2016; Smyth et al., 2018); and largely unstructured and uncertain (Austin et al., 2001; Macmillan et al., 2001; Burger et al., 2019) its influencing role in the success of projects little understood (Hwang & Ho Jia, 2012) and is varied from one project to another (Yun et al., 2012) in practice.

Gibson et al. (2010) highlight the link between successful benefits delivery to structured FED processes. The authors argue that FED processes are important in helping highlight any *'project unknowns'* alongside any efforts to develop the scope and define project goals. The authors also add that as part of this process, projects can be structured ready for implementation. The careful implementation in this approach it is argued, together with the capacity of the project team to address any emergent issues in FED, is critical to the success of projects.

FED processes and decision making is therefore crucial in drawing out interdependences and uncertainties in factors and attributes, and presents opportunities for optimising them (Williams & Samset, 2010); notwithstanding any inherent complexities and uncertainties. Decision support tools' capabilities in modelling project complexity as part of a structured FED are discussed in section 3.2. It is seen that decision making using such support tools able to model complexity also contributes to structured and planned FED, particularly in Requirements Management. Elzomor et al. (2018) add that a planned FED is essential to reducing uncertainty in downstream processes. Therefore, as argued by Smyth et al. (2018), value creation ought to be seen from a front-end perspective for its opportunities to improve Benefits Realisation through structured FED decision making.

1.4.2 Benefits Realisation

As an outcome of a positive change for stakeholders (see earlier in 1.2) benefits realisation runs from the organisational down to processes level (Bradley, 2016). A successful Benefits Realisation program, therefore, not only aims to manage the delivery of benefits but also to engage stakeholders and end-users in drawing up realistic and measurable requirements for collaborative implementation (Del Águila & Del Sagrado, 2016; Horkoff & Yu, 2016). This approach to collaborative multi-disciplinary value generation has sometimes drawn relations with value co-creation (Fuentes & Smyth, 2016; Cohen et al., 2017; Zhao & Cheng, 2017; Liu et al., 2018; Smyth et al., 2018; Ranjan & Read, 2019).

Value co-creation has been described as a means of end-users engaging with organisations in creating value (Ranjan & Read, 2019). The conceptual complementarity means that processes can identify and quantify benefits following which they value and appraise them; and finally plan, realise and review the defined benefits (Kagioglou & Tzortzopoulos, 2010; Jenner, 2012); processes that are of particular importance to FED. This conceptual basis suggests that the use of value co-creation as part of Benefits Realisation both in understanding and practice can ensure deeper engagement between the organisation, its objectives and the end-user in the management of project requirements and ultimately in the process of design decision making.

While a more extensive exploration of Benefits Realisation is presented in section 2.3, it suffices to highlight here that since its conception, its adoption has brought profound benefits in sectors for instance in IT/IS (Ward et al., 1996; Coombs, 2015). Of late, Benefits Realisation has also been applied in the AEC sector, particularly in Health projects (Kagioglou & Tzortzopoulos, 2010; Azhar, 2011; Ghaffarianhoseini et al., 2017).

A key focus of much of the current Benefits Realisation approach is the delivery of strategic objectives based on the organisation's investment objectives (Serra & Kunc, 2015; Bradley, 2016). Farbey et al. (1999) draw attention to uncertainty within Benefits Realisation programmes, arguing that it necessitates rigorous decision making in the evaluation of results of organisational change. This evidence base as part of a Benefits Realisation approach, moreover, is seen to allow for adjustments to be made during the cycle to inform the project lifecycle decisions and take into account any emergent needs. Authors including Smyth (2018), Bradley (2016), and Kagioglou and Tzortzopoulos (2016) among others have, therefore, argued for a need to move away from mere attainment, stating that benefits need to be delivered by looking at the process of Benefits Realisation in its entirety.

1.4.3 Uncertainty and Knowledge Modelling

Uncertainty has been described as a process of '*indecision'* on a *'subjective probability or relative frequency of a future event'* based on past observations (Davidson, 1991; Daniel & Daniel, 2018). *'Indecision'* lends to a decision-making process, a vital element of FED. The process of FED benefits realisation is also highlighted as a process of value co-creation (see 2.2.2). Design today is, therefore, so that the myriad of stakeholders has a vested interest in project Benefits Realisation over and beyond traditional design practice. Mok et al. (2017) have, however, noted that this myriad of stakeholders is a significant source of uncertainty in the realisation of project benefits. Walker (2015), on the other hand, highlights uncertainty inherent in design and construction practice. Uncertainty can also occur out of context-specific factors that not only bear on the design processes and stakeholders by influencing their decision making (Zhao et al., 2018); but also, from macro factors for instance geopolitics, technological, societal, environment or socioeconomic influences among others (Kwan, 2018).

The different elements create complex preference structures, competing and interdependent objectives and attributes in decision making that also often means biases during trade-offs that demand complex modelling (Naeni & Salehipour, 2020). Daniel and Daniel (2018), therefore, argue that new tools are needed that not only integrate this subjectivity in decision making (Ye et al., 2015; Ding et al., 2016); but also model the resulting uncertainty to assess project performance (Naeni & Salehipour, 2020).

Utility Theory is an example of a multi-attribute decision support technique that attempts to model a decision-makers complex preference structure with a focus on the utility of decision making (Blavatskyy, 2007; Navarro-Martinez et al., 2018). In this decision-making approach, the uncertain and imprecise information is modelled around the decision maker's utility function to ensure consistency of their decision making (Keeney & Raiffa, 1993; Dozzi et al., 1996; Blavatskyy, 2007; Karni & Schmeidler, 2016; Navarro-Martinez et al., 2018). It is also vital that as emergent needs arise, the decision-making process can accommodate them (Lawson, 1983; Tam et al., 2002; Lawson, 2005).

The works by Karni and Vierø (2017) and Karni and Schmeidler (2016) are essential in drawing focus to other mathematical understanding and modelling capabilities based on probability theory of changing knowledge to account for how this change may affect decisions. Such approaches based on Bayesian conditional probability for instance Dempster-Shafer theoretic (Shafer, 1976; Dempster, 2008); have been applied widely in other sectors of industry to account for uncertainty in the knowledge frame (Beynon et al., 2001; Dempster, 2008; Awasthi & Chauhan, 2011; Tang, 2015; Del Águila & Del Sagrado, 2016; Wang et al., 2016a; Altieri et al., 2017; Denœux et al., 2018; Kukulies & Schmitt, 2018).

The Dempster-Shafer theoretic (DS-T) can quantifiably establish the belief and plausibility structures in a body of evidence as a way of informing decision-making using probability theory. Examples of application of the approaches include (Kukulies & Schmitt)'s works in

Requirements Management and forecasting in product design; Altieri et al. (2017)'s works in transport mode decision making and Wang et al. (2016)'s works in medical diagnosis all demonstrating how uncertainty modelling can support decision making. These applications highlight opportunities in such capabilities, that have their original roots in manufacturing, in modelling knowledge, complex preference and belief structures in FED design decision making.

1.4.4 Forecasting in Design

According to Jayatilleke and Lai (2018), the fact that not all project requirements may be fully known during design means that they can often change. The changing nature of user needs, and expectations means new tools are needed to predict events to support Benefits Realisation. The design process ought to engage with emergent needs by embedding capacity in processes to adapt and meet new and changing user needs.

The research by Boudaren et al. (2012) is crucial in establishing that vital link in mathematical modelling of today's user requirements and how these are likely to change in the future. This link and approach are based on Bayes' theory and extended by the Hidden Markov Modelling (HMM). HMM has been applied in many analytical realms to assess contextual data in order to support decision making on future changes in the data sets (Bunks et al., 2000; Shieh & Wu, 2009; Xu et al., 2011; Boudaren et al., 2012; Mallya et al., 2012; Yu, 2012; Lethanh & Adey, 2013; Asadabadi, 2017; Liu et al., 2017; Pino et al., 2018). HMM uses transition (the probability of moving from a current to a future state) and emission (the probability of the observed state) probabilities in understanding the current state of events as a basis for predicting corresponding future states (Shieh & Wu, 2009). HMM is, therefore, a powerful application for accounting for changing user requirements (Shieh & Wu, 2009; Asadabadi, 2017); and can help design decision making in projecting user needs to inform current design decisions (see detailed discussion later in section 5.2).

Boudaren et al. (2012) explored combining uncertainty modelling and predicting images in sensor recognition technologies using HMM probability theory. The researchers were able to predict signals in changing imagery using the Dempster-Shafer theory for accounting for uncertainty in the body of evidence whilst fusing data using HMM. This research presents opportunities to overcome a lot of uncertainty both in current and future predictions in design while allowing for a robust analysis of the body of evidence supporting design decision making (see later in section 5.2). There is also research in the complementary use of HMM with Quality

Function Deployment (QFD) Requirements Management and analyse how these are likely to change over a given set of parameters (Shieh & Wu, 2009; Asadabadi, 2017).

QFD is aimed at the transformation of the Voice of the Customer (VOC) using matrices in the House of Quality (HoQ) (Cristiano et al., 2001; Liu, 2011; Lima-Junior & Carpinetti, 2016; Akbaş & Bilgen, 2017; Yazdani et al., 2017; Babbar & Amin, 2018). The application of QFD in the decision-making process while largely limited in AEC, presents opportunities for this research and wider practice to quantify subjective attributes whilst supporting complementarity with probabilistic modelling using HMM and Dempster-Shafer theory (Babbar & Amin, 2018). Complementarity is vital in supporting an integrated approach in modelling the uncertain and dynamic design contexts in FED with more detailed conceptualisation explored in section 5.3.

FED in AEC is currently a rational process with limited research into the application of mathematical modelling of the complex phenomena relating to Requirements Management and inherent interdependences. To facilitate improved Benefits Realisation of projects, the vital role of FED first and foremost needs more exploration in research. Similarly, the role of uncertainty and knowledge management and Requirements Management need further study; regarding the subjectivity of decision making and the complex interdependences among design attributes in impacting on Benefits Realisation. Using complementary probabilistic HMM and DS- T, this research explores a new approach to FED decision making built around QFD and utilitarian assessments to propose an improved process to benefits delivery. The concepts are explored throughout the rest of this thesis.

1.5 Research Aim and Objectives

The research aim is:

To develop a Front-End Design decision-support System for Benefits Realisation in Dynamic Contexts. This is formalised as the Decision Support in Design from here on called DESIDE.

1.5.1 Research Objectives

1. To describe the state-of-the-art (through a systematic literature review) in Front End design and Requirements Management and their relationship to Benefits Realisation in project life cycles.

2. To identify and describe current decision support tools for FED and identify their limitations in accounting for dynamic and contextual factors that impact on Requirements Management.
3. To Propose and describe an integrated FED decision support system based on probabilistic mathematical modelling.
4. To validate and evaluate the proposed decision system through case studies in assessing how it improves Benefits Realisation during FED decision making.

1.6 Research Method

A mixed-methods research (MMR) approach has been adopted to support the development of the system, that is based on probabilistic modelling on one hand and qualitative and subjective data from stakeholders on the other in an integrated and convergent manner. According to Bergman (2008) MMR has *"at least one qualitative and one quantitative component"* for a given research discourse. This research seeks to develop a decision system that integrates both rational (qualitative) and empirical (quantitative) data to support FED decision making. The mathematical computations behind the decision system are integral to the systems integrity but must support the subjective nature of design. MMR is therefore best placed to support this research approach. McKim (2015) argue that this unique combination of strategies can add to the rigour and validity of research results as well as to knowledge. This approach is, therefore, able to exploit the complementarity of the two approaches in order that one method supports, enhances, informs; and that the results from one can be recast in the perspective of the other. Above all, however, is that MMR is able to support mixed philosophies as is exploited in this research; particularly relating to axiology, ontology and epistemology in an integrated manner (Johnson et al., 2007; Schoonenboom & Johnson, 2017).

The purpose at this point, therefore, is to briefly outline design and implementation of the research methodological approach including the design and data collection together with the proposed validation process adopted. This is with the aim of highlighting how these contribute to modelling, understanding and improvement of the dynamic design decision making processes in meeting the research aim and objectives. The research adopts a four stage process including the research definition stage, the development stage in which the empirical studies aim to support validation of the conceptual bases of the proposed framework (see Figure 1-1).

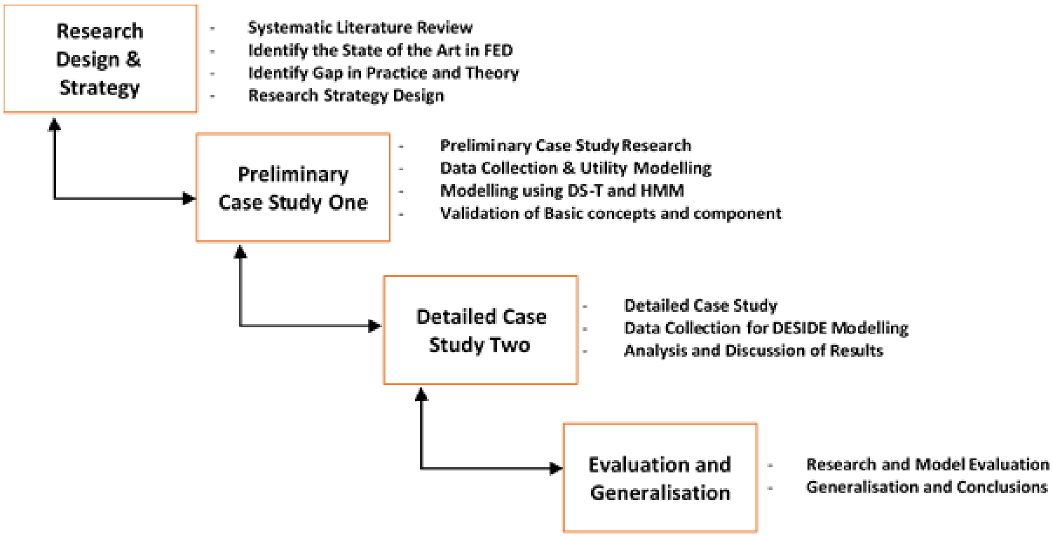

Figure 1-1 Outline of Research Methodology

Finally, is the detailed study and evaluation stages which aims to validate the full component leading to a full evaluation, respectively. In the first stage, the research establishes the theoretical concepts in FED, including design decision making in dynamic contexts. At this stage, the research particularly focusses on the state of the art of design practice drawing out the role of FED in the realisation of project benefits. Also important at this stage is the complementary concepts of requirements management and drawing out the relationships with project contexts. In the second stage, the research uses preliminary case studies to validate the basic component parts of the framework to support any parameter or model adjustments. The case studies data collection is through observations, interviews, questionnaire surveys and document reviews after which further and progressive literature review supports inclusion or exclusion of the concepts. The first case study was applied to support validity of the decision systems components. At the detailed case study stage, the research applied the full decision model followed by an evaluation and validation process. Validation and evaluation support the subsequent generalisations and theories in supporting both the research aims and objectives and the decision support system.

1.7 Research Contribution

The contribution of this research is the proposed novel analytical decision support system based on probability theory that harnesses three complementary capabilities:

i). Complex interdependences modelling of the user and design requirements in dynamic and uncertain contexts using the Dempster-Shafer theoretic and QFD. Probabilistic approaches have been widely used in many sectors of industry e.g., in complex evaluations of transport solutions (Altieri et al., 2017), stabilising production flows (Kukulies & Schmitt, 2018) and in fault recognition in machinery (Chen et al., 2018) among others. Such applications have not been replicated in technologies in AEC and particularly for FED where contextual uncertainty plays a major role.

ii). HMM approach to support requirements forecasting. This probabilistic approach supports decision making through modelling of changing user needs. Again, there is no evidence of its application in wider AEC design practice currently.

iii). Utilitarian assessments incorporating a mathematical cause-effect analysis of user benefits based on subjectivity modelling and interdependence analysis among attributes in QFD. A focus on the utility of outcomes in design decision making brings a Benefits Realisation perspective to the decision making. The model can, therefore, integrate a utilitarian analysis alongside Requirements Management in FED; modelling changes attributes and assessing uncertainty within design decision making.

The significance of DESIDE is how it brings these concepts together in one integrated approach. The proposed model can augment current rational/explanatory practice in design decision making; in supporting complex decision making in dynamic and uncertain contexts, with many emergent user needs.

1.8 Thesis structure

Chapter one introduces the background to the research, including keynotes on FED, Requirements Management and Benefits Realisation. The conceptual interrelationships among them and their relationship to this research are illustrated in *Figure 1-2*. *Figure 1-2* also highlights the points the research related published works integrate into the wider development of the thesis (including published journals papers JI-JIV and conference papers CI-CVI).

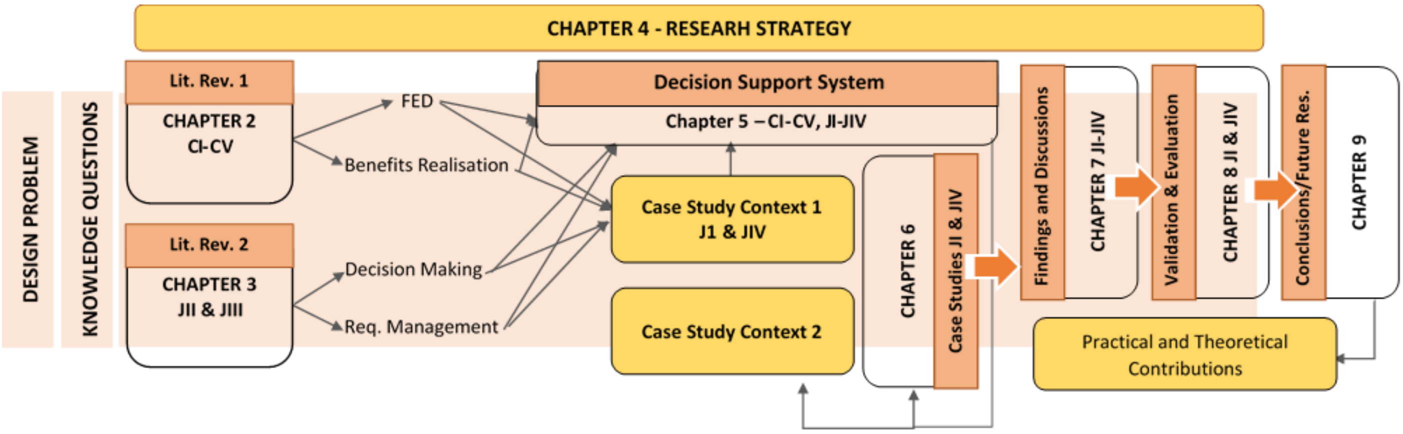

Figure 1-2 Outline of Thesis Structure and Research

The chapter also draws links between these concepts to uncertainty and requirements changes in FED. It also lays out a summary of the thesis aims, objectives, research methodology. It concludes with the structure of the thesis. Chapter two is the detailed literature review exploring current theory and practice in Benefits Realisation and its relationship to decision making. The chapter explores the essential understanding of including FED and how it contributes to wider benefits realisation in projects. Chapter three looks at the state of the art in requirements management and decision making alongside utility theory. It relates these to capabilities of uncertainty and forecasting modelling. Chapter four describes the methodological approach for the research including the research design. Chapter five introduces the concepts of probabilistic DS-T and HMM in supporting the development of the decision support system. Bayesian DS-T and HMM are presented in how they facilitate uncertainty modelling for requirements forecasting successful benefits delivery. A model for DESIDE is also presented. Chapter six presents the case studies and models the data gathered from the research and finally presents the results. Chapter seven is the findings and discussions drawing lessons from literature to highlight the implications of their in addressing research objective four in relation to the results from chapter six. Chapter 8 discusses the strengths of the proposed model, including a presentation of the validation and evaluation criteria. The scope for future work, follow in chapter 9, which also presents the conclusions, limitations, and contributions of the research.

2 FRONT END DESIGN, BENEFITS REALISATION AND DYNAMIC CONTEXTS

2.1 Introduction

Chapter one briefly introduced the key conceptualisations for this research as well as setting out the research problem and need. In this chapter, a detailed literature view is presented to underpin the research problem and justify it through identifying current gaps in the literature and practice; in supporting the research, objectives as set out. This chapter looks at the broad range of theoretical positions and concepts in FED[1] cast in utilitarian decision making. The chapter, therefore, explores wider understanding of FED and how it contributes to Benefits Realisation. The chapter also explores FED decision making and how this relates to the project contexts in influencing benefits delivery. This builds on the dynamics of decision making and contextual uncertainty. The chapter, therefore, presents the theoretical concepts and applications in understanding uncertainty and requirements changed in FED in supporting the value[2] generation. Gaps that are identified in current dispensations are illustrated in addressing the needs of FED. The chapter sets the basis for further theoretical exploration of requirements management and decision making in chapter three.

2.2 Front End Design (FED)

There has been an emergence of a body of knowledge on the need for better performance in AEC projects more especially in the delivery of intended benefits during FED (Choo et al., 2004; Ross et al., 2004; Gibson et al., 2006; George et al., 2008; Jung, 2008; Gibson et al., 2010; Gibson & Bosfield, 2012; Hwang & Ho Jia, 2012; Yun et al., 2012; Oh et al., 2015; Collins et al., 2016; Fuentes & Smyth, 2016; Oh Eun et al., 2016; Samset & Volden, 2016; Almqvist, 2017; Elzomor et al., 2018; Burger et al., 2019).

There are many characterisations of design processes in AEC including the RIBA Plan of works (Riba, 2013) and others by Markus (1969) and Lawson (2005) among many. Markus

[1] In this research, Front End Design is used in place of Early Stage design but where both words exist, they represent the same meaning i.e. all design processes coming before the detailed design stage.
[2] This research adopts the understanding of value as that which refers to the “centrally held cognitive elements that stimulate motivation for behavioural response” (Vinson, Scott and Lamont, 1977 p.45). They are influenced by culture, society, its institutions and personality (Rokeach 1973) and subcultures (Lawson 1983).

(1969) for instance, characterises design as synthesis, analysis, appraisal and decision; while Lawson (1983, 2005) sees the process as synthesis - analysis – evaluation. The RIBA plan of works, on the other hand, gives a guide to best practice in design as *'A-Inception, B- Feasibility, C- Outline proposals, D- Scheme design, E- Detail design, F- Production information, G- Bills of quantities, H- Tender action, I- Project planning, J- Operations on-site, K- Completion, L- Feed-back'* (Riba, 2013). All these characterisations aim to, in part at least, present design as a staged and structured process as demonstrated in *Figure 2-1*.

Firstly, despite this apparent distinction in phases, in practice, the boundaries are not as distinct as highlighted by Lawson (2005). Secondly, the characterisations suggest nothing about the essential dynamics in design that is inherently contextual. Particularly for complex projects, the stages of inception all through to specification drawings can be as varied as they are complex. Thirdly, the characterisations appear to be more about deliverables than fostering value generation. The first observation appears to lend to the inherently contextual nature of design. The second and third observations, on the other hand, are essential in the discussion throughout this thesis, helping to draw focus on the delivery of project benefits with a focus on the utility of decision making.

Figure 2-1, in aiming to capture these essential distinct stages, also highlights the front end of the design process, but merely for purposes of general understanding. FED in this case can be characterised as inception, scheme development and selection and concept design. Characterisations as these, therefore, present the first and initial understanding of FED though this can only be understood in the context of deliverables up to this point.

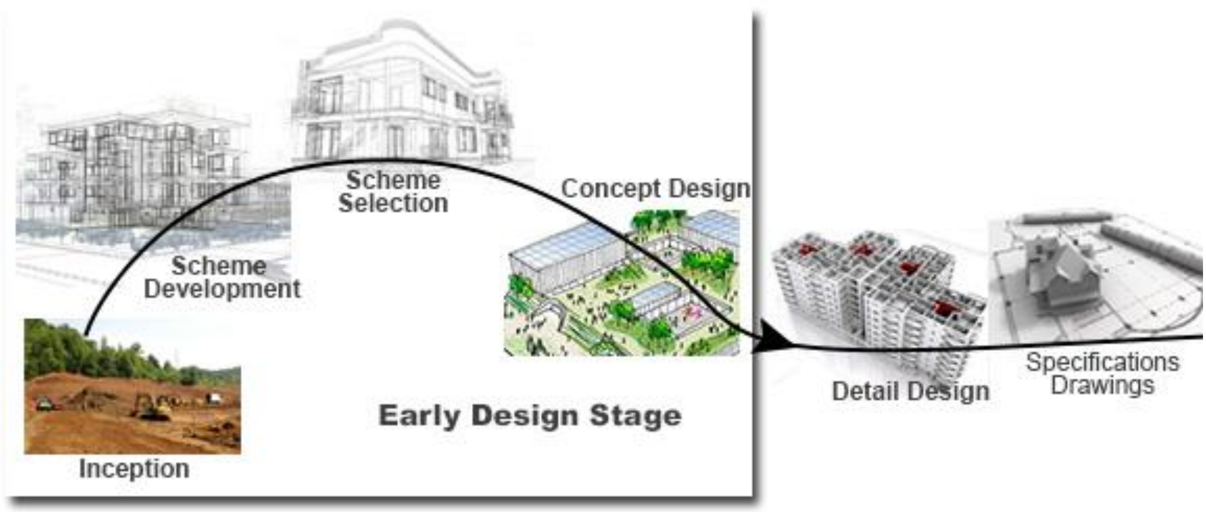

Figure 2-1 Progression of Design Processes Adapted from: Lawson, (2005), p. 35; Riba, (2013)

At the inception stage, according to the RIBA plan of works 2013, the design processes consider the strategic and project-specific business case for the project; suggesting high-level requirements and project benefits. This stage, therefore, presents the first opportunity in developing decision-making practices that foster the utility and value of the project at an abstract level. There, however, appears very limited research into this stage and not much is understood in the way of the dynamics and its importance in the context of the whole life project life cycle. The next stage is the scheme development where alternatives may be developed and compared in the selection stage, suggesting lower-order requirements and benefits. While at inception stage quantification of benefits and requirements may not be possible, it appears that at this stage onwards, this is something that projects processes can facilitate. This gets even more possible in the development of concepts stage. This is because these have to reflect the specific lower-order objectives of the project, following which detail designs are developed. Like the inception stage, little research explores these stages and their dynamics.

However, as argued by Lawson (2005) these characterisations while they may facilitate decision making, it is not evident in literature and practice how they impact on it in supporting the inherently dynamic FED.

2.2.1 The Role of FED

Burger et al. (2019), Almqvist (2017) and earlier George et al. (2008) are among an increasing body of research to recognise the role of FED in the efficacy of benefits delivery. The authors essentially argue that the realisation of project benefits starts from FED processes. Gibson et al. (2006) argue it is the most critical stage in a project's life cycle. The authors all separately suggest that the many important decisions that affect the whole project life cycle are made in FED. These decisions can relate on the one hand to opportunities for value creation for instance value co-creation in FED processes highlighted by Smyth et al. (2018).

On the other hand, poor decision making can lead to value loss because of waste. Costs can, for example, be borne out of changes in design scope and insufficiencies in later project processes, all of which may negatively affect project benefits. It is also highlighted that FED presents opportunities for swifter and less costly changes resulting in any iterations as compared to later project stages. However, Fuentes and Smyth (2016) argue that more research into understanding the exact links between value co-creation and benefits delivery is still needed.

At a macro level, this appears to be on account of continuing underperformances in wider AEC processes, such as the continuing lack of integrated approaches (Tezel et al., 2018), optimisation (Gibson et al., 2010) and information loss (Almqvist, 2017) among others. At a micro level, this is the basis for the understanding of the project requirements in accounting for context-specific influences in design. Regarding integrated product development environments in a FED perspective, Oh Eun et al. (2016) argue that failures in later processes, including those relating to such issues as constructability; result from and into waste cyclically. Such author positions are essential in highlighting waste across the project delivery process perhaps more particularly from a FED perspective. The majority of the waste according to Halttula et al. (2017), Gibson et al. (2010) and earlier Cooper et al. (2008, p. 53) can be traced back to a poorly planned front end e.g., in poor Requirements Management processes. A later study by Kukulies and Schmitt (2018) reinforced this understanding. Dick et al. (2017) therefore, argue for getting the requirements right at the start adding that this can be key to later project lifecycle successes. In this light, it can be argued; therefore, that there is a link between Requirements Management processes in FED improved benefits delivery for projects (Dick et al., 2017).

A study by George et al. (2008) highlighted how information and knowledge sharing is critical to FED processes as it affected flow and exchanges. The knowledge and information deficit issues identified in this study included those relating to defining scope resource planning, risk management, process planning, and establishing collaborative environments, all of which affect communication and information flow. However, Gibson et al. (2010) add that while FED presents opportunities to embed processes that facilitate information and knowledge sharing; later project processes still suffer as a result of unstructured FED. This can be important in helping uncover project unknowns while facilitating the definition of scope and bringing structure to this essential stage in project delivery (Gibson et al., 2010). Similarly, FED, according to Jung (2008) can also present opportunities for more accurate project costings and scheduling by drawing to specific project contexts and detail. Pohl (2016) defines a project context as *"that part of the project environment that is relevant for the definition as well as the understanding of the requirements of a project to be developed".*

Other opportunities for FED beyond the project context lie in improved accuracy in project objectives as a result of collaboration and information sharing something that positively contributes to project value (Gomes et al., 2016). Information sharing can, for instance, underpin Requirements Management whilst ensuring that FED processes keep pace with any changes in requirements that ultimately impact Benefits Realisation as demonstrated in this research (see later in sections 5.2, 6.2.7, 6.3.2 and 7.6). FED is, therefore, vital in improving accuracy in the body of evidence that supports design decision making and ultimately, overall project benefits and performance.

Despite this emergent knowledge in the vital role of FED in the delivery of project benefits, studies still point to limitations in understanding of its conceptual contribution and the essential dynamics that influence its processes. A study by Almqvist (2017) for example, highlights continuing knowledge loss in FED and later processes as a result of the inherently fragmented nature of AEC processes. Samset and Volden (2016) on the other hand argue FED is less studied and represented in current literature and research while Hwang and Ho Jia (2012) argue that perhaps its influencing role in project success is still not yet fully recognised. FED, according to Gibson and Bosfield (2012) is under-resourced; and is varied from one project to the next, according to Yun et al. (2012). Elzomor et al. (2018) and Collins et al. (2016) argue that FED needs to be held in the same rigour space as the entire project processes for both small and large projects. Such research positions point to both issues of *'structure and agency'* of FED (see discussion later in section 2.2.4). Research is, therefore, needed to bridge this gap, in supporting both Requirements Management and modelling of the context-specific complexities in the design environments.

The foregoing discussion highlights, on the one hand, the essential role of FED processes and activities in the successful realisation of benefits in AEC. On the other, a planned and structured collaborative FED is seen as crucial to reducing waste in downstream project processes. However, research still suggests that understanding of FED for its vital role in the delivery of project benefits still lags that of other stages in the design cycle, for instance the detailed design or implementation stages. It is also highlighted that FED is integral to the design processes in facilitating early stakeholder[3] engagement and management, the extent of Requirements Management, harnessing the contextual dynamics that impact on design decisions as well as influencing the knowledge flow and exchanges underpinning those decisions. Stakeholder participation in the design process, therefore, emerges as a key element of FED (Kushniruk & Nøhr, 2016).

[3] A stakeholder in this thesis is regarded as anyone with a direct/indirect influence on the FED process and project requirements (Pohl, 2016)

2.2.2 Participatory design and Co-creation in FED

Decision Making in FED is a participatory and collaborative process, and therefore, the understanding of these concepts plays an increasing role in focussing design decision making on project outcomes. Regarding Participatory Design the concept has its roots in the 1990s (Schuler & Namioka, 1993; Kensing & Blomberg, 1998; Donetto et al., 2015); emerging then from a social sciences based design practice (Sanders, 2002). The primary position of Participatory design embodies all design practice that puts the end-user at the centre of the design process, together with corresponding research and theories (Muller, 2009). This embodiment, according to Simonsen and Robertson (2012) was for the collaborative involvement in design processes by those affected by the design decisions. Participatory design thus first saw changes in design research and practice in areas of design such as healthcare (Donetto et al., 2015; Kushniruk & Nøhr, 2016).

Authors, however, argue that participatory design should not be simply for the sake of participation. The key issues with this relatively recent concept were in as far as the design process was able to define the *'who', 'how', 'when'* and *'what'* in regards to the interests and objectives of design (Schuler & Namioka, 1993). The process of participatory design was, therefore, that of engagement with the various stakeholders during design to reinforce the evidence base that informed design decisions, rather than simple participation. Participatory Design in terms of this research was therefore, geared towards integrated environments and systems that facilitated professional collaboration among design teams and professional stakeholders in shared understanding and definition of project requirements. While research has since opened the discussion regarding the understanding of the vital role of collaborative and integrated design processes; the complex dynamics of design in respect to Requirements Management do not appear to be adequately addressed; vis-à-vis user engagement. The main gap in Participatory design practice, therefore, extends to the modelling of the complex but vitally crucial contributing role of end-user dynamics to the successful understanding of project objectives.

Björgvinsson et al. (2010), underscore this position adding that the principles of the participatory design needed to move beyond the workplace. Recent research by Bratteteig and Wagner (2016) has also argued for a new understanding of the intricate design decision making processes that support participatory design. Additionally, the methods and techniques that support participatory FED appear mainly explanatory/rational[4]. According to Bae et al. (2017) and earlier Lawson (1983), these approaches merely rely on the experiences of the designers. Some research argues that these may be unable to cope with the complex dynamics of FED and project contexts (Bae et al., 2017).

Additionally, Participatory design in a Benefits Realisation perspective appears to be targeted towards the organisational/portfolio/program level of project implementation (Kensing & Blomberg, 1998; Muller, 2009). The new concept of participatory design suggests a vital new movement in design practice in embedding user participation in the process. Gaps in its original conceptual understanding and continuing application, however, suggest a need for more research to support complex contextual collaboration among stakeholders. New knowledge can also harness opportunities for participatory design from a task, activity, and process levels project implementation.

Crucially however is a similar position of value co-creation from a lean perspective (Koskela et al., 1997; Mota et al., 2019). Koskela et al. (1997) are among increasing research that argues for integrated product development processes to focus on value to end-user. Lean design management, according to Mota et al. (2019), allows for design processes to focus on the inherent chaos in design. In participatory design just as in lean design management, design processes are noted to have improved communication, knowledge sharing and information exchange among stakeholders in the delivery of value alongside better transparency in processes (Mota et al., 2019). The success of both concepts appears to hinge on a level of structure in the processes to support stakeholder engagement. A structure can be in the form of logical, methodical and objective processes, according to Bae et al. (2017). Bringing structure to FED is, therefore, a crucial part of the delivering value through integrated and participatory design processes that also ultimately supports planning and control of project processes.

Approaches as participatory design principles and value co-creation, therefore, present significant opportunities in FED processes. However, these opportunities remain yet to be fully harnessed as a driver to improved end-user focussed value in FED processes. For instance, while participatory design principles and co-creation are vital in supporting process management, the nature of design means that often, the intended structures in design processes

[4] Rational/Explanatory in the understanding of this research relates to Design thinking dominated by logic or reason

can be impacted on by uncertainties as a result of the *'structure and agency'* nature of design (see section 2.2.4). New understanding of these dynamics is therefore vitally needed in FED.

On the other hand, participatory design seeks to integrate stakeholder needs into design decision making early in the project life cycle, including the aspects of needs of end-users and the community. FED, however, remains understudied (Hedges et al., 1993; Hwang & Ho Jia, 2012; Samset & Volden, 2016; Smyth et al., 2018); which limits the application of such principles in this project delivery stage.

2.2.3 Conceptualising the Structure of FED

It has been highlighted in section 2.2.1 how increasing research points to a still largely unstructured FED process in practice and the uncertainty this bears on design (Austin et al., 2001; Macmillan et al., 2001; Burger et al., 2019). It is also seen that its contributing role in value generation is still limited (Hwang & Ho Jia, 2012). Yun et al. (2012) note the varied structure and dynamics of FED processes among projects even those in similar contexts; while Gibson et al. (2010) highlight the vital link between successful Benefits Realisation and a structured FED.

Structuring FED according to Oh et al. (2015) facilitated a collaborative design process enabling information sharing; action that ultimately contributed to addressing issues of constructability. Regarding project time and budget forecasting, Jung (2008) highlighted the vital role FED plays by drawing focus on project specifics, contextual nature of teams and available evidential support. The influencing role of FED in forecasting and prediction in green design is, for example, highlighted by separate studies by Hollberg et al. (2018) and Tiwari and Jones (2015). According to Hollberg et al. (2018), FED presents a significant opportunity for optimising these parameters for the successful delivery of project objectives. Structured FED decision making is, therefore, crucial in drawing out interdependences in user and design attributes for optimising them. Elzomor et al. (2018) argued that a planned/structured FED is essential to reducing uncertainty and hence waste in downstream processes.

Additionally, as argued by Smyth et al. (2018), value creation ought to be seen from a front-end perspective for its opportunities to improve Benefits Realisation through structured design decision making. The key elements from the foregoing in the understanding and practice of FED are, therefore, that:

- Structure needs to be brought to FED processes to cope with contextual dynamics (Gibson et al., 2006; Gibson et al., 2010).
- Collaborative, participatory and integrated product development environments need to be fostered (Simonsen & Robertson, 2012; Bratteteig & Wagner, 2016; Kushniruk & Nøhr, 2016).
- Value co-creation is essential in bringing the needs of stakeholders and end-users in particular to FED design decision making. This can support trade-offs in decision making in ensuring stakeholder goals and desires are reflected in the intended project benefits (Haddadi et al., 2016; Cohen et al., 2017; Smyth et al., 2018; Ranjan & Read, 2019).
- That design decision making in FED impacts Benefits Realisation in projects (Serra & Kunc, 2015; Waring et al., 2018).
- That overall, the interdependences among all these dynamics are iterative.

Figure 2-2 illustrates a summary of these concepts and how they relate to the research problem.

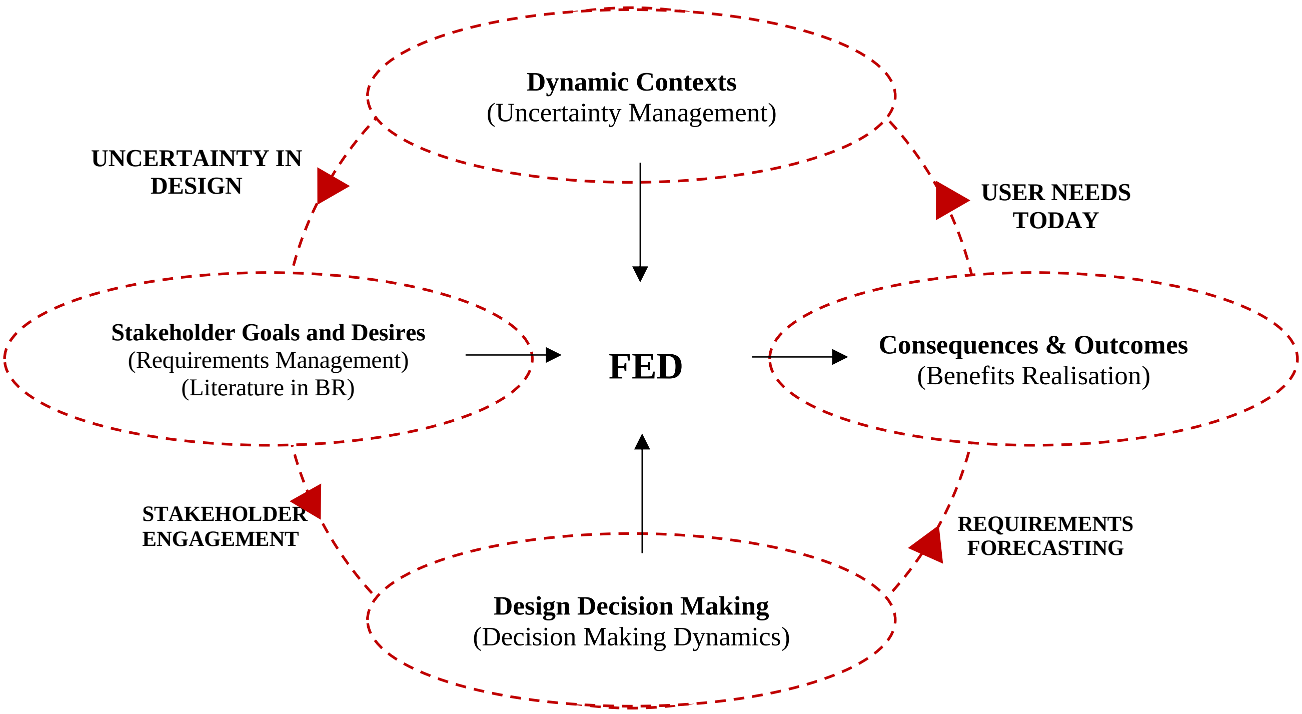

Figure 2-2 The Decision-Making Context in FED

The FED framework in *Figure 2-2* illustrates and summarises how these key conceptualisations interact in a system[5] to bring about value in FED. First is the dynamics in project contexts that form a key influencing element in decision making impacting on stakeholder goals and desires,

[5] The term 'System' is taken as the set of processes, elements, and their interactions both within the system and outside of it.

and the consequences and outcomes arising out of any trade-offs. Design decision-making process itself, therefore, relies on the delicate balancing of these elements, including stakeholder engagement that runs alongside a Requirements Management process in harnessing user needs and defining project objectives. Influencing factors such as these, for instance, impact on the extent of collaboration, participation and integration in the project delivery, information flow and exchanges, and lastly the knowledge management for design decisions.

Influencing factors and attributes are explored in more detail in chapter 3 for their interdependence and practical applications in a systematic review, exploring the concepts of Requirements Management and tools for uncertainty modelling and requirements forecasting in FED. A key element in this interaction is changing requirements. This brings requirements forecasting to the centre of the design dynamics, including the need for new understanding, tools and mechanisms that can support modelling, to keep in pace with change because of contextual factors. Thus, the rest of the literature review explores these concepts in FED and how they relate to Benefits Realisation.

2.2.4 Mapping FED

A vital part of structuring FED lies in understanding and mapping of its processes. Two theoretical positions emerge in understanding FED, i.e. the nature and process of design. The first involves analysis and synthesis as theorised by Codinhoto et al. (2006); while the second relates to the process of design itself as understood and represented by authors as Markus (1969); Lawson (2005) and the Sinclair (2013). Both author positions are vital in mapping the *'structure and agency*[6]' of design as understood in the social sciences.

Regarding the *'structure'*, Kagioglou and Tzortzopoulos (2016) highlight this as *"action and the actors involved in both undertaking and enacting processes"* while *'agency'* is referred to as the representation of the different stages and phases in design. It, therefore, is apparent that the *'structure'* of design underpins the *'concepts and logic of analysis and synthesis'* in the design process (Codinhoto et al., 2006). The authors have argued for a stronger rational method and linked this to waste reduction opportunities in design. Herein lies the foundations of the debate; however, that has dominated the *'structure and agency'* debate in social sciences.

[6] The debate on the structure and agency (see section 2.2.4) is considered in wide detail in the social sciences about what hold primacy in institutional theory. The positions and debate adopted for this thesis is that by Harmon et al. (2019) and Cardinale (2018)

Harmon et al. (2019) and Cardinale (2018) highlight the constraining impacts of *'structure'* in orienting actions towards a choice of possibilities for actors alongside any enabling opportunities. The authors additionally highlight that '*agency'* can be both pre-reflective and reflective in nature. Essentially, both these positions suggest that design can be impacted on by social positions and habitus as part of the analysis and synthesis processes. Contextual influences such as these can impact on any logic, uncertainties in processes alongside any rational thinking as highlighted by Codinhoto et al. (2006). On the other hand, the debate is essential in bringing to the fore the question of whether design is only limited by the individual, organisational and societal factors.

This debate suggests that design as a rational process has its limits potentially bounded by current biases within bodies of research be it in paradigms, practice, or AEC design processes. The suggestion here is also that subjectivity and preferences structures in design decision making (discussed later in section 3.4.3) are influenced by the *'structure and agency'* nature of design. Moreover, simplified decision making, e.g., that based on model-based decision support tools and frameworks, continues to focus on similarly simple deliverables. A move to map FED, therefore, presents opportunities to explore the intricate dynamics of design decision making and model the complex contextual dynamics that influence as it appears to be constrained by the *'structure and agency'* nature of design. This step is also essential in exploring the role of utilitarian decision making (see later in section 3.4.3) in integrating subjectivity in its modelling approach, something that is central to the development of DESIDE.

The RIBA plan of works previously introduced provides an underlying schema that is a basis to characterise FED. RIBA sees FED as a process of 1) assimilation, 2) general study, 3) communication and 4) development. In light of the preceding discussion, the last RIBA characterisation lends to the *'agency'* of design and can rely on the reflective consciousness of the designer in as much as it is constrained by the first three *(the structure).* Similarly, the different positions in understanding from Lawson (1983), RIBA, Markus (1969) and later Maver (1970) are interpreted in the illustration in *Figure 2-3*.underscoring the divergence of the concept of FED; yet unifying in process concepts to guide understanding of the potential *'agency and structure'* issues that may arise.

Lawson (2005) describes that in the general study phase, the design process investigates the nature of the problem and any possible solutions or means to them. In the Assimilation phase, it is suggested that the design process accumulates and orders general information that are specific to the problem. The development phase sees the design process develop and refine viable alternatives while the communication phase engages with having these alternatives discussed among stakeholders, both internal and external (Lawson, 1983, 2005).

Markus (1969) for example, views design as a duo process of *'decision making'* and *'design'* in which analysis, synthesis, appraisal and decision-making work in tandem. Markus (1969) view of the design process is superimposed on the model in *Figure 2-3* as analysis, synthesis, briefing, and evaluation. In the analysis stage, the design process explores relationships for any patterns in the information and attempts to classify objectives. In this stage, therefore, according to Markus (1969), the design process will order and structure the design problem.

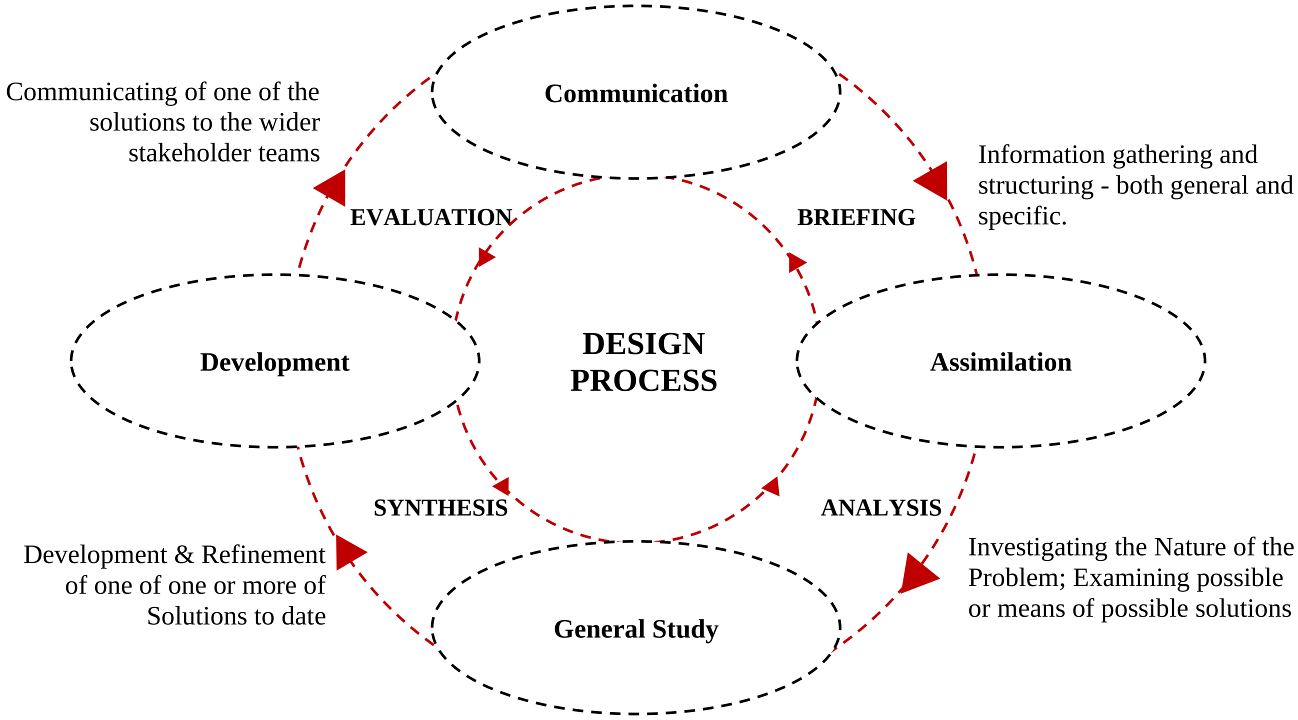

Figure 2-3 Conceptualisation of Front End Design Adapted from Lawson (1983 p.24)

Synthesis, on the other hand, involves responding to the design problem through the generation of alternatives in terms of potential solutions. The appraisal stage is the stage for evaluating and analysing the alternatives against set project objectives critically. Analysis, for instance, involves assimilative processes in which possible patterns in available information are identified and used to define the high-level goals. In the synthesis stage, the design process attempts to produce an outline solution to the problem. This is followed by the appraisal stage in which any alternative developments are judged against the objectives identified previously.

Lawson (1983 p.24), however, highlights that such mapping and similar ones only form part of the design process itself besides their incompleteness. Additionally, as pointed out by

Lawson (1983), these characterisations may not necessarily appear in any particular order. The illustration in *Figure 2-3*, therefore, maps the inherent *'agency'* nature of design involving analysis and synthesis and the evaluative and briefing processes that rely on information exchanges and flow. Similarly, the illustration relays the *'structure'* nature of design decision making that relies on communication, listening/assimilation, development, and general study.

The concept of analysis and synthesis appears to be at the centre of the intensely cognitive and rational basis of FED processes; just as it is vital in the broader design processes (Codinhoto et al., 2006). Codinhoto et al. (2006) have explored historical perspectives of '*analysis and synthesis'* going back to philosophical positions of Aristotle, Descartes, Newton, Kant, and Popper among others. In arguing for new models to support design decision making focussed on *'synthesis and analysis'*, the authors reinforce that deeper understanding is needed of these cognitive processes essential in waste reduction and value addition. However, these authors are not explicit in the link of the micro-system influences to design decision making such as those relating to *'structure'* influences. It, for instance, appears that *'Synthesis and Analysis'* are inherently prone to impacts of contextual influences during design decision making. However, these should run alongside the collaborative processes of evaluation and briefing to close the structure. It is, therefore, notable that FED is a thought process that can be improved through mapping the path in its processes e.g., in collaboration and integration of processes. Through an integrated thoughtful process, this structure can facilitate iteration of all these phases in development of the feasibility studies, brief, outline proposals, scheme design and concept designs.

2.2.5 Overview of FED Practice

Research in Serugga et al. (2020e), Gibson et al. (2010), Codinhoto et al. (2006), and Markus (1969) highlights the need for understanding design and perhaps to an intricate and structured basis. Other authors like Lawson (2005) however question whether any structure can develop the sufficiency and rigour on its own to support a successful design process.

Ultimately, each design will be specific to the *'structure and agency'* factors borne upon it. Even with logical maps, as suggested in the foregoing discussion, it may be impossible to anticipate the contextual uncertainty to impact on the processes fully. As observed by Lawson (1983), a structure can be constraining in itself in the search for the right information to support decision making reflecting the constraining influence of *'structure and agency'*. None the less, increasing research points to the benefits of mapping processes including understanding and bringing structure to FED processes e.g. in infrastructure (Gibson et al., 2010; Gibson & Bosfield, 2012; Yun et al., 2012; Exner et al., 2016; Horkoff & Yu, 2016), product design (Yang et al., 2015; Exner et al., 2016; Sousa-Zomer & Cauchick-Miguel, 2017); sustainable planning and development (Ritter et al., 2014; Tiwari & Jones, 2015; Ramaji et al., 2017; Taghizade et al., 2019), product and service systems design (Ross et al., 2004), manufacturing (Markou et al., 2017) and many others.

Table 1 is a summary of the key positions in current design practice relevant to this research. Firstly is Laurent and Leicht (2019) and Almqvist (2017) who separately explored how FED was essential in facilitating collaborative project teams. The authors found that project processes were able to enjoy flexibility in capacity while allowing teams to evolve alongside project needs. Projects were also able to leverage individual skills to meet these changing needs while contractual constraints were correspondingly less. Horkoff and Yu (2016) and Yang et al. (2015) separately explored Requirements Management in FED.

Table 1 Summary of Key Concepts in FED.

Current research	**Concept**	**Key Positions**
Samset and Volden (2016), Rezaee et al. (2014) Kim and Grobler (2007),	Design Decision Making	Decision-making impacts on FED processes and therefore vitally important to understand and contextualise during design.
Horkoff and Yu (2016) and Yang et al. (2015)	Requirements Management	The main objectives and key driver to the realisation of project benefits rely on adequately capturing, defining, and managing of project requirements.
Codinhoto et al. (2006), Koskela and Kagioglou (2006) Gibson et al. (2010) and Markus (1969), Lawson (2005)	Structured FED Processes	Bringing structure to FED processes is vital in supporting the quality, nature, flow, and exchanges of information that supports design decision making.
Almqvist (2017), Laurent and Leicht (2019), Boukhris et al. (2017) Halttula et al. (2017) Exner et al. (2016)	Collaborative and Integrated environments	Collaborative and integrated environments in projects are vital to project success and are better fostered in FED of projects.
Fuentes and Smyth (2016); Boukhris et al. (2017); Zhao and Cheng (2017)	Value Co-Creation	The purpose of projects is to deliver value to end-users. Value, therefore, can better be delivered through co-creative environments.
Ramaji et al. (2017), Ye et al. (2015), Rezaee et al. (2014), Gibson et al. (2010)	Modelling and Optimisation	FED presents opportunities for optimisation and modelling of the complex dynamics of design decision making to facilitate value delivery.

While Yang et al. (2015) highlighted inadequacies in current approaches, Horkoff and Yu (2016) argued the need for new models to support FED requirements definition and management. The authors at the same time point to potential difficulties in Requirements Management based on limited project information that impacts the evidence base informing design decision making. Additionally, the authors argue that in FED, requirements are in the main primarily high-level presenting challenges for empirical based models to support performance assessments. Both studies, however, point to experiences in the IT and information systems and their approach is again in the main still explanatory; perhaps adding to the challenges in coping with contextual complexities. A more relevant study by Kim and Grobler (2007) explored decision making in FED and highlighted complexity in current approaches to adequately support processes at this stage. Ramaji et al. (2017) add that errors and, therefore, waste abounds in the process due to the limited interoperability between such tools adding to the tedious decision making. There are inherent uncertainties among decision-makers that ought to be accounted for (Rezaee et al., 2014; Ye et al., 2015). Rezaee et al. (2014) argue that current tools inherently lack an assessment of confidence level among decision-makers as to the extent their decisions support the overall design and project objectives. Samset and Volden (2016), therefore in reinforcing continuing insufficiencies in current decision-making approaches argue for more research into this knowledge area.

A study by Boukhris et al. (2017), highlighted the positive impact of early user participation in FED processes in contributing to value co-creation. Laurent and Leicht (2019), Boukhris et al. (2017), Halttula et al. (2017) and Exner et al. (2016) on the other hand explored opportunities for FED to facilitate integrated early customer engagement. Exner et al. (2016) found that when FED is planned, organisations are allowed the space to *'innovate their portfolio'* something that supported creativity and development of adaptable solutions. While creativity and innovation appear to have a central role in FED, Fuentes and Smyth (2016) argue that more research is needed to explore further the opportunities for value co-creation in AEC processes.

2.3 Benefits Realisation in FED

Bradley (2016) has highlighted (see sections 1.2 and 1.4.2) Benefits Realisation to be a positive outcome of change to project stakeholders, a concept that is currently gaining wide appeal in many sectors. The concept has roots in the 1990s IT/IS sector (Tillmann et al., 2010). Its main aim is in satisfying end-user needs, be it in terms of benefits or utility, also referred to as *'Value-In-Use'* (Sweeney et al., 2018).

The Benefits Realisation approach is broadly to identify and quantify benefits followed by valuing and appraising them, and finally planning, realising and reviewing the defined benefits (Kagioglou & Tzortzopoulos, 2010; Jenner, 2012). Esteves (2009) argues that Benefits Realisation should take a whole project life cycle view of benefits delivery. According to authors such as Yates et al. (2009), the Benefits Realisation approach extends the measurement of project success from delivery time, quality/scope and cost savings to target and derived benefits. Project Benefits are, therefore, the driver of performance assessments a significant change from traditional approaches. There is however still a limited application of Benefits Realisation, according to Smith et al. (2008). Remenyi et al. (1998) add that in some cases when it has been applied, the process of continuous evaluation has been limited. Yet, it is vital in focussing projects the processes on the change needed both at the business strategy level and in use during the project life cycle. The change at the heart of Benefits Realisation is often seen at an organisation-portfolio-program level where strategies reinforce business objectives in implementing projects (Serra & Kunc, 2015).

In this view of Benefits Realisation, the benefits support business strategies. However, Kagioglou and Tzortzopoulos (2016) have argued such a position may falsely assume a link between a business strategy and project outcomes. In terms of FED, this requires a look at processes at the process-activity-task level by examining and understanding the decision-making dynamics crucial in linking the business strategy to value in use. It is, therefore, important to look at the whole spectrum of the design process, including its key influencing factors such as contextual dynamics, inherent stakeholder biases, project aims, and use need changes. It also means effective processes and models that support the critical link between inputs-outputs and outcomes to move beyond target benefits (Maylor et al., 2006; Kagioglou & Tzortzopoulos, 2016). Benefits Realisation in FED is, therefore, a vital anchor for design decision making, Requirements Management, value co-creation, optimisation of project objectives and embedding of collaborative and integrated environments within the design process.

"What we should make is the wall on which everyone can write whatever he/she wants to communicate to others" Hertzberger (1971)

According to Hertzberger (1971), design should ultimately be a process of creating experiences from derived benefit. Similar sentiments have since been raised by researchers such as Koskela (1992) arguing for a focus on value to users in AEC processes. However, research continues to show challenges within the wider AEC in the delivery of intended projects benefits (Bradley, 2016; Tezel et al., 2018; Burger et al., 2019). Some research attributes this continuing failure in the delivery of core project objectives in part to contextual complexities and uncertainties inherent within many projects environments (Burger et al., 2019); and insufficiencies in Benefits Realisation practices (Bradley, 2016). In regards to Benefits Realisation practice, Kagioglou and Tzortzopoulos (2016) highlight the continuing need to move beyond simple deliverables and focus on the benefits in use during projects delivery. A focus on benefits in use places the necessity on design to look further into the future and embed structures and processes in projects that are responsive to the changing needs of the user. A successful Benefits Realisation program is therefore not only aimed to manage the delivery of target benefits but also to engage stakeholder's and end-user realistic through measurable requirements for collaborative implementation their desired benefits (Del Águila & Del Sagrado, 2016; Horkoff & Yu, 2016).

According to the PMI's PMBOK Benefits Realisation is the *"outcome of actions, behaviours, products or services that provide utility to the sponsoring organisation as well as the program's intended beneficiaries"* (Larson & Gray, 2015). This definition presents a few concepts important for design decision making, namely, the outcomes, i.e. the design product, beneficiaries – the end-users, behaviours reflecting stakeholder engagement and the organisation. The concept of utility is also vitally important for the understanding of the critical dynamics underlying design practice and extends from this understanding of Benefits Realisation in this research. It is this Utility in this understanding that, proposes Benefits Realisation as value-in-use according to Sweeney et al. (2018) and Tillmann et al. (2012), and consequently an assessment *'of and by'* the end-user of the derived benefit.

2.3.1 The Concepts of Benefit and Value in Use

The concept of value in use and benefit has been discussed interchangeably in many research (Tillmann et al., 2010; Tillmann et al., 2012; Sweeney et al., 2018). Sweeney et al. (2018) postulate benefits as *'value-in-use'* as opposed to *'value in exchange'* another value proposition. Philosophical positions on value have roots in history, including Aristotelian and Platonic times. Plato sees value as that which is *"intrinsic to the ideal form underlying the item"* while Aristotle sees it as that which is *"intrinsic to the natural end the item serves"*. Both positions lend to something beyond the output of a process such as utility or benefit. Value derives its meaning from the original word *'Valere'* that later transformed into the old French word *'Valoir'* which both stand for *'to be worth'*; essentially meaning that one regards something to deserve higher importance/worth/usefulness/significance than another in the process of interaction with it. The position that value-in-use lends to utility (Kleinaltenkamp & Dekanozishvili, 2018) is much in agreement with early conceptions of value.

According to Shewhart (1931), value is a collection of subsystem level conceptualisations, the aggregate of which constitute the overall value. Shewhart (1931) earlier argued that a minimum number of these subsystems is required if one should represent the overall value conceptualisation. Over time, rationalisation thus aligns the subsystem value that becomes the basis for future judgements for any given group of a value proposition (Shewhart, 1931). The subsystem level conceptualisations thus are seen to be the basis for the higher importance in any value judgement. This is the basis of the value theory that can be traced back to the Aristotelian's *'doctrine of the mean'*; that states that *'virtue is the mean state toward good activities, and a virtuous person behaves appropriately out of his mean state'*.

Since according to Sweeney et al. (2018), benefits are value-in-use, firstly, this places derived benefits into two realms, i.e. one of decision making and rationalisation and explanation of behaviour towards the benefit. According to Shewhart (1931), it thus follows that an end-user N is assumed to derive a benefit X from an attribute Y and that in that course, N takes seriously the subscription to X in his/her actions when making relevant choices in its regard. The actions contributing to attribute Y are reflective of $N's$ subscription to X. Aristotle earlier had alluded to the intrinsic value being that which is inherently useful out of reason to the end-user. Authors such as Sweeney et al. (2018) and Shewhart (1931) merely reinforce human cognition in value perception something that makes rationalisation a vital element of design decision making.

The cognitive role implies firstly that an end-user's perception of derived benefit, therefore, relies on the causes and the reasons and motivations. It is also secondly imputed that *'reasons and actions lend to end-user goals'* underlying user preference and judgement structures of a benefit. Subscription/devotion, on the other hand, lends to both reasons and causes that the end-user tries to justify through explanations during the interaction. According to Sandström et al. (2008), value-in-use is a reflection of the sum of *'the functional and emotional value'* of that interaction.

The first suggestion from the preceding is that preferences/judgement and goals are what an end-user soon confounds as a benefit, and therefore the latter are indicators of the former. The second is that alluded to by Ballantyne and Varey (2006) that value-in-use is co-created with the end-user so that it is relational and communicative to them and that it relies on knowledge derived from them. This position draws relations to design as understood by Lawson (1983 p.172) that it is a decision making and value judgement process that is intensive in language and communication. Ballard and Koskela (2013) also add that design is a co-creation endeavour that it involves communication among various stakeholders. The authors add that communication and language in the form of *'rhetoric*[7]*'* are essential to the process of planning and coordination of design. After all, communication and language are useless if no one else is involved, Lawson (1983 p.172) asserts. The understanding of Benefits Realisation from these theoretical positions suggests a link between its key conceptualisations and those of participatory design, the role of *'structure and agency'* and the need to map FED processes in the delivery of project benefits.

2.3.2 Benefits Realisation in Practice

Benefits Realisation as a concept has gained wide use across many sectors of industry from its early days of the 1980s (Darwin et al., 2002; Sapountzis et al., 2008c; Breese, 2012; Doherty et al., 2012; Serra & Kunc, 2015). Many applications are reported in healthcare, IT, and social enterprises. In the IT sector, a Benefits Realisation approach delivered great successes for rural Cambodia (Grunfeld et al., 2011). Grunfeld et al. (2011) report of social benefits delivered through community empowerment and bringing interconnectivity and many more others exist in literature. Benefits Realisation models have been devised to draw focus on the essential elements in the implementation of Benefits Realisation in all such cases (Sapountzis et al., 2008c); to support Benefits Realisation management and planning. According to Farbey et al. (1999) Benefits Realisation management is that process by which benefits are organised and managed to be realised. Serra and Kunc (2015) demonstrate through one such model the intricate dynamics in Benefits Realisation and management, including how strategic initiatives relate to organisational capabilities in supporting change. The authors illustrate the transformation from current to desired value through enabling outputs to desired outcomes that deliver benefits that ultimately generate desired value for end-users. Such author positions, therefore, suggest a need for structured processes to be able to track outcomes throughout the realisation cycle.

However, Kelly et al. (2014, p. 53) add that structured benefits management should be a continuous process from the start through to implementation and beyond. Adopting such a structured approach thus presents potential opportunities in the delivery of benefits as it can

[7] That which lends to *'reasoning that oratory'* (Ballard and Koskela 2013)

draw focus on such intermediate benefits as FED. Serra and Kunc (2015) have argued that it is these cumulative intermediate benefits that are essential in contributing to the realisation of the full end benefits; which in turn contribute to the achievement of strategic organisational benefits. Badewi et al. (2018) add that achieving any higher-level benefits relies first on realising a significant number of intermediate ones. Conversely, it can be deduced that a lack of success in such intermediate benefits as FED can mean adverse outcomes including those relating to lean wastes such as making do, waiting, over-processing, inventory and others; leading ultimately to lost value. It, therefore, appears that continuity is a key element of a Benefits Realisation strategy and is particularly crucial in linking intermediate benefits from processes such as FED to downstream processes in implementation and project end of life.

Figure 2-4 summarises the essential theoretical positions in reflecting FED as part of this continuum if the delivery of project benefits in AEC. The illustration casts FED in an organisational/program/portfolio frame in as much as it fits in the wider project lifecycle from an implementation perspective. Essentially, *Figure 2-4* illustrates that FED is the anchor in the cycle right from the strategy, at organisational, portfolio and program through to corporate and business levels on the one hand. On the other iteratively, FED links the implementation and use phases.

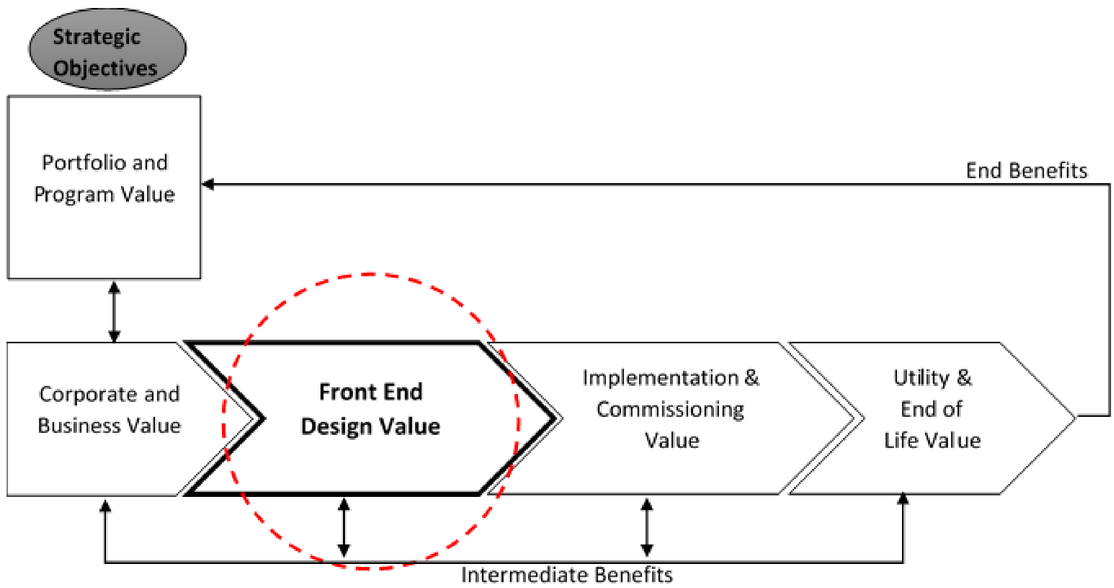

Figure 2-4 Illustration of value generation in a Benefits Realisation Perspective – Adapted from Kelly et al. (2014, p. 303)

In the process of realising benefits, Sapountzis et al. (2008c) observe that change can sometimes mean unplanned or emergent benefits/disbenefits. Williams and Parr (2006) attribute this in part perhaps, to ambiguity in defining the project and program goals. It, therefore, seems that bringing structure to intermediate processes within a Benefits Realisation plan can be a critical element in the project success as it brings clarity in aims and goals of processes while ensuring ownership of the same. Similarly, it appears logical by extension to infer that any structure, even at a generic level, can contribute to added value as it can draw out opportunities in promoting integrated and collaborative environments around the project goals. It is such opportunities that can be essential in focussed decision making, e.g., in the management of project requirements in the often complex and uncertain design processes.

Despite an increasing body of research around and practice of Benefits Realisation and its increasing contributing role to delivery of projects, there is little evidence of bringing these benefits to intermediate processes, particularly in design practice. It also suffices to mention that any successes in FED as an intermediate process depends on understanding and managing the process-specific complexities; and contextual complexities that impact on benefits delivery. An example of a practice-based Benefits Realisation strategy that aimed to address part of these issues is the U.K. HaCIRIC in the U.K. health sector. This research and implementation developed a Benefits Realisation (BeReal) model for the built environment infrastructures (Sapountzis et al., 2008b; Sapountzis et al., 2009; Yates et al., 2009). The BeReal model for U.K. health built infrastructure aims to be a collaborative platform that supports decision making and promote continuous improvement and learning within the organisation by being evidence-based (Sapountzis et al., 2008b; Sapountzis et al., 2009; Yates et al., 2009; Kagioglou & Tzortzopoulos, 2010, p. 172). Conceptually, Benefits Realisation's focus appears to be on projects delivering strategic business and organisational objectives through change that impacts on outcomes *".....overarched by the continuous improvement principle resulting into a continuum of Benefits Realisation and organisational learning"* (Sapountzis et al., 2008c). At the same time, Benefits Realisation brings structure to project processes in focusing on outcomes and benefits.

Such models have been important in demonstrating the practical applications and conceptual interpretations of Benefits Realisations. Such models firstly, suggest that a structured approach that involves building a strategy, profiling and mapping, devising a realisation plan and evaluation and review process (Kagioglou & Tzortzopoulos, 2010) is essential. However, such models as BeReal need to go beyond their current applications at the project performance level it is suggested. This extends to the acknowledgement of the role of intermediate successes in contributing to overall strategic objectives. New approaches with a focus on decision making that draw to the specific complex trade-offs processes in realising benefits in FED need to be devised. However, it is also increasingly accepted, and as highlighted in chapter 1, the increasing complexities in project delivery and contexts mean these new tools have the capacity to adapt to the changing dynamics in projects continually. For instance, emergent and unplanned benefits can be dynamic; just as communication, rationalisation and reasoning/trade-offs that are essential in the Benefits Realisation processes. Robust new and complementary tools that model such dynamics present that step-change in Benefits Realisation practice contributing to structure and agency in Benefits Realisation.

It is important to reinforce that design as part of Benefits Realisation remains while peripheral, a heuristic process. Rationality in this case as established by authors such as Breese (2012); Doherty et al. (2012) Friedman (2003) and Darwin et al. (2002) meant that the current role of design in Benefits Realisation is one of thoughtful transformation into something new or something more desirable through problem-solving. Darwin et al. (2002) use terms such as *'logic, linear thinking, reductionism, split between thinking and doing'* all of which espouse rational design decision making. Esteves (2009) however proposes that design decision making should carry along with it not only the focus on the outcomes but also evaluations of their impact and problem solving all of which are key elements of decision making. It, therefore, suggests that sometimes, the complexity of these endeavours mean that robust processes based on structure, empiricism and quantifiable evaluations can better cope with these complex dynamics. The foregoing thus brings to the fore two important observations in regards to the role of FED as an important intermediate process in Benefits Realisation of projects all of which are illustrated in *Figure 2-5*.

- Benefits management strategy be it at organisational, program, portfolio or project level should engage with important intermediate processes key to delivering intermediate benefits to foster organisation strategy.
- Benefits Realisation planning, including defining high-level benefits goals and evaluation and reviews have to align with key intermediate goals to support any intermediate benefits in a structured and measurable manner; with robust processes able to cope with any emergent complexities and dynamics.

2.3.2.1 A Benefits Capture Model for FED

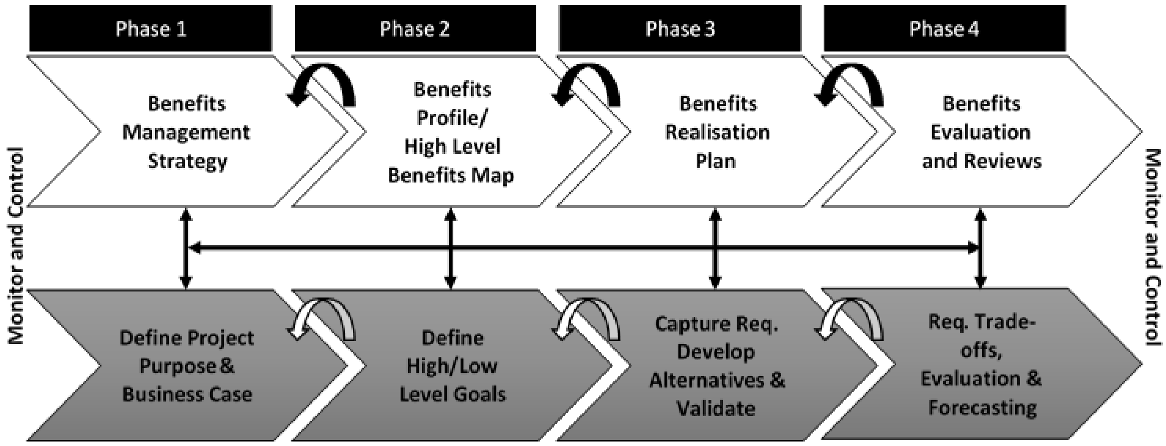

Figure 2-5 The Benefits Realisation Model - Adapted from: Kagioglou & Tzortzopoulos, (2010, p. 172)

From *Figure 2-5* aim is to capture the essential elements of Benefits Realisation and interface them with FED processes as an intermediate Benefits Realisation process in a four staged approach to attempt to recast the foregoing discussion in a FED perspective.

Phase 1 represents the development of the benefits management strategy. Such a strategy at FED level involves ideation and inception and developing the business case around the idea and aligns with organisational strategy. A high-level purpose that aligns with the organisational aims is vital to be established, and the feasibility should espouse the target benefits. In this stage, clarity in identifying strategy, to underpin later project successes is required. Workshops serve as good opportunities in establishing early collaborative frameworks involving stakeholders to inform the definition of essential requirements.

In phase 2, the essential benefits that are gathered at this point are defined, including understanding any interdependences that will impact on overall system benefits. At this stage, measurement criteria are defined. Authors argue that it is essential to clearly define the project methods and goals (Turner & Cochrane, 1993). Simon (1996, p. 8) argues that only the overall outer goals and characteristics.

Either way, from a FED perspective, phase 3 represents the development and validation phase in which the Benefits Realisation plan considers the alternatives that align with the project goals. Outline designs, models, 2D and 3D drawings are developed of alternative solutions to be tested against any explicit and implicit benefits (Lawson, 2005, p. 48). This stage is vital in requirements capture and benefits definition as detailed design plans probably may do less to illuminate and inspire user collaboration. Collaboration can, for example, mean that stakeholder interaction with 3D illustrations and any imagery can elicit clarity in defined user requirements enhancing the body of evidence from any feedback. Complex requirements modelling tools such as QFD can also be used in this stage to enhance knowledge and evidence gathering, essentially establishing knowledge and dependence matrices among attributes.

Phase 4 is the stage when decisions are taken on the expected value-in-use or derived benefit through trade-offs. In this stage, measurable and quantifiable attributes and consequences have to be established. Keeney and Raiffa (1993) say that it is vital that all attributes identified are distilled into their lowest quantifiable form something important in this stage. In the absence of a quantifiable level for an attribute to be distilled, the authors argue that a focus on utility allows for proxy attributes and direct preference measurements to be used.

The preceding section has sought to discuss Benefits Realisation and to link it with FED. It has been illustrated that Benefits Realisation planning and management can enhance FED as an intermediate process contributing to wider end benefits and ultimately organisational strategy. The next section aims to extend this understanding to the wider value theory.

2.3.3 Value Management in FED

A brief philosophical conceptualisation of value was introduced in section 2.3.1. Maguire (1971) argued that designs have to deliver *'near needs'* that sometimes can be abstract or concrete. Beyond this basic position and the emergent understanding of value-in-use, value management more generally has emerged as an aim for projects. In practice, however, challenges still exist resulting from knowledge deficits that contribute ultimately to uncertainty in decision making and rationality inherent in the FED processes (Drevland & Gonzalez, 2018; Hatoum et al., 2018). Chen et al. (2010a) define value management as *"the use of combined common sense and technical knowledge to tackle non-value-adding costs".* This definition firstly lends to exploiting organisational resources to generate value through effective and collaborative production processes while improving efficiencies as earlier highlighted by Faniran et al. (1997). This understanding of value places the importance of FED seen earlier in 2.2 at a crucial and essential stage in the evolutionary processes of project delivery cycles.

It secondly suggests that rationalism and use of 'experience' in the process of value generation yet leaving room for empirical processes. This point is covered widely in this research throughout.

Thirdly, it suffices from this definition that value management is integrated and collaborative (Kpamma et al., 2017; Arroyo & Long, 2018; Schöttle & Tillmann, 2018), communicative (Ballantyne & Varey, 2006); through design that addresses a problem (Lawson, 1983, 2005), by the understanding the end-user goals and desires (Almqvist, 2017; Mok et al., 2017) in supporting any trade-offs in the definition of the goals and methods of a project. Such important elements are captured in the illustration in *Figure 2-6.* from a means-end-chain perspective. [8] The figure illustrates value evolution, starting from the goals and desires of stakeholders through to terminal value.

Abstract goals and desires are intangible and are essentially a summary of constellations of the concrete attributes; while concrete goals are usually explicit, one-off attributes.

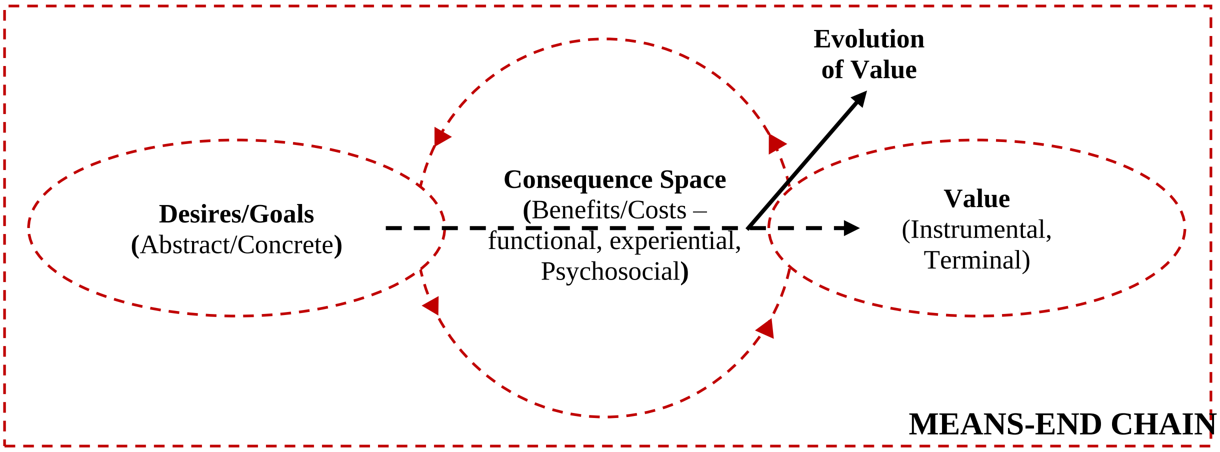

Figure 2-6 Means End Chain - A Design Perspective Adapted from Gutman (1982)

Consequences are transformational in the sense that they straddle from functional (such as space requirements, costs/money) to psychosocial (including status that is judged by others towards self and self-esteem gained from oneself); to experiential consequences (essentially sensual experiences of the space that bring happiness and wellbeing to the user). In terms of value, it thus transpires that it can be instrumental in which case it is action-based or terminal in which case it is the value as an ultimate personal experience. The evolution of value propositions, judgements and conceptions appear to implicitly assume *'utility'* or value-in-use. However, it appears that value in this understanding can be difficult to quantify and sometimes qualify across the spectrum as opposed to benefits (value) that can be quantified and optimised on the basis of utility/outcomes for efficiency and effectiveness of design processes. Value

8 Mean End Theory lends to user values, desirable end-states of existence that crucial in choice patterns and that in consumption decisions, decision makers compound choices such as based on competing products to simplify their choice decisions (Gutman & Reynolds, 2001)

management, although important in FED, ought to adopt this latter position as a way of embedding quantifiable processes in its evolutionary course, particularly in the consequence space during decision making.

According to Dlouhy et al. (2018) the effectiveness and efficiency in processes should be for the sole purpose of value creation for the benefit of the end-user. FED represents an early opportunity in the project development cycle for end-user participation and participatory Requirements Management. However, Dlouhy et al. (2018) argue that generally, there have been limited studies to support understanding of this value proposition. This more generally could impact on how design practice can embed value management practices early in the project development. Lawson (1983) adds to the increasing body of research to confound this growing dilemma in architectural practice. Lawson (1983) for instance observes that during design, there is intense rationality ongoing in the mind of the designer[9] during analysis, synthesis and making decisions. There is little evidence in practice and research on how this rational thinking can contribute to value in design.

Arroyo and Long (2018) add that much of this important decision making often takes place in isolation devoid of the critical collaboration and integration required of successful processes. However, it has been highlighted that all these elements are essential in value generation and may be critical for FED. Lawson (1983) adds that this endeavouring conflict between the value proposition of the design and the designer's inherent biases is a part of the uncertainty in value understanding in design. This draws to the role of *'agency'* seen earlier in section 2.2. in influencing such processes as requirements transformation and understanding as well as the nature of structure in any value proposition process.

Lawson (2005) has observed that design predicated on the part of the designers inherently already limits the number of alternatives, something that in turn limits the possible value propositions. This has been seen earlier in section 2.2. to be at the heart of the *'structure and agency'* debate in facilitating or constraining design thinking. Perhaps in light of the complexity brought about by the furore of this endeavouring conflict, Maguire (1971)'s position that *"the one thing that is essential…….is formulation of the brief in terms of the need rather than the solution"* might suffice. The aim for design, according to Drevland and Gonzalez (2018) should be merely to seek answers to the problem before any undertaking of the technical formation of the design. However, these latter positions it is argued merely serve

[9] In this section, and often throughout the research, 'designer' means the professional teams as a whole including architectural, engineering, technical teams etc.

to accept modernist paradigms in managing design complexity that emphasises simply strengthening of the strategic capacity of processes around a core purpose even in the face of limited information. The reality it appears is that sometimes the brief may not fully reflect the problem in which case the solution may not be fully fitting either. Besides, even a fully formulated brief may still come under the influence of emergent contextual factors.

Kpamma et al. (2017) argue for design approaches to take on a more participatory role in understanding user goals and desires in place of roles concentrated in the design office a sentiment shared by Schöttle and Tillmann (2018); perhaps with tools to cope with any emergent complexity. Such tools are explored in this thesis for their opportunities and limitations in practice in supporting participatory and collaborative design decision making. Such tools as QFD (Mallon & Mulligan, 1993; Cristiano et al., 2001; Bolar et al., 2017) can provide for example support engagement among stakeholders to understand and map their desires in design. However, they appear to cope differently with contextual complexities e.g. the changing user needs in part due to the evolving sociocultural needs. This can be important as with Lasdun (1965) earlier who decried the pain of seeing his new designs almost *'destroyed'* by their new occupants when they made immediate changes to them. Hertzberger (1971) on the other hand notes that this perhaps reflected how design needed to foster the evolving user attitudes rather than constrain them. Such positions highlight the essential role of uncertainty in FED and the need to explore tools that better support design in coping with it. Kukulies and Schmitt (2018) and Shieh and Wu (2009) present such an approach that seeks to explore applications of mathematical principles to uncertainty to help bridge the gap between the target and derived value.

The suggestion from the foregoing, therefore, appears threefold; first, that value management in design should aim to aggregate the functional value of space in such a way that allows flexibility of form and function. The second is that value management in design should foster an environment of decision making based on co-creation and co-production that engages stakeholders along the project life cycle. The third is that design decision making ought to explore new opportunities away from traditional rational thinking to cope with contextual complexities and emergent influences.

2.3.4 Value Proposition in FED

"*Designers and those who make design like decisions which profoundly impact on the lives of many can no longer expect their value judgements to be made in private*" (Lawson 1983 p.62)

The concepts of participatory design and co-creation have been highlighted throughout the preceding sections in this thesis. It is noteworthy, however, that both concepts are interdependent with the concept of a value proposition[10] that Frow and Payne (2011) agues is the essential link between both concepts and project objectives. Value propositions, for instance influence such things as stakeholder roles and processes that underpin value generation in projects (Lusch & Nambisan, 2015). An integrated and collaborative design process is key to delivering value to the end-user (Gomes et al., 2017a; Rischmoller et al., 2018). An increasing body of research is arguing for value co-creation and co-production as a way of assuaging the divide between production processes and end-users (Fuentes & Smyth, 2016; Haddadi et al., 2016; Boukhris et al., 2017; Cohen et al., 2017; Kruger et al., 2018; Liu et al., 2018). The multi-stakeholder nature of FED means that value co-creation through collaborative, participatory and integrated environments is essential in developing value propositions able to map the stakeholder needs to derived benefits. The conceptualisation of a value proposition is thus considered important for FED in this research for its influencing role on design decision making. Skålén et al. (2015) highlight three important elements of a value proposition i.e. that relating to the i) provision, ii) representational and iii) management and organisation of production practices. The authors also add that these three practices can constitute innovations in new value propositions if they are integrated and collaborative in new ways and deliver on either existing or new practices or resources. Value proposition is, therefore, an essential element of value management in a co-creative environment.

Value propositions in design, however, rely in part on *priori-knowledge* (Lawson, 1983, 2005) to address a design problem by mapping any available information on the way to an innovative solution. It is a conceptual basis that suggests a link between value proposition and the *'agency'* nature of design. In a co-creative environment, Lusch and Nambisan (2015) argue that there is a need for mechanisms to support roles and processes that underpin stakeholder participation. Lawson (1983) however, cautions against rushed approaches that focus on the solution rather than the full understanding of the problem in identifying any key processes, for example, and

[10] Value Propositions is that which lends to generation, delivery, and perception of value in use

progressively building detail collaboratively. This perhaps is to guard against the constraining nature of the *'structure'* of design. The value proposition thus lies in successfully articulating the problem at hand (Lawson, 1983); essentially managing the project requirements within the *'structure and agency'* framework of design decision making.

In terms of the roles according to Chandler and Lusch (2015), value propositions should be seen as an invitation for participation among stakeholders; that is followed by active engagement and alignment along with the design problem following which the derived solution should deliver end-user benefits. Lawson (2005) therefore cautions on symbolism *(agency)* that can potentially conceal the problem at hand. However, he observes that too much of design practice quickly looks at existing symbols as a knowledge base to underpin new solutions; in a way, solutions predicate new design problems. Symbolism as a basis for value proposition in this case appears unable to account for dynamic contextual specific events. This also appears to hinder collaborative engagement and co-creation in design in a manner that supports new roles and processes based on the specifics of the new design problem, in addition to constraining potential alternatives.

The important point here, therefore, is that in the value proposition, integration, and collaboration work in tandem and provide the necessary vantage points among the collective skill set to address a design problem. Additionally, the concept of value proposition presents opportunities for design problems to be distilled into their subcomponent problems at the lowest level of problem definition. However, Lawson (1983) cautions against traps that disguise as solutions in the distillation process. A focus on value propositions, therefore, can ensure that design focusses on the core purpose and embed practice to cope with any emergent problems in the process. There thus should be continuity in the evolution of value during design throughout *'transformation of the design's fabric'* be it its materials or meanings (Lawson, 1983). Value propositions in design are therefore not only a process of adaptation sometimes through selectivity (when designs survive change moments and gradually ultimately through to the design's extinction), but also are also artefacts of emotional engagement with those that interact with them (Kolko, 2015).

The conceptual understanding of value proposition and its intricate dynamics with participatory and collaborative design suggests most importantly that in the evolution of value, not only does the artefact undergo a transformation, but so too does the problem to which it was originally designed to be a solution (Lawson, 1983) . Emergent and evolving problems can place levels of uncertainty on FED processes which calls for new ways in design decision making to keep solutions in tandem with design problems. In other words, the solution can only be fitting in eternity if the problem remained stable (Lawson, 1983), something that may not always be the case.

2.3.5 An integrated approach in FED

Deutsch (2011) defines integrated design as *"a collaborative approach to design characterised by early stakeholder participation who share risks, rewards and other benefits."*

Deutsch (2011) highlights that integrated design aims to tackle inefficiencies and waste while improving stakeholder engagement in the process of value creation at the level of *'structure'* of design. Lawson (2005) on the hand, highlights integration in design as reliant on language and communication. As a result, it appears that a major feature of integrated design is transparency. Integrated design is applied in such approaches as integrated project delivery.

The experience of value is influenced by *'agency and structure'* events which are many times learned states that change with time creating complex value judgements and user expectations (Rooke et al., 2010). While design has the role of meeting these complex rationales of users in an integrated manner (Li & Ma, 2017); authors such as Martinez et al. (2016) observe that design is still largely prescriptive and has not engaged with complex preference structures fully. The authors support the position that the rationale of a value proposition in design should only be about the end-user – and by extension, the goal of design is only in meeting end-user needs. In placing the user at the centre of design practice, Koskela (2000) adds that design practice needs an integrated understanding of these user goals and desires.

Similarly, one of the major constraints to value delivery in current design practice is limited integration of its process (Kpamma et al., 2017). Yet Lawson (1983, pp. 171-186) argues that with the wide acceptance that design is *'language and communication'* for demonstrating ideas and stated value propositions to others, it is essential that the process is participatory. In highlighting the inherently integrated nature of language, communication and design, Lawson (1983) argues that it is essential to understanding design in how it can represent the world around it.

"*In the undifferentiated experience of childhood, everything is woven together, drawing and words, representations and symbols, functions and meanings and only gradually are things put into separated categories*" Lawson (1983, pp.173)

The implicit suggestion is that integration is much more naturally facilitated in FED; and that when defining value propositions design has to explore opportunities in the design problem (Martinez et al., 2016); in the yet woven constructs be it in perceptions or requirements. Rooke et al. (2010) and Lawson (1983) argue for value perceptions as social constructs that are acquired over time. This learning and cultural orientation together with rational belief in objectivity lends to *'agency'* and '*Self-expression'* accounts for the more individualistic attitudes in design than for integrated processes (Lawson, 1983). Zhang and Su (2018) and Dernie (2016) argue for this individual creativity to remain fundamental to the primacy of design problem-solving. Dilnot (2018) however in quoting US designer Jay Doblin, argues that the rational designer is devoid of altruism; and thus, that integration ought to emanate from inside-out. Such theoretical positions indicate a dilemma at the heart of design thinking and decision making for integrated processes which call for more understanding into the extent they have to be supported to keep the focus on project benefits.

In progressively fleshing out the project functional and design attributes and their importance (Goswami et al., 2017), integration presents opportunities for devising solutions based on trade-offs for the various preference structures in view of the design problem. It suggests firstly that only with others can value propositions representative of the connected intellectual effort emerge. Secondly, it emerges that ultimately what value stands for is the aggregate of these expressions (self and social expressions) co-created in design, in what then becomes its symbolism and thought provocation connotations representational of the extent of the participatory environment.

2.4 Dynamic Project Contexts

Dynamic projects contexts have been shown to influence project outcomes in many ways positively and negatively (Collyer & Warren, 2009; Collyer et al., 2010; Petit, 2012; Collyer, 2015; Locatelli et al., 2017). In literature, they have been referred to as complex project contexts (Locatelli et al., 2014), dynamic environments (Collyer & Warren, 2009; Collyer, 2015), and dynamic contexts among other references. According to Collyer and Warren (2009), a dynamic project context is determined by *'rate of appearance and resolving of emergent unknowns'*. According to the authors, in a dynamic context, the appearance of unknowns supersedes the rate at which they can be resolved. The authors add that while convention suggests that dynamic environments be made static, this is not always possible because of the critical loss of productivity and opportunity.

Flyvbjerg et al. (2002) underscore the extent to which context-specific uncertainty influences benefits delivery because of dynamism in contexts resulting in context specific factors. In one study by Flyvbjerg et al. (2002), for example, it was found that projects in Europe and the USA, saw lower rates of perpetual underestimation than those in developing countries. There are perhaps various reasons for this but the fact such reasons confound to specific contexts draws focus on the importance of new approaches to understanding and underscoring contexts in projects. The differences between dynamic and static contexts are summarised in Table 2.

Table 2 Contrasting Static and Dynamic Environments - Source: Collyer (2015)

	Static Environments	Dynamic Environment
Pace of change	Gentle	Fast
Predictability	Realisable	Hard to Realise
Business cases	Stable over long periods	Quickly out dates
Change impact	Mostly Negative	Scope for opportunities and problems

Collyer and Warren (2009) and Simon (1996) describe dynamic systems as those involving the many interactions of many parts and that in these systems *'the whole is less than the sum of the parts'*. Dynamic systems are characterised by drastic, abrupt and volatile events (Floricel et al., 2016). It is also observed in the literature that dynamism and ultimately uncertainty are a present feature of all construction projects and processes to some degree (Simon, 1996; Collyer, 2015; Ahmad et al., 2018). According to authors, uncertainty can affect project benefits delivery in a variety ways and stemming from a variety of sources (Atkinson et al., 2006); not least from people and the environment (Fageha & Aibinu, 2013). Williams (1999) describes uncertainty borne out of dynamic contexts as a major part of complexity together with structural complexity. Moreover, some complexity in FED processes is borne out of and inherent of design processes Lawson (1983, p. 76). Lawson (2005) further adds that while some complexities stem from the integrated nature of design, others arise out of decision making biases on the part of the designers. Baccarini (1996) defines complexity as that which *'consists of many varied interrelated parts'* expressed by *'differentiation and interdependency'*. It thus emerges that a major part of uncertainty in FED does, in fact, relate to complexity in the interdependencies of design elements and attributes and stakeholders, acting in a context. Petit and Hobbs (2010), therefore, say that sources of uncertainty and complexity can be varied. In order to underscore the uncertainty associated with such contexts, Collyer (2015) lists in a table some peculiarities of dynamic environments as opposed to the static one seen in Table 2.

Moreover, Vidal et al. (2007) observe that most underlying risks in projects are a result of uncertainty and complexity in their contexts. According to Fageha and Aibinu (2013), understanding such concepts seems key to addressing their effects though, on a technical level, there is still a lacks of convergence on a common position across the policy, academia and research realms. As a result, uncertainty, risk and complexity appear to be used commonly in the same realm in the literature (Floricel et al., 2016). According to Williams (1999) however, there is a marked distinction between uncertainty and complexity. While uncertainty refers to the level of stability of assumptions upon which tasks/elements in a processes/system depend; complexity, on the other hand, is all these plus the nature of the various tasks/elements within such processes/systems/subsystems and their various levels of interdependences (Williams, 1999). Perhaps to underscore the distinctness between the two concepts *Figure 2-7* and *Figure 2-8* serve as illustrations.

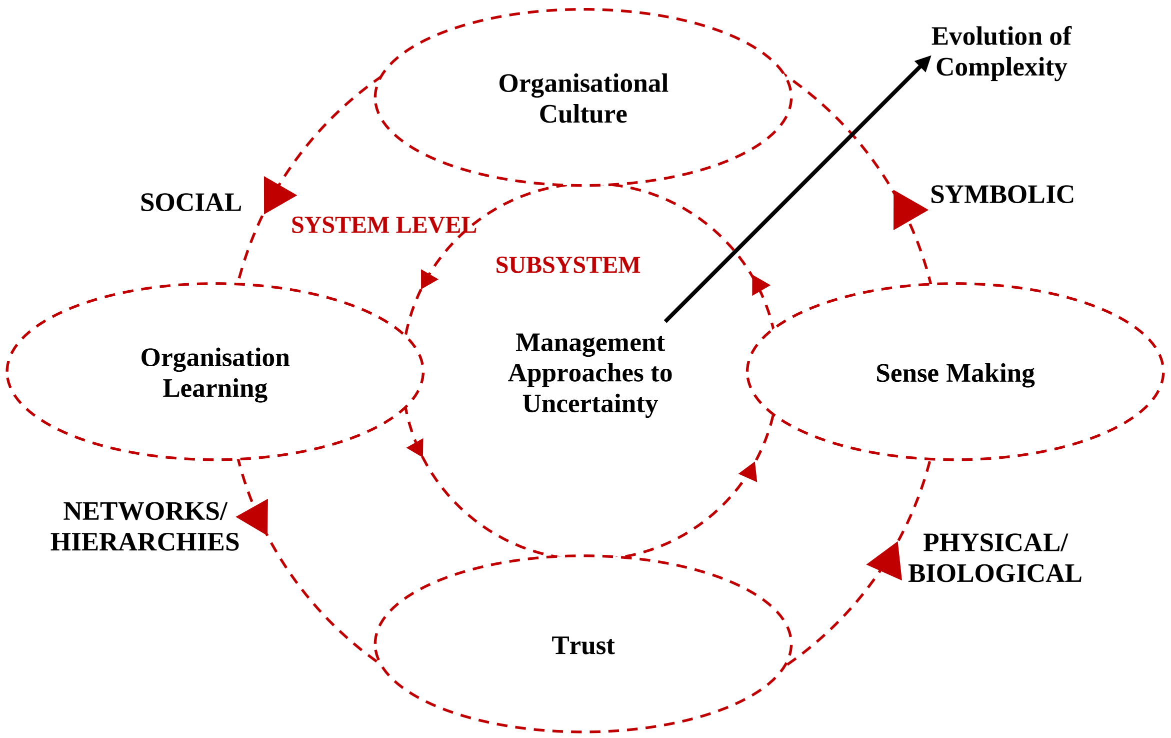

Figure 2-7 Evolution of Complexity at a Conceptual Level

Figure 2-7 illustrates the interactions between different system and subsystem constructs at a conceptual level. Complexity is seen to evolve from the subsystem level to the systems level and largely in part due to stakeholder biological and physical constraints, symbolic inferences, social dynamics and the nature networks and hierarchies between the stakeholder interactions all in a cycle. On another level, however, complexity relates to trust, degree and ability of sense-making and problem solving, and finally organisational culture and learning capacity. There is interaction at all levels of this model complexity, and management approaches are seen in literature to be responding to the complexity stimuli. The evolution of complexity according to *Figure 2-7*, therefore, propagates from the subsystem to the system level influences.

On the other hand, it is demonstrated in *Figure 2-8* that decision making and uncertainty are intertwined espousing such constructs as goal and purpose definition, learning and problem solving and evaluation and validation processes. Unclear goals and imprecise methods give rise to uncertainty (Turner & Cochrane, 1993).

Throughout relevant literature, uncertainty is seen at various levels; relating to planning, organisation, stakeholders and processes (Atkinson et al., 2006). However, according to Turner and Cochrane (1993), at the centre of uncertainty is how well defined the goals and methods are an approach that espouses their goals and methods approach to uncertainty.

FED in any construction project will face uncertainties relating to methods to be employed and lack of clarity beyond the core purpose because of the chaotic nature of information exchanges at least at this time. Authors such as Fageha and Aibinu (2013), moreover argue that it often transpires that a lack of clear understanding of uncertainty in definition stages and the interdependences that give rise to it for that matter can often in part lead wastefulness in projects such as costly design changes and reworks, delays, cost and schedule overruns, among others all of which negatively impact value delivery.

Moreover, as Broadbent et al. (2008) argue that in facing the unknown future without any certainty about it, decision making itself is fraught with uncertainty about any process interdependences. It, therefore, appears that uncertainty reflects understanding and rationality of interdependency of various Intra and inter subsystems a basis for pairwise comparisons in such Multi-Criteria Decision Support methods as Analytical Network Process (ANP)/ Analytical Hierarchy Process (AHP), or utility theory. It also suffices as illustrated in *Figure 2-8* that in order to understand uncertainty in decision making during project implementation from purpose definition through to the realisation of benefits, processes have to engage with defining goals and their preference structures, learn from experiences, solve problems and evaluate outcomes iteratively. Uncertainty appears to influence the core of goals and methods definition processes (Turner & Cochrane, 1993).

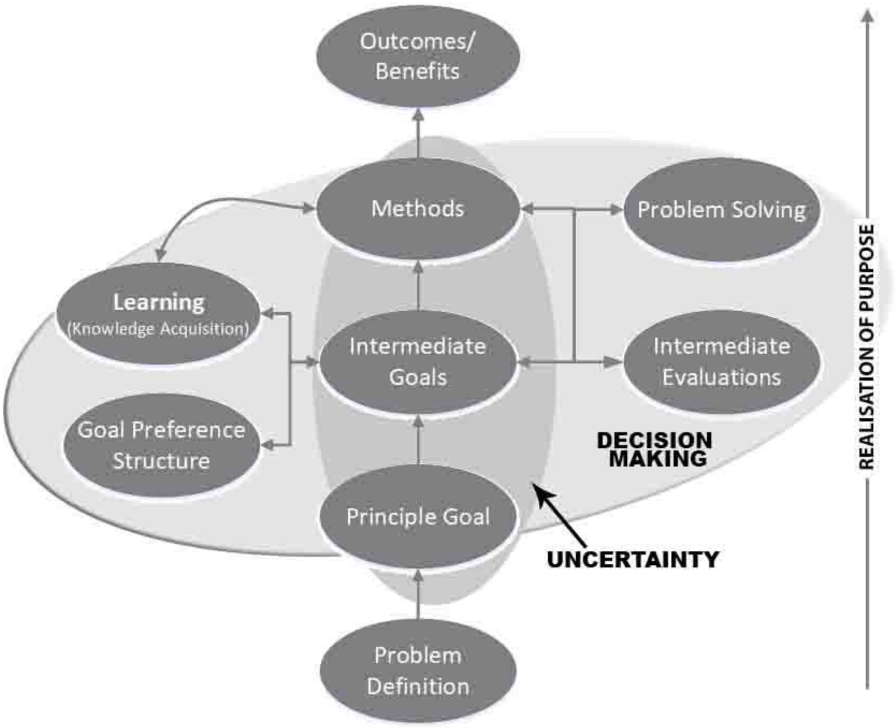

Figure 2-8 Uncertainty and Decision Making Interfacing in Dynamic contexts

2.4.1 Management approaches to decision making in a dynamic context

Pérez et al. (2011) describe decision making in dynamic contexts as that which lends to *'managing dynamic decision situations'* in the face of incomplete information about the problem. Decision making in dynamic contexts has come in for some attention in research and academia with the increasing dynamism of decision problems (Busemeyer, 1999; Pérez et al., 2011; Pérez et al., 2018). At a conceptual level, Simon (1996, p. 193) suggests a process that takes with it iteration in the course of finding a solution. He analogises a *'difficult theorem'* and discusses that, to solve for this, a *'maze-like'* approach is necessary which starts with the transformation of the *'axioms and previously proved theorems'* through a process of trial and error until a logical sequence can be arrived at that satisfies the goal, with *'persistence and good fortune'*. This process can involve many paths akin to a maze.

Management approaches can exploit the stable intermediate states during problem-solving argues Simon (1996). Authors argue that even this approach is only a simplifying one that up to this point exploits little in the way of heuristics and rationality (Brattico, 2008). Brattico (2008) underscores the importance of heuristics and rationality as central pillars of decision making. Brattico (2008) adds that the quick and simplifying assumptions decision making often takes in the interest of speed, often ignore seemingly peripheral but still rational decisions eliminated from the processes of decision making so as its quick. Brattico (2008) makes that point that while eliminating these seemingly remote alternatives, all that is happening is a trade-off between rationality and heuristics. The mention of heuristics and rationality invokes the notion of knowledge, how its influenced by contextual uncertainty and how in turn it influences decision making. There has been an increasing debate on the concepts in academia and research (Sahlin-Andersson, 1992; Sahlin-Andersson, 1992; Koskela & Howell, 2002; Ballard & Koskela, 2013b).

Sahlin-Andersson (1992), for example, argues that it is possible for some projects benefits to be delivered without the full set of information; i.e. that prior clarity of information *'intention and restrictions'* is not necessary. Koskela and Howell (2002) observe that in this case, *'commitments, dependences and expectations'* can be sufficient in moving the project forward. The position held by such authors is that a level of ambiguity can be necessary to exploit stakeholder participation and have the capacity for any uncertainty that may arise out of conflicting goals and desires in delivery of project benefits. This position constitutes, on the one hand, the notion of strategic capacity discussed in the following section 2.4.2 as a basis of uncertainty management in dynamic contexts in some applications. On the other hand, however, this constitutes accepting intermediate stability of a subsystem seen earlier in this section argued by Simon (1996). Lawson (2005) and Simon (1996) however has argued that this is a precipice of instability as any slight perturbation to any of the subsystems can have drastic effects on the entire system. It appears that the assumptions made by Koskela and Howell (2002) and Sahlin-Andersson (1992) are that the subsystems remain or are maintained in perpetual intermediate stability state; and that the total system entropy is defined and set. This assumption is, however, pointed out to be a delicate one to hold as complex systems are better off with no intermediate stable states than if there is (Simon, 1996). Such conceptual positions are important in informing uncertainty modelling in FED decision making discussed later in section 5.5.

2.4.2 Management approaches to Uncertainty in Practice

According to Petit and Hobbs (2010), because there are varied sources of uncertainty, in an FED perspective, such uncertainties can arise out of both individual and team level stakeholder interactions such as those between and among professional teams, technical teams and end-users or clients among others all of which serve to constrain value delivery. These clearly go over and beyond complexity that is physical/biological. Such variations will and have led to varying levels and approaches to the management of uncertainty in projects. Collyer and Warren (2009) describe some approaches to project delivery in dynamic environments. They observe that as the level of unknowns increases/decreases, there's increasing/decreasing need for elaboration and exploration of project goals and methods, respectively.

The numerous of prescriptive approaches to value delivery in dynamic and complex contexts range from systems engineering (SE) approaches (Locatelli et al., 2014), strategic capacity in decision making (Giezen et al., 2015; Rojo et al., 2018), transformation leadership (Gundersen et al., 2012), to scope management (Mirza et al., 2013) and complex systems thinking (Pich et al., 2002; Allen et al., 2007).

Mirza et al. (2013) for instance, cite scope management as the key element to delivering value in such manners of contexts. They argue that would realise value performance if only at the start, approaches endeavoured to understand and define the *'project and product scope'*. Lu et al. (2015a) used the *'task and organisation (TO)'* to suggest a measurement model for hidden work complexities. They suggested that hidden work reflected emergent dynamism in projects and that their model attempted to identify and map them. Sensemaking is suggested by authors such as Fellows and Liu (2016) as an approach to addressing uncertainties arising from sociocultural differences in project contexts and stakeholders that affect Benefits Realisation. The authors argue that uncertainty on this basis arises from the increasing diversity among stakeholders in many projects that create differences in perceptions in both processes and decision making.

Locatelli et al. (2014), on the other hand, suggest that applying principles of SE can help deliver value in dynamic contexts. They contend that by capturing user needs and requirements early on in the project cycle, and defining them, followed by *"design synthesis and system validation"* keeping view of the design problem and all stakeholder needs, this sets a strong basis for value delivery. Locatelli et al. (2014) cite the success of the metro extension in *'the Rotterdam Region in the Netherlands'* as a case example where SE principles were successfully applied. Moreover, Giezen (2012) observed that a lot of current practise aims to simplify complexity during decision making simply. Projects in dynamic contexts invariably have many varied interrelated processes that present challenges in clearly identifying the goals and objectives (Baccarini, 1996) and scope (Mirza et al., 2013). Such factors can be external dynamic and unpredictable geopolitics, economic, socio-cultural and environmental events or stakeholders dynamics serving to constrain the necessary processes and change, decisions, schedules, procedures or strategies underpinning the delivery of project benefits (Chapman, 2016). Sometimes they can be inherent subsystem level events such as decision making within professional teams as to the right course of action.

What appears from the foregoing is that simplistic management approaches only further to underestimate the nature of dynamism, behind uncertain contexts. Giezen et al. (2015) state that this approach can, in fact potentially, affect benefits delivery. Some of these approaches assume the unknowns can be mitigated in some way yet some complexities arising out of dynamic contexts are not only unknown but also unknowable in the beginning and are in the main emergent (Giezen, 2012; Giezen et al., 2015).

2.4.2.1 Strategic Capacity in Dynamic Contexts

The position adopted by authors such as Rojo et al. (2018), Stieglitz et al. (2016), Giezen et al. (2015), Allen et al. (2007) and Pich et al. (2002) is gaining wide appeal in management of dynamic contexts. The authors draw parallels to the evolutionary nature of the universe in which the world has evolved over 3 billion years in a manner and state that is as ambiguous as its selective through *'instructionism'* and learning (Simon, 1996). This position is later reinforced by Rojo et al. (2018) who add *'absorptive capacity'* and *'organisational learning'* as essential elements in embedding strategic capacity in dynamic contexts. They suggest that projects need to build in a strategic capacity as a basis for decision making in ensuring value delivery. The methodology in strategic capacity involves *"strategic flexibility"* (Stieglitz et al., 2016), *"strategic ambiguity, redundancy and resilience"* (Giezen et al., 2015) actions that not only ensures flexibility but also allows for room for change in interfacing subsystems, while simultaneously accommodating knock-on effects of such interdependences such as reworks and feedback (Williams, 1999). By allowing for strategic ambiguity, Giezen et al. (2015) state that processes benefit from not only setting a preference structure when projects face competing purposes but also allows projects to adopt an appropriate level of abstraction in their wider goals built around a strategic or principal purpose/goal/value for the project. They add that setting concrete ideas at this stage does not help. In adopting strategic capacity, it appears that the level of abstraction and strategic ambiguity adopted should support and utilise rather than stifle or seek to simplify conflicting and competing purposes and goals during decision making (Giezen et al., 2015) through fostering open reflection a key feature of FED. Ultimately what is happening is reality in this approach is allowing a complex system to be adaptive through an integrative paradigm operating from both within and outside the system via feedback mechanisms as suggested by Allen et al. (2007). In allowing for this adaptability and learning behaviour in systems, Allen et al. (2007) postulate that these systems are able to evolve around their stable subsystems as other previously stable subsystems are perturbed into instability. The point is that in any system, however much the perturbation/instability or uncertainty, there is potential for a subsystem to adapt conditions of stability around which other unstable subsystems can align for their future stability that Allen et al. (2007) call *"structural attractors".* This position is held by Pich et al. (2002) who similarly add that this ambiguity can be expressed in terms of information adequacy. *Figure 2-8* (seen previously) summarises the key conceptual positions considering process dynamics in FED. The interfacing of uncertainty and complexity attributes of methods and goals definition and attributes of rationality including learning, evaluations and goal preference structures in decision making makes these conceptual approaches a sound basis for the development of a conceptual decision-making model for FED.

2.4.3 Discussion and Synthesis

Locatelli et al. (2017) observe that the subject of project contexts more generally is understudied even though dynamism in these projects contributes to how successful project target benefits are realised. Therefore, few tools are available to prepare projects for emergent uncertainty bar The PMI Standard for Portfolio Management, sense-making approaches (Petit & Hobbs, 2010; Fellows & Liu, 2016); balancing efficiency and flexibility (Eisenhardt et al., 2010) and similar. Collyer (2015) points out that much of current practice is based on traditionally prescriptive assumptions geared towards static environments. Other authors label these approaches based on process control insufficient for the inherently ever-changing project context (Koskela & Howell, 2002; Collyer et al., 2010). On the other hand, research by Um and Kim (2018) revealed that collaborative environments fostered resilience in processes during uncertainty while opportunism ran counter to it but that both co-existed in a dynamic environment. (Pérez et al., 2011)

Padalkar and Gopinath (2016) and earlier Petit (2012) argued whether current weaknesses in understanding of uncertainty and complexity are a result of deterministic[11] approaches of much of current research. This, they argue has, in turn, contributed to weak theories in current dispensations in part due to the inability of research to reach beyond the ineffective practices currently available. Determinism in complexity seems to have its roots in its complementary terms of *'Chaos'* and *'Catastrophe'* that took hold in the 1970s and 80s (Simon, 1996, p. 174).

[11] Deterministic theory avers that 'theory that all events, including moral choices, are completely determined by previously existing causes' – Source: Encyclopaedia Britannica

It is important to point out that these two references were fitting in as much as they would support solutions to complexity at the time and should be regarded as complementary rather than substitutes to *'complexity'*. Simon (1996) continues by observing that chaotic systems are indeed deterministic. Yet in this very theory of chaotic systems, Simon (1996) argues, lies the foundations of understanding of complex systems. This position is earlier reinforced by Levy (1994) who observes that Chaos theory at a conceptual level does, in fact, present an opportunity to identify patterns amid the unpredictable and nonlinear dynamic interactions of systems.

This, it is established from Simon (1996) and Levy (1994) among a host of authors, suggests that even amidst the chaos of dynamic systems (determinism), there can emerge *'stability in motion'* or rather what Levy (1994) calls an *'underlying order amidst unpredictability'*.

Stability can emerge from subsystems in a hierarchical or network interaction of subsystems and their subsystems (Simon, 1996). Interactions in terms of FED can for example be seen in interdependencies among the many stakeholder and design attributes. This position informs much of later studies into complex and uncertain systems. It thus emerges that if current approaches to uncertainty that have largely remained insufficient are deterministic, then to facilitate new understanding of uncertainty in dynamic contexts calls for new solutions in the non-deterministic realm, i.e. models that are predictive through a better understanding of the interdependent interfaces within a dynamic environment that affect the knowledge base underpinning decision making. Simon (1996) calls this moving beyond possibilities in current dispensations and their conceptualisations, while Levy (1994) observes that this is a necessary component of new decision making support tools.

Figure 2-7 and *Figure 2-8* illustrated earlier serve at a conceptual level as guides to the dynamics of complexity and uncertainty. In terms of FED, this dynamism can come from a host of sources, including from the various processes, stakeholder interactions and context-specific parameters, among others. All these levels of interactions, by and large, are representative of the network nature of rationalisation that is ongoing during project progression. Levy (1994) has argued that the starting point on the way to value delivery is for a full understanding of complexity in context. In this regard, some constructs of concepts in *Figure 2-7* become of interest, first in contextualising uncertainty manifestly as a social construct. This, for instance, relates to sociocultural influences on processes in FED meaning that people and culture inevitably influence the second layer of complexity/uncertainty evolution in FED processes, and similarly do stakeholders in representing their respective needs/desires during decision making. Secondly is complexity/uncertainty in physical and biological processes manifesting in everything tangible and that lives. This can be due to complex tools/equipment, terrain, ecosystems, materials, or influencing infrastructure. These all provide some controlling and constraining layer or mechanism to guide the knowledge base and ultimately decision making.

Thirdly is complexity/uncertainty in symbolic systems where influences stem from the appreciation of the inherent arrangement of components, constructs/processes or subsystems in a way that is acceptable. There is an inherent appreciation of stakeholder responsibilities (e.g. professional or technical teams) while some decision making may have to conform to cultural norms in FED through sense-making. On the other hand, contractors undertake specific works while suppliers stand ready to meet the needs of specified materials/services/systems to support project benefits delivery. All these elements in the sense of the preceding literature are in main merely symbolic in keeping with the specific calls of specialism each stakeholder brings to the project. Still, above all, their interaction adds a layer of complexity/uncertainty that should be managed. Similarly as observed by Simon (1996), in the same way, cell subsystems give rise to complex biological existences, while simple tasks and activities at subsystem level can be a source of complexity at the system level.

Essentially the point made is that dynamic systems with all their inherent complexities and uncertainties retain a high potential for *'rapid evolution'* based on the independent yet interdependent but stable sub-components. It also means in this condition that the efficiency of one subsystem is independent of the others. Simon (1996, p. 193) avers that even when, for instance, a subsystem is indeed performing well, the overall system may still be inefficient and underperforming. What this appears to suggest is that when dealing with dynamic contexts, understanding should be drawn to the subsystem level performances and their interdependences, perhaps at the level of FED.

On the other hand, Vidal et al. (2007) have argued that complexity, and by extension, uncertainty is not always negative. Rand (2014) and Markus (1969) have argued that complexities do have a contribution to the development of value propositions. Rand (2014) sees part of this contribution to be in symbolism and communication. As complexity increases, it appears the symbolic nature of a design value proposition increases among stakeholders. What appears to be the suggestion again is that as complexity increases, the role of, and focus on these systems becomes more important, something that contributes to the value proposition. The preceding forms a basis for a contextual understanding of the uncertainty of FED processes in dynamic environments. Modelling this does ultimately present the potential to improve decision making and along the way can ensure better value delivery. According to Atkinson et al. (2006), uncertainty is not just about its varied sources but also about its varied effects on Benefits Realisation Atkinson et al. (2006) argue that uncertainty affects knowledge and information exchanges in FED and ultimately, decision making. This first element is important for Benefits Realisation in FED and is explored later in section 5.5 in the development of the conceptual model on the basis of uncertainty modelling. The second element is that argued by Locatelli et al. (2014) in regards to Requirements Management as a way of facilitating uncertainty management in dynamic contexts. This is also explored in sections 3.2 and 5.2 with the approach to applying probability theory to underscore changing user needs as a way of contextualising uncertainty that arises from it.

Regarding benefits realisation, In the Australian IT/IS government sector, a Lin and Pervan (2001) study found, among other concerns, little end-user participation in Benefits Realisation programs something that affected benefits delivery. This firstly could account for what the Balta et al. (2015) study highlights as mismatches between target and derived benefits in government projects. Secondly and most importantly is a need for new approaches to explore integrated practices in Benefits Realisation that support structured collaborative and participatory processes for value co-creation in FED. Balta et al. (2015) further argue for a process of continuous evaluation a sentiment earlier raised by Yates et al. (2009) and Remenyi et al. (1998). There is little evidence to support the practice of continuous evaluation although this has been raised by many authors as essential for benefits management. It has also been argued that evaluations over long process lead times for target benefits amid changing user needs would require better tools to keep benefits evaluation through the process up-to-date (Shieh & Wu, 2009).

Farbey et al. (1999) in addition, draw attention to uncertainty within Benefits Realisation programmes something they argue necessitates rigorous decision making on the basis of evaluation results and organisational change. Thorp (2003) adds to this notion of uncertainty within Benefits Realisation programmes highlighting the space-time nature in perception and deriving of benefits. Additionally, uncertainty in processes can affect the knowledge quality, flow and exchanges and ultimately decision making (Machina, 1987; Pich et al., 2002; Kwong et al., 2011; Torp et al., 2018). FED is particularly exposed to *'agency and structure'* based uncertainties, particularly the emergent and those emanating from contextual dynamics.

Ultimately, uncertainty causes '*disbenefits'* within Benefits Realisation, and thus Fox (2008) and Ward et al. (1996) argue that any Benefits Realisation strategy must take this into account. Often times, for example, a cause-effect analysis of the design influencing factors for instance socio-cultural, political, legal and compliance, governance, and economic performance among others is required so that design can draw on any specific interdependences among these factors for any potential (dis)benefits (Andrade et al., 2016).

Thorp (2003) further points out that Benefits Realisation is a continuous protracted process of ideation, planning, implementation, evaluation of intermediate perceptions and in use benefits. The nature of all these processes imply the success of FED processes depends on knowledge flow and exchanges among stakeholders and interdependence in uncertainties thereof. More critically for FED, it further implies that Benefits Realisation strategies should be dynamic processes to allow adjustments to be made to the Benefits Realisation path. Strategies therefore according to Thorp (2003) should go beyond the design-develop-test-current approach but rather adopt concepts of value proposition, integration and co-creation in a collaborative and iterative environment; with a broad end-to-end focus of delivery of targeted project benefits. Benefits Realisation, therefore, according to Ward et al. (1996) should carry along its processes the ability to continuously forecast how benefits can be delivered while constantly evaluating any impacts from contextual uncertainty borne upon it.

2.5 Summary

The preceding sections in this chapter have explored concepts in Benefits Realisation and the practice of FED together with how they are influenced by project contexts. The key concepts in Benefits Realisation are highlighted to revolve around organisational change management among change agents as a driver to realisation of benefits (Waring et al., 2018). As part of benefits realisation, Mossalam and Arafa (2016), however, have drawn focus to the potential breakdown in decision making among change agents, that can perhaps lend to their lack of belief that in turn, creates uncertainty. Amidst this uncertainty, however, Andresen et al. (2002) argue that Benefits Realisation programs have to engage with a continuous process of delivery and prediction of benefits. According to research, successful programs depend on knowledge management (Zyngier & Burstein, 2012). However, these positions do not draw to a solid predictive base for practice. According to Dupont and Eskerod (2016), change agents can be vital in steering through shared compliance alluding to the importance of knowledge flow. This notion of knowledge management and how critical it is to Benefits Realisation is a key and important element in both uncertainty and forecast modelling in decision making particularly for FED and is explored throughout the rest of this thesis.

Secondly, the preceding sections introduced the role of FED as an intermediate process in the Benefits Realisation but one that can be influenced by the project context. Broadly, authors like Balta et al. (2015), Reiss (2006) and Farbey et al. (1999) among others highlight challenges in practice of Benefits Realisation and obsolete practices and gaps in the current literature. Other research as presented in this thesis (see Chapter Seven) notes that practice is still predominantly rationalistic which often is insufficient to cope with the dynamic nature of design and emergent needs adding to the complexity. The authors argue for new approaches based on quantification of benefits to support planning through to evaluations of benefits. A Doherty et al. (2012) study found differences in Benefits Realisation successes among organisations that attempted to adopt it. Similarly, Ashurst and Doherty (2003) found differences in the application of Benefits Realisation, particularly regarding the definition of pronounced and explicit target benefits. Th differing research positions suggest a lack of unified structure in application and evaluation of Benefits Realisation strategies among projects. Reiss (2006) highlights issues relating to vagueness in defining target benefits. Vagueness contributes to inaccurate representations in designs and unstructured decisions contributing to unplanned reworks according to Gomes et al. (2017a). A further study by Chih and Zwikael (2015) found little evidence base to support the formulation of target benefits among organisations. Regarding the obsolescence in some Benefits Realisation practices, authors like Smyth (2018), Bradley (2016); Kagioglou and Tzortzopoulos (2016) argue for practice to move away from simply stating benefits to be delivered to actually looking at the process in its entirety. The foregoing research positions further reinforce the need for both structured and empirically grounded Benefits Realisation practices in supporting decision making, particularly for the dynamic FED.

Regarding benefits realisation in FED processes, this is a particularly important and a necessary approach as processes in this stage are dynamic, intensive in information flow and exchanges yet remain unstructured (Austin et al., 2001). Horkoff and Yu (2016) therefore point to the fraught FED also referred to as the *'fuzzy'* front end (Almqvist, 2017) as it is characterised by uncertainty *'imprecision and ambiguity'* (Muñoz-Fernández et al., 2017).

Ward et al. (1996) highlight some of these insufficiencies for post-commission evaluations of benefits as an example. Breese (2012) goes further to argue that the underlying conceptual issues in current Benefits Realisation practice be addressed while pointing out that many current practices not only add to complexity but are possibly also *'flawed'*. The foregoing sections have sought to argue, therefore, that the current conceptual highlights and theoretical positions in Benefits Realisation concepts be revisited to address the specificity and dynamics of some critical intermediate processes like FED. This research aims to contribute to new knowledge in addressing the current insufficiencies identified in literature and understanding to facilitate improved Benefits Realisation in a FED perspective. The next explores the conceptual basis in literature for requirements management and decision making in benefits realisation from a FED perspective.

3 REQUIREMENTS MANAGEMENT AND DECISION MAKING

3.1 Introduction

The previous chapter discussed some key theoretical concepts relating to FED, value propositions and their importance and linkages to participatory design processes in contributing to Benefits Realisation. This chapter presents the state of the art in Requirements Management and decision making in a FED perspective. The systematic literature review (as part of extant published work in Serugga et al 2020b and Serugga et al, 2020c) presents a detailed exploration of (i) the various requirements and any taxonomies (discussed in sections 3.2 and 7.3) and (ii) how these relate to design decision making, in contextual design including the different techniques and methods in decision making from a utilitarian perspective (discussed in sections 3.3 and 7.4). The aim is to create a foundation for the development of DESIDE through requirements categorisation, and adoption of the right decision techniques.

3.2 Requirements Management in Design

Research into Requirements Management and Benefits Realisation has contributed to addressing a growing need for improved performance in AEC projects. The latter concept was explored in sections 1.4.2 and 2.3. Regarding the former concept, according to the IEEE-STD (1998), a requirement is a statement that identifies a product or process, operational, functional or design characteristic or constraint which is unambiguous, testable or measurable and necessary for the product or process acceptability by users or internal quality assurance guidelines. Requirements Management, on the other hand, is defined as

"…the discipline concerned with elaborating the requirements for a given project, program or system to be developed in a given context, based on the needs of all the relevant stakeholders, analysing and negotiating these requirements, tracing them, validating them with the relevant stakeholders and managing their change over time (Kossmann, 2016, p. 13)."

The first important element in a Requirements Management process similar to FED is the elicitation of stakeholder needs that form the basis for transformation into design requirements to devise a solution to a design problem (Kossmann, 2016). Dick et al. (2017), therefore argue that requirements are the basis of every project as they reflect the stakeholders' needs.

This section explores how requirements and their categorisations in design can contribute to modelling using DESIDE for Benefits Realisation. This section secondly presents a FED conceptual change and control framework for Benefits Realisation and Requirements Management to espouse the various literature in requirements management in relation to benefits realisation.

3.2.1 Requirements Management and Benefits Realisation

Increasing research in Requirements Management casts it as a critical driver for Benefits Realisation (Baxter et al., 2008; Shieh & Wu, 2009; Bae et al., 2017; Dick et al., 2017; Laplante, 2017). It is argued that project requirements need to be adequately captured, defined, transformed, delivered and evaluated during project delivery (Bae et al., 2017; Dick et al., 2017; Laplante, 2017). Project performance, therefore, appears to depend on how well project requirements are managed throughout the project's processes. For successful Requirements Management, practice dictates that stakeholders should engage through participatory and collaborative processes (Inayat et al., 2015), as in Benefits Realisation processes. Despite this understanding, according to Burger et al. (2019) and Tezel et al. (2018), there are continuing underperformances in AEC across many life cycle processes. This can be argued to contribute in part to the insufficiency in the understanding of the various processes resulting from the fragmented practice; and inadequacy in support tools to support complex analysis of continually emergent and changing user needs resulting from the limited research (Serugga et al., 2019c).

Emergent research has also sought to demonstrate the critical role of FED in contributing to broader project benefits (Gibson et al., 2010; Fuentes & Smyth, 2016; Elzomor et al., 2018). Therefore, as a process that espouses the early stages of project development, FED stands at the critical interface between Requirements Management and Benefits Realisation in capturing, defining and managing the changing user needs. It has, however, been argued that FED remains understudied and unstructured (Gibson & Bosfield, 2012; Serugga et al., 2019c) while it is information-intensive at the same time, i.e. reliant on knowledge sharing (Macmillan et al., 2001) and presenting the most critical opportunities for benefits co-creation (Fuentes & Smyth, 2016) in a project’s lifecycle. It has been highlighted in this research that a lot of downstream project underperformances can be attributed to insufficiencies in FED processes (Blacud et al., 2009). The foregoing suggests that project processes in FED that are essential in ensuring delivery of early and intermediate project benefits for instance, managing project requirements can be optimised early in a project’s lifecycle through a structured process.

Current bodies of research in Requirements Management in FED and Benefits Realisation are, however, in the main discussed separately in research at present (see results from the systematic literature review in Chapter 7). However, a converged understanding is vital in drawing focus on the intricate complexity of project delivery that is mainly influenced by the *'structure and agency'* nature of design practice (see discussion in 2.2.4). The separate research realms also continue to increase the gulf between them, yet clarity and convergence are now vital, in a unified new understanding of the essential complementary concepts for design. Kagioglou and Tzortzopoulos (2016) have attempted to explore the concept of *'structure and agency'* as a key conceptual understanding in Benefits Realisation, although much more research is needed as earlier discussed to bring this into AEC. Moreover, although recent research in Benefits Realisation and Requirements Management concepts represents a fresh approach to project benefits delivery, both require reformulation in the perspective of FED as an intermediate benefit delivery stage essential for the realisation of the broader project and organisational benefits.

Therefore, it can be inferred that although the individual concepts of Benefits Realisation, requirements and FED have been developing over the years, what the results indicate (see analysis later in chapter 7) is that they have been doing so independently and individually with limited linkage. As a highlight, for example, the plethora of research into Requirements Management (Jallow et al., 2008; Cavieres et al., 2011; Müller et al., 2017); has been limited in its explicit adoption of Benefits Realisation principles (ul Musawir et al., 2017). A study by ul Musawir et al. (2017), for instance, points to potential benefits in project governance and stakeholder management as two requirements important for project success. It is, however, important to highlight that this and similar studies have been unable to cover the full spectrum of project requirements essential in project benefits delivery in FED (see section 7.3).

Moreover, despite these and other benefits, there is limited evidence of convergence in the practice and understanding of Requirements Management as a critical process in Benefits Realisation practice (Jallow et al., 2008). It is also widely acknowledged that at the centre of a Requirements Management process is a change and control process (see *Figure 3-1*) in which understanding of requirements runs alongside a value management process (Jallow et al., 2008). The conceptual model in Figure 3-1 consolidates the understanding of Benefits Realisation and Requirements Management in a FED perspective informed by current conceptual positions from the papers studied.

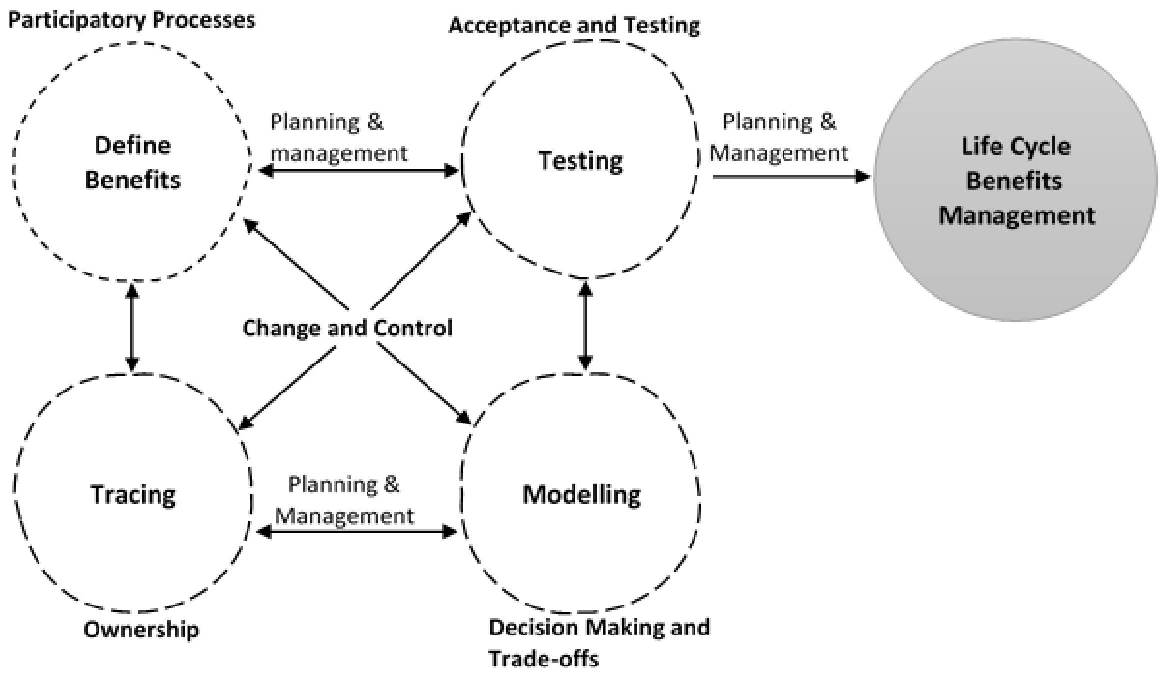

Figure 3-1 The Change Control Model for Requirements Management and Benefits Realisation in a FED perspective

Change control is vital in the crucial dynamics of benefits through requirements definition – *'the process of identifying, understanding and representing different stakeholder perspectives'* (Darke & Shanks, 1996), testing - *'validation of the requirements'* (Raja, 2009) and the main aim of *'checking the stated requirements for completeness'* (Brahmkshatriya, 2007), modelling, and tracing. In regard to tracing, Heindl and Biffl (2005) defines it as *'the ability to follow the life of a requirement iteratively through its transformation'*.

This process is also observed to be key to Benefits Realisation. It is, however, necessary to acknowledge research positions as those by ul Musawir et al. (2017), Elf and Malmqvist (2009) and others that point to potential benefits of Benefits Realisation as an anchor in the Requirements Management process. The absence of a conceptualisation convergence in practice means potentially that decision making in FED lacks the full spectrum of support and understanding it needs to utilise and deliver project benefits. This is because it is essential to recast the crucial dynamics in a FED perspective in a manner that supports further understanding of these key conceptualisations, as is demonstrated in *Figure 3-1*. On the one hand, the model captures the essential elements of requirements and benefits ownership within a participatory process. This creates space for benefits and requirements to be defined while ownership ensures that they are traceable. On the other hand, are the trade-offs in decision making and testing and acceptance of the requirements and benefits as they address the project objectives on the other. Both sides work iteratively and are part of the essential planning and management process in realisation of wider lifecycle project benefits. With this, requirements and benefits can be modelled and tested to again fit the project objectives. In this illustration, it is demonstrated that the key conceptualisations are essential in drawing out project lifecycle performance through integrating participatory processes where participants accept ownership during decision making and in which defined benefits can be modelled defined, , traced and tested and for project lifecycle performance.

3.3 Decision Making in FED

The preceding sections have highlighted the complex dynamics important in the realisation of project benefits in construction processes that often emanate from an interaction between various stakeholders, activities and tasks; and influenced by the *'agency and structure'* nature of AEC processes. That dynamics also means that often there are competing, and conflicting interests and that decision-making techniques and methods are an essential element in dealing with the complex dynamics for delivery of projects benefits. This section explores current applications and tools in design decision-making and recasts them in a utilitarian perspective. The most dominant decision-making techniques and methods are explored for their strengths and limitations in supporting the multi-criteria, dynamic and uncertainties in FED processes.

3.3.1 Decision-Making Methods for FED

Decision-makers continually make subjective decisions influenced by *'structure and agency'* (see section 2.2.4) factors such as social, economic, environmental, political or technology among others (Wey & Wei, 2016; D'Agostino et al., 2019). The result some times is potential waste and dis-benefits resulting from inefficient and inadequate decision making that ultimately affects Requirements Management and project processes.

The complexity of construction processes on the other hand often means interaction between various stakeholders, activities and tasks (Ballard & Koskela, 2013a; Koskela & Ballard, 2013; Goodfellow et al., 2014; Koskela, 2015; Kpamma et al., 2017); sometimes involving argument, or demonstration in pursuit of individual interests (Buchanan, 1985). The interactions in turn, lead to competing and sometimes conflicting requirements (Eleftheriadis et al., 2018). However, expected benefits and performance requirements now go beyond traditional milestones of time, costs and quality (Sapountzis et al., 2008a). The implication is that project processes, particularly design decision making need revisiting to keep pace with rising expectations. This is more acutely important in FED to cope with the dynamics of this stage.

The dynamic information flow and chaos highlighted in a study by Austin et al. (2001) among others in FED suggest that stakeholder collaboration is just as important as structured decision making (Eleftheriadis et al., 2018). Similarly, according to Lawson (2005) design as a problem-solving endeavour needs to stay in pace with changing user needs and requirements to deliver successfully the perceived and derived project benefits. Traditional approaches to design, therefore, need to be updated to reflect new realities in design by augmenting rational (based on reason and logic) processes with structured or empirical analytics. Rational approaches can be insufficient in capturing and modelling the complex interdependencies among project attributes; and keep pace with the evolving needs of the intrinsically iterative and dynamic nature of FED (Hammond et al., 2000). In fact, according to Gomes et al. (2017b) poor decision practices in design are among the two main factors behind conflict among stakeholders, poor briefs being the other. Both can reflect on an inadequate Requirements Management process and ultimately will contribute to dis-benefits in projects.

It, therefore, follows that alongside a robust stakeholder regime of defining the project objectives, right at the start, there should be a match in the robustness of decision making to better define the project in terms of its benefits and outcomes. It is conceivable that hundreds of decisions will have to be made in the course stemming from the many processes, activities and stakeholders required to deliver a typical construction design. Arroyo et al. (2016b) however argue that decision making in the AEC sector follows neither a structured regime of management nor is there profound understanding of its importance.

3.4 Multi-Attribute Decision Making and Utility Theory

The design process in FED often deals with sets of incomplete information to inform concepts, attributes and criteria for design decision making (Malak Jr et al., 2009). Malak Jr et al. (2009) adds that because of the range of stakeholders, this can mean that these parameters can be varying and wide-ranging. In turn, this can correspond to numerous final alternatives; implying impreciseness in FED processes. Delivery of intermediate FED benefits means that design decision making ought to capture the subjectivities and uncertainties in the design alternatives and attributes. This places importance in the trade-offs processes in the transformation of attributes through consideration of their consequences. This also suggests that it is relevant that qualitative and quantitative characteristics are defined including any restrictions, conditions and assumptions (Keeney & Raiffa, 1976). Some of the quantitative issues the analyst can look at as important to the final decision is defining the boundaries of the attributes.

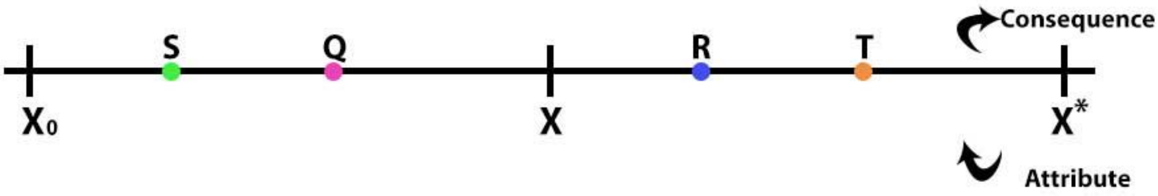

Figure 3-2 Utilitarian Transformation of Attributes to Consequences – adapted from (Keeney & Raiffa, 1976)

In a Multi Attribute Utility Theory (MAUT) decision making, Figure 3-2 represents how the trade-offs process can generically handle design attributes and consequences, including the ability to define any boundaries of a design problem. A preference structure representing these trade-offs is built along with the consequences X in a manner that requires design decision making to define a preference for $(X_0, X_2)\ or\ X_1$. More generally this follows the form $< X_{i+1}, X_{i-1} > or\ X_i;\ i = 1,2,3 \ldots \ldots 9$. This is the basis for defining a utility function to capture indifference points for the decision-maker which essentially defines the certainty points $\widehat{X_i}$ put more generally as $\widehat{X_i} =< X_{i+1}, X_{i-1} > or\ X_i;\ i = 1,2,3 \ldots \ldots 9$. This definition is also important in establishing uncertainties and subjectivity in decision making based on indifference through a decision maker's risk position, prone, averse, or neutral called the risk premium. The difference represents the risk premium $X_i - \widehat{X_i}$ using the following relationship.

$$If\ the\ X_i - \widehat{X_i} \begin{cases} Increases \\ Decreases \\ Constant \end{cases} then\ the\ DM's\ UF\ is \begin{cases} Increasingly \\ Decreasingly \\ Constantly \end{cases} Risk\ Averse$$

This, however, does not suggest linearity in decision making and neither to the transitivity (Keeney & Raiffa, 1976). How a decision-maker responds in assessing design attributes can be linear, so the utility function is $U(x) = -e^{-cx}$; or exponential $U(x) = -e^{-ax} - be^{-cx}$, where $a, b, c, and\ x$ are constants

Considering the following attribute clusters for example relating to FED adopted in part from Figure 3-4, decision making first aims to define User Needs – say L, then interpret the Design Needs – say R, define Design Processes – say D and finally validate and evaluate Processes – say C. Utility (U) can assume additivity of multiplicative functions (Keeney & Raiffa, 1993). The additive function is defined as

$$U_{l,r,d,c} = U_L(l) + U_R(r) + U_D(d) + U_C(c) \quad (1)$$

This can be summarised as (Zahedi, 1987) –

$$U_{l,r,d,c} = \sum_{i=1}^{n} U_i(X_i) \quad (2)$$

And with a scaling factor λ (say a probability) equation above transforms into

$$U_{l,r,d,c} = \sum_{i=1}^{n} \lambda_i U_i(X_i) \quad (3)$$

Where $i = 1,2, \ldots, n$ and $\sum_{i=1}^{n} \lambda_i \quad = 1 \; when \; \lambda > 0$

Navarro-Martinez et al. (2018) argues that decision-makers will be expected to choose a utility for which $\sum_{i=1}^{n} \lambda_i U_i(X_i)$ is higher. Determining the utility function is much in like determining the value function in terms of the process. The relationship between the attributes, their consequences is illustrated in *Figure 3-3* and see full conception in Appendix A. In the utility space $u(.)$[12], attributes transform into utilities differently. For instance, the $u(R)$ is smaller than the $u(S)$ yet in the consequence space, it is the opposite.

[12] This is the von Neumann-Morgenstern (vNM) utility function see Navarro-Martinez et al. (2018)

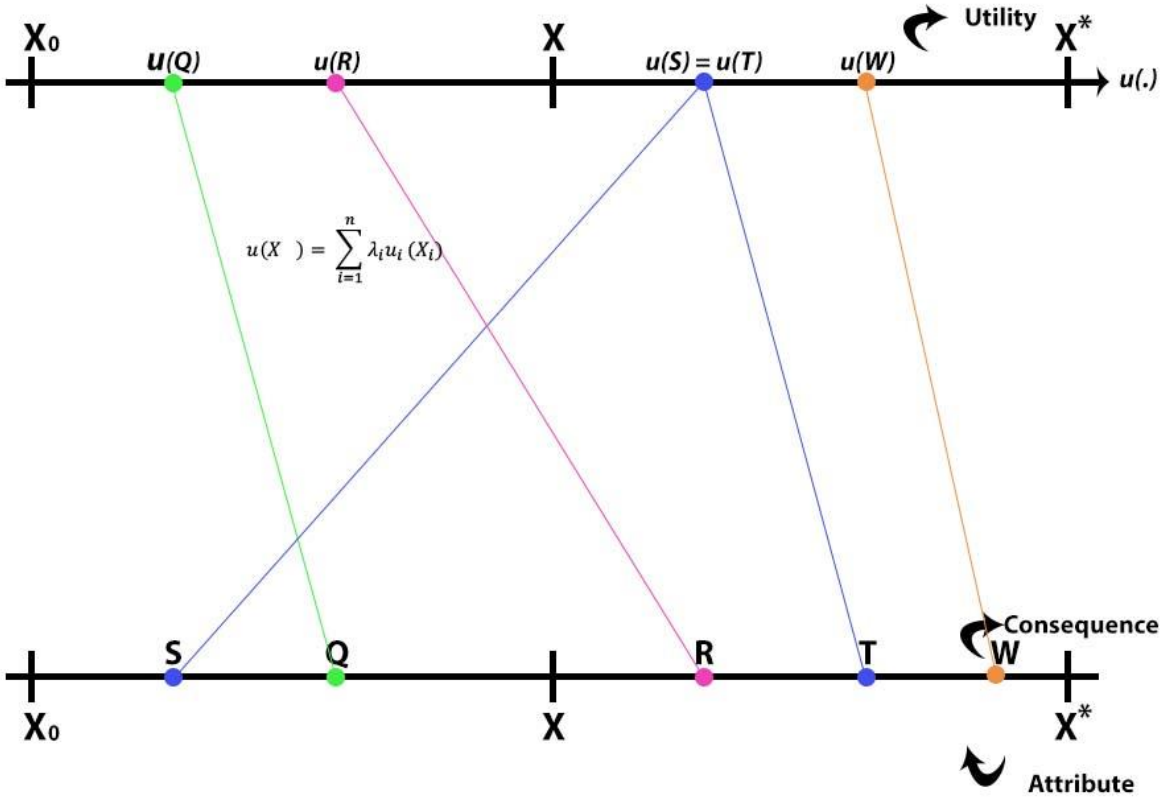

Figure 3-3 Attributes and their Consequences and How they transform into utilities - adapted from (Keeney & Raiffa, 1976)

3.4.1 Probability Distribution across attribute Spaces

Given S is the attribute for several years that a road design can deliver. It might suffice that for this specific design, the service time of the new design depends on how many on how many years the residents stay continuously in two housing blocks. Call these attributes S_1 and S_2. Dependency creates an extra layer of complexity in the sense that one cannot carry out an analysis of one without the consideration for the other. It so suffices that an analytic approach could define new attributes based on the average of the two and the difference between the two, i.e. $A = \frac{S_1+S_2}{2}$ and $B = |S_1 - S_2|$

Utility theory allows the attributes A and B to be functionally related to S_1 and S_2 meaning that a probabilistic distribution over S_1 and S_2 can be extrapolated over A and B drawing similarities in preference structures over to $S_1 x S_2$ and AxB spaces.

3.4.2 Analytical Network Process (ANP)

The complexity in requirements and their sometimes, conflicting nature was highlighted in section 3.2, alongside any interdependences among them. Systems can as a result be complex at a conceptual level requiring decision-making tools that can cope with this complexity. The ANP model is another of the multi-criteria decision making (MCDM) tools to model complexity in decision making (Saaty, 2005; Ignatius et al., 2016; Zhang et al., 2016). More so for this research, it is a tool for modelling uncertainty owing to the dependences of subsystems in complex systems (Ignatius et al., 2016). This section attempts to draw the interrelations between the two concepts and that of value management is demonstrated in *Figure 3-4*.

3.4.2.1. ANP for Complexity Modelling

The ANP methodology is essentially a tool that helps decompose a problem into various interdependencies and feedback among attributes in order to determine their relative importance (Niemira & Saaty, 2004; Huang et al., 2005; Aragonés-Beltrán et al., 2010; Zaim et al., 2014). This support is unlike its predecessor the Analytical Hierarchy Process (AHP) that only considered the hierarchy of attributes and not their interdependences (Saaty, 2005; Asadabadi, 2017). As illustrated by various applications like Asadabadi (2017). The approach uses a pairwise comparison of attributes in a matrix format (Saaty, 2001; Pang & Bai, 2013).

In the ANP approach, dependence can be modelled in a way that the magnitude of influence of one attribute on the other can be represented by a weighting factor/influence coefficient; on the basis of a decision maker's knowledge, judgments or experiences (Asadabadi, 2017). There being subjectivity on the part of decision-makers, Saaty (1986) introduces a consistency checking method to set a basis of a threshold of the validity of the comparisons; normally adopted as $consistency\ ration\ (CR) = 0.1$. Another element of the ANP approach is the consistency index (CI) represented as $CI = (\lambda_{max} - n)/(n - 1)$ with a perfect consistency being 0 while any random matrix with a CI of 0.1 or less is deemed acceptable. If not, then the analysis should be redone to obtain $CR = CI/RI < 0.1$ (Saaty, 1986; Asadabadi, 2017). Saaty (1999) adopts a scale of absolute numbers $1 - 9$ for interdependence analyses. A scale of 1 indicates that the two attributes are of equal importance, while that of 9 indicates the extreme importance of one attribute over another (Saaty, 1999; Asadabadi, 2017). For a typical comparison, b_{ij} is a representation of the importance of the ith element over the jth so that in a reciprocal format, $b_{ij} = 1/b_{ji}$. The weighting w_i/w_j is a single number in the range $1 - 9$ allows for the inner dependences between attributes to be captured (Saaty, 1999; Saaty, 2001).

Vidal et al. (2011) in attempting to measure complexity has observed using ANP is able to help identify the principal sources of complexity within a system. Other applications have been emerging over the years where the ANP has been successfully applied to solutions. Pang and Bai (2013) used the method for supplier selection in which the interdependences between various supplier selection criteria was important to be reflected in the process. Chen et al. (2011) ERA.Airport model for highway risk assessment in China, in capturing user requirements in combination with the quality function deployment (QFD) in product development (Zaim et al., 2014). The Fuzzy ANP was used by Wu et al. (2009) and Soltani and Marandi (2011) for selection of a hospital location; while Dey et al. (2012), Galankashi et al. (2015) and Vinodh et al. (2011) used it successfully in the selection of suppliers in their respective research. More recent applications include the ANP used in conjunction with probability theory when Asadabadi (2017) applied it to assess the changing needs of customers together with QFD. Aragonés-Beltrán et al. (2017) explored the use of ANP to understand stakeholder influences in projects in the railway sector; highlighting that the contractor and signalling systems subcontractors weighted the most in the event.

3.4.2.2. *ANP and Decision Making for FED*

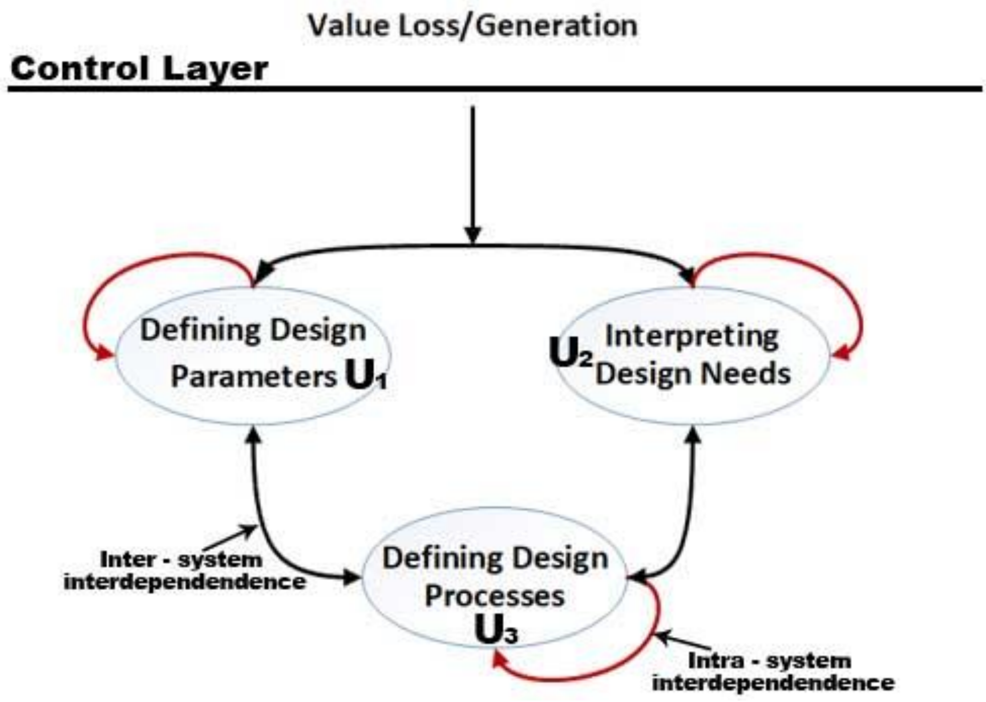

Figure 3-4 ANP structure for FED Value Network – Adapted from: Saaty (2002)

Figure 3-5 is an illustration of the major stakeholder dependencies in FED basing on literature. From special interest groups to policy, professional teams, value chain, financing, end-users, and government entities, each can play their role in constraining of facilitating design processes in a way that affects value delivery. These interdependencies can occur at a system level, inter subsystem or Intra subsystem level. Dependency interfaces include communication, technology, information exchanges and leadership structures, among others. Facilitative interfaces include rhetoric and heuristics, trade-offs, problem-solving, visual aids, and communication.

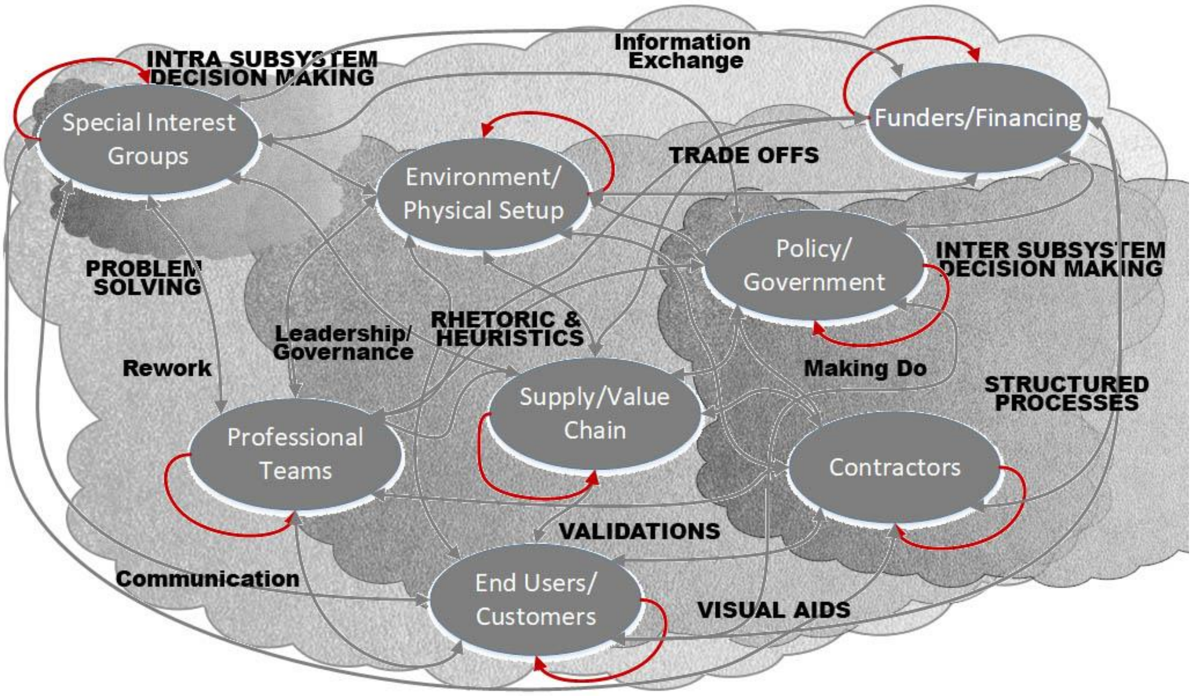

Figure 3-5 Stakeholder based Interdependences at FED (Developed by Researcher)

At the heart of their conception is the construct of flow between elements, alternatives, and clusters in pursuit of outcomes. *Figure 3-5* demonstrates constructs in relation to uncertainty and complexity in a decision-making setting. Constructs in a design perspective typically are tasks, activities, processes, that aim to deliver the intended outcomes of a project. The AHP, the predecessor of the ANP, assumes a linear relationship, i.e. a top-down flow without any apparent interdependences between the constructs in a hierarchical form (Lai et al., 2002). It has been widely applied successfully to a range of decision-making problems on this basis (Al-Harbi, 2001; Lai et al., 2002); sometimes in combination with other decision-making adaptations like the PROMETHEE model by Macharis et al. (2004).

3.4.2.3. Theory of the Fuzzy Sets

Introduced by Zadeh in 1965, fuzzy numbers allow for analysis of data of decisions where the decision-maker is vague/imprecise (Zadeh, 1965; Dağdeviren & Yüksel, 2010; Zaim et al., 2014; Akkaya et al., 2015). According to Dağdeviren and Yüksel (2010) fuzzy sets allow for the representation of objects in a '*continuum of grades of membership'*. Linguistic judgements from a fuzzy set are represented by a membership function ranging from $0\ to\ 1$ for each object (Yan & Ma, 2015). The fuzzy sets according to Yan and Ma (2015) can be useful in extending capabilities of other tools like QFD and ANP helping to account for subjectivity of the decision-maker and heterogeneity in customer feedback. Arabsheybani et al. (2018), Akkaya et al. (2015) and Dey et al. (2012) separately used the fuzzy sets in multi-objective optimisation ration analysis (MOORA) to support supplier selection decision making. The authors reported improved efficiency based on much more precise analysis. Dinçer et al. (2018) and Akbaş and Bilgen (2017), for example, applied the fuzzy method in conjunction with QFD. The authors used the approach was able to address inconsistencies in crisp values of QFD arising from variability in judgements by decision-makers. Similarly, the fuzzy sets and QFD approach was used by Yan and Ma (2015) for design Requirements Management. Using fuzzy sets and QFD, again Babbar and Amin (2018) were able to improve green supplier selection for the drinks industry again by accounting for subjectivity and vagueness from decision makers. Other studies that employed fuzzy sets include Chen and Ko (2010) in new product development (NPD), Dağdeviren and Yüksel (2010) for competition analysis by addressing *'complexity and vagueness'* within decision making in the concept.

Particularly for this thesis, the fuzzy sets can potentially be exploited both in Requirements Management using QFD and determining interdependences using ANP to account for subjectivity of the decision-maker. Galankashi et al. (2015) are one of several authors that have applied the fuzzy ANP (fANP). Using the fuzzy ANP approach ensures the triangulation of the decision maker's subjective and sometimes vague and imprecise views in the definition of their goals and desires (Wu et al., 2009). Wu et al. (2009) also point to the method's strengths in dealing with interdependent relationships in various constructs both at a system and subsystem level within decision making.

On this basis together with Figure 3-5 and following extensive literature review, three high-level functional purposes of FED are identified: 1) Defining Design Parameters, 2) Interpreting Design Needs and 3) Defining Design Processes.

For a triangulated fuzzy set '$\sim'$' for a problem M with n elements to be prioritised example as illustrated below as $\widetilde{M}$, and that a decision-maker can pronounce themselves on a decision set $\widetilde{M}_{ij}$ of $m \leq n(n-1)/2$ fuzzy comparison judgements and that $i = 1,2,3 \ldots\ldots\ldots, n,\ j = 2,3,4 \ldots\ldots, n, j > i$ denoted by $(l_{ij}, m_{ij}, u_{ij}) - see\ Figure$ 3-6 (Galankashi et al., 2015) to represent the low, medium, and upper values of the set, it the membership function is described so that:

$$\mu(x/\widetilde{M}) = \begin{cases} 0, & x < l, \\ (x_{ij} - l_{ij})/(m_{ij} - l_{ij}) & x \leq x \leq m, \\ u_{ij} - x_{ij}/(u_{ij} - m_{ij}), & m \leq x \leq u, \\ 0, & x > u \end{cases} \quad (4)$$

A fuzzy number is now able to be represented by both its left and right parts for a given degree of membership.

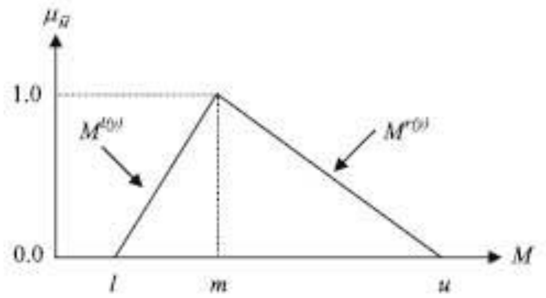

Figure 3-6 Representation of triangular fuzzy number $\widetilde{M}$

$l_{ij} = \min B_{ijk}, m_{ij} = \sqrt[n]{\prod_{k=1}^{n} B_{ijk}}, u_{ijk} = \max B_{ijk}$. In this case $\widetilde{M}$ is represented as

$$\widetilde{M} = (M^{l(y)}, M^{r(y)}) = (l + (m-1)y, u + (m-u)y,\ y\text{v}[0,1] \quad (5)$$

Where $l(y)$ and $r(y)$ represent the left and right fuzzy number, respectively. From here on, rankings of the constructs can be made of which many methods exist today (Dağdeviren & Yüksel, 2010). So, the following steps can be followed from here on -

Step 1. So, the first step is to identify the attributes and lower-level attributes

Step 2. Structure of the ANP Network

3.4.2.4. <u>Structuring the ANP Model</u>

Following on from Figure 3-4 its seen that the ANP model structure is of two layers; first, the control layer to which the purpose and goals are defined and the network layer where interdependent high-level goals are defined (Saaty, 1996).

From equation 1, the first step is to define a prioritisation of the problem, i.e. derive a crisp priority vector $w = w_1, w_2, w_3, \dots\dots, w_n$ so that:

$$l_{ij} \lesssim \frac{w_i}{w_j} \lesssim u_{ij} \quad (6)$$

Where $\lesssim$ referrers to fuzzy less or equal to and the ratio w_i/w_j lies within the fuzzy set limits.

With an attribute set similarly, i.e. $U = (U_1, U_2, U_3 \cdots \dots, U_i, \cdots, U_N)$, $i = 1, 2, \cdots, N$, where N is the number of attributes; and each U_i represents lower-level attributes $U_i = U_{i1}, U_{i2}, U_{i3} \cdots \dots, U_i, \cdots, U_{ini}$ where n_i is the number of lower-level attributes in each attribute.

Step 3. Determine the local weights for attributes and lower-level attributes using pairwise comparisons. The scale proposed by He et al. (2015) is adopted for this part. Experts are elicited for their preference based on a criterion.

It suffices to mention that to implement a successful benefits management process, contextual complexities and uncertainties have to be relatively understood at least at a conceptual level. This is quite important for the complex design and construction setting and more specifically, when trying to understand interdependences in contextual complexities and uncertainties that affect FED. Yet He et al. (2015) have demonstrated the strength of the fuzzy ANP in quantifying those interdependences.

3.4.3 Multi-Attribute Utility Theory of Decision Making

"In designing for building, every architect (designer) is involved in foretelling what is going to happen" (Price, 1976)

The observation by the design theorist Price (1976) alludes to the fact that the traditional method of *'design-by-drawing'* is too simplistic to cope with the increasing dynamics of the modern world; and that current methods used by designers are inadequate (Lawson, 1983).

Multi-attribute utility theory was introduced briefly earlier at the start of this section for its role as a decision-making technique. It was revealed how its concepts have been applied to managing conflicting and subjective stakeholder goals and attributes and the trade-offs in risk positions of decision-makers. It was also seen in this section how decision-maker would aim to maximise their expected utility on a given choice of attributes. This sub section explores the detailed key underlying concepts in MAUT.

Cost, maintainability, accessibility, green performance, and functionality are some of the many attributes end-users will expect from design performance. Yet many of them will be uncertain, dependent on contextual events (Malak Jr et al., 2009) and at time conflicting (Min, 1994). As argued by Atkinson et al. (2006), the basis of successful project management practice today is in how well uncertainty around the project can be managed; or rather how well the goals and methods can be defined (Turner & Cochrane, 1993). Broadbent et al. (2008) describe this as the root for rationalisation of any decisions to be taken in facing up to the future unknowns a position supported by Sanderson (2012). Carneiro et al. (2018) and Malak Jr et al. (2009) have observed that processes in FED are the multivariate nature where decision-makers are dealing with incomplete and fast-moving information. Sanderson (2012) adds that decision making in this regard relies on past experience weighted against possible future outcomes. This is only, however, part of the decision making dilemma Sanderson (2012) points out. This is because according to the authors, this assumption means that objectivity thrives at all levels of decision making to maximise the decision maker's expected utility which is not always true. Malak Jr et al. (2009) adds that problems in FED are not only multivariate but are also uncertain, which necessitates decision support tools appropriate for the processes. This is because as highlighted by Sanderson (2012), many times in FED, decision makers find difficulty in their rationality simply as they view the past as having no bearing on the future; and that in this situation, the decision-maker considers the *'unknown future unknowable'*. Malak Jr et al. (2009) thus argue that by allowing for uncertainty Utility theory (UT) can address this subjective and uncertain nature of decision making. Utility theory is also able to account for conflicting attributes during decision making (Min, 1994). Further, the method allows the mapping of a decision maker's preference structure via their utility function for consistency (Keeney & Raiffa, 1993).

3.4.3.1 Decision Making in Utility Theory

User goals in FED processes are effectively subjective high-level qualitative goals in decision analysis that are difficult to quantify and are prone to uncertain events (Keeney & Raiffa, 1976). Bell and Farquhar (1986) describe utility theory as *'a branch of decision analysis that is concerned with building models to explain and guide choice behaviour under uncertainty...'*. The goal of utility theory is in part to interpret the high-level choice goals into measurable objectives and ultimately attributes while capturing their influencing events (Vargas, 1987). Utility theory provides a mechanism to translate the high-level objectives into quantifiable attributes that can be modelled via a decision maker's utility function and probability distributions (Keeney & Raiffa, 1976; Vargas, 1987). Utility theory allows each criterion/attribute to be considered for its utility by defining a utility function (Dozzi et al., 1996; Navarro-Martinez et al., 2019). A criterion's utility function is a representation of a decision maker's preferences when presented with a series of options as trade-offs of the expected value of the utility (Keeney & Raiffa, 1976). Expected Utility Value (EUV) is the aggregation of all expected utilities of a given criterion.

According to Dozzi et al. (1996), defining a utility function for any given criterion takes the three steps below for an attribute X;

1. Determining the upper and lower scales of the criterion (X, X_L). A minimum of two is needed for a function to be derived.
2. Determining the threshold (X_T) - the neutral point between the two which is given a value zero; and the most preferred (X) point that is set to 1. i.e. $U(x_r)_j = 0 \; and \; U(x_M)_j = 1$
3. Anchoring the points to define a cardinal utility and connecting the points to define a utility function either with a straight line as $U_j(x_j) = A_j y_j + B_j$ or exponential function as

$$U_j(x_j) = A_j e^{B_j y_j} + C_j \tag{7}$$

After which the utility constants can be determined.

Where; $U_j(x_j)$ = utility of the criterion j while $A_j, B_j \; and \; C_j$ are constants.

Keeney and Raiffa (1976) have, however, demonstrated that the utility function is equally important in informing the nature of the decision-maker, whether they are risk-averse, prone, or neutral. Their work is quite important in underscoring decision making in dynamic contexts with many uncertainties. They demonstrate that when a decision maker's risk premium $X_i - \widehat{X}_\iota$

$$If\ the\ X_i - \widehat{X}_\iota \begin{cases} Increases \\ Decreases \\ Constant \end{cases} then\ the\ DM's\ UF\ is \begin{cases} Increasingly \\ Decreasingly \\ Constantly \end{cases} Risk\ Averse$$

Setting the optimum quantifiable and qualitative variables for the objectives, for example, can better be captured by understanding the intricate nature of the decision-making process.

The utility function allows all this information to either be captured or interpreted and used for consistency assessments (see Figure 3-7). In FED, it is as much important to understand the underlying expectations of the stakeholders as it is to map out the correct processes that better deliver the project benefits.

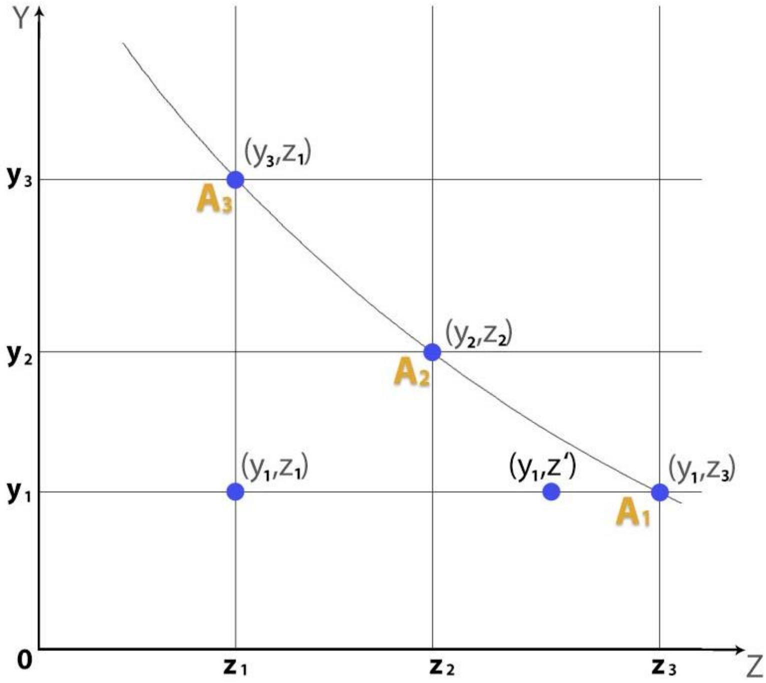

Figure 3-7 Mapping the Decision Making with a Utility Function

In Figure 3-7 the utilities of A_3 (Y_3, Z_1),A_2 (Y_2, Z_2), A_1 (Y_1, Z_3) are equal. Keeney and Raiffa (1976) argue that utilities as a result have to be explored with the decision-maker.

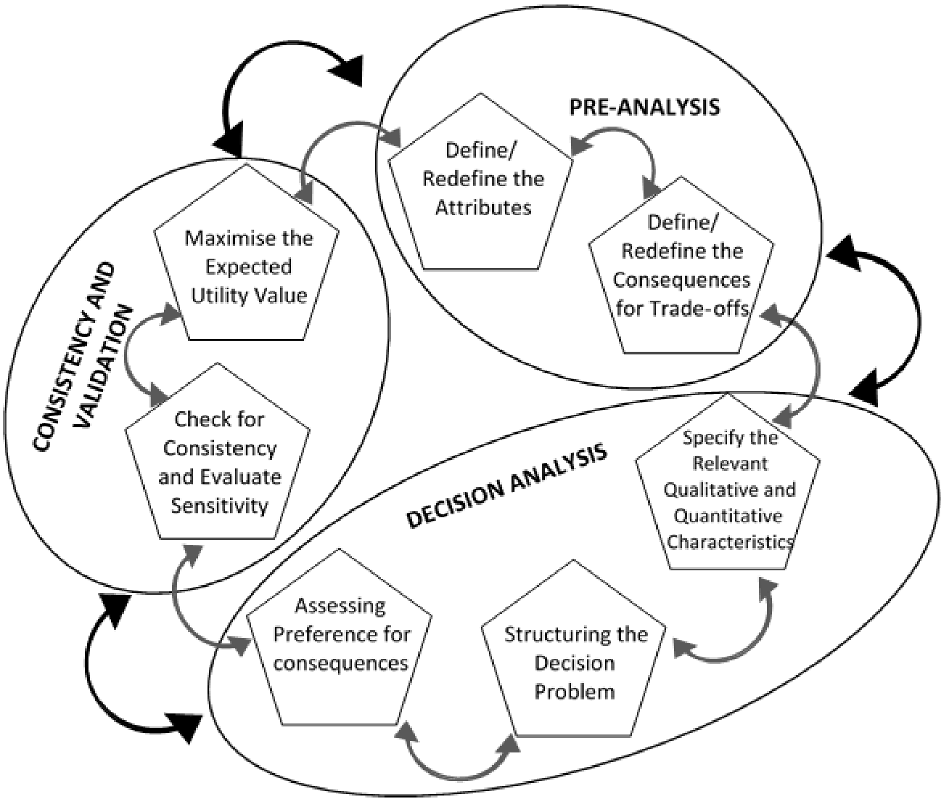

Figure 3-8 The Stepped Approach to Decision Making in Utility Theory Source: adapted from (Keeney & Raiffa, 1976)

This can mean defining the nature of the utility function of key stakeholder leaders to help bring about a convergence of decisions. This is a stepwise process that Keeney and Raiffa (1976) summarise (Figure 3-8) as;

- Drawing up any preliminaries of an assessment that draws focus between process analysis and decision making.
- Fully defining the relevant qualitative parameters relating to the project, that is – time frames, cost structures and any incentives; quality or environmental requirements that define the intended objectives.
- Specifying quantitative limits based on lower-level attributes relating to these broad, high-level goals/objectives.
- Choosing a utility function of the parameters.
- Carrying out consistency checks to ensure any results align with not only the objectives but also decision making.

The above steps are quite key in setting the overall environment of defining appropriateness of decision making. However, utility theory further allows for analysis of the utility function and possibility to use to shape not only the function but also focus and streamline decision making on the intended benefits. Again Keeney and Raiffa (1976) have been able to suggest a five-step process for analysis of a utility function including an attribute basis;

1. A pre-analysis process of examining the nature of the functions.
2. Structuring a problem.
3. Assessing the judgmental probability distributions.
4. Carrying out an assessment for all consequences relating to the decision-making process and preferences.
5. Exploiting opportunities in Maximising the expected utility (EUV).

The Basis of understanding of a utility function can perhaps better be illustrated using first a single attribute, for example, X that is previously highlighted previously in the attribute-consequence space in *Figure 3-3*, with corresponding consequences S, Q, R, T.

Specifying the limits of the attribute X in terms of X_0 and X' for example, so that an expected utility X is reflected by $X_0 \leq X \leq X'$ it is easy to use the lottery analogue to define a utility function as seen earlier in *Figure 3-7*. In reality, when an attribute X is, say the number of years to finish a project between 3 and 8.5 years, it is a good approach the limits of X are set appropriately for example for $X_0 = 0$ and $X' = 10$

It is important to point out that for some cases, attributes can easily be quantifiable say in monetary terms, the share of the market, or time (spent or elapsed). In other cases, the analytical process only has qualitative attributes like comfort, aesthetics, functional performance among others. It is suggested that in such cases, a better approach to adopting a benefits strategy that better focusses processes on the *'real outcomes'*. While approaches analogous to this can help in building a quantifiable basis for a utility function definition, they have to be captured, so they are the true reflection of the benefits; a task that can be uniquely challenging for mega projects in high-risk regimes. It perhaps, for this reason, Keeney and Raiffa (1976) adopt a lottery approach to demonstrate the clear choices important in capturing decision-making preferences for a utility function.

The nature of processes in construction means that there is inherent interdependency of tasks, activities, processes, and sometimes projects and programs. As buildings are elements of space and time, it is entirely expected to have trade-offs all along the spectrum from macro to microdomains. For example, attributes relating to the time-space can be traded off for those in the cost or quality space. Utility Theory still allows for capturing the utility value for multi attributes.

Considering the following attribute clusters for example relating to FED adopted in part from Figure 3-4, decision making first aims to define User Needs – say L, then interpret the Design Needs – say R, define Design Processes – say D and finally validate and evaluate Processes – say C. Utility (U) can assume additivity of multiplicative functions (Keeney & Raiffa, 1993). The additive function is defined as

$$U_{l,r,d,c} = U_L(l) + U_R(r) + U_D(d) + U_C(c) \quad (8)$$

This can be summarised as (Zahedi, 1987) –

$$U_{l,r,d,c} = \sum_{i=1}^{n} U_i(X_i) \quad (9)$$

And with a scaling factor λ (say a probability) equation above transforms into

$$U_{l,r,d,c} = \sum_{i=1}^{n} \lambda_i U_i(X_i) \quad (10)$$

Where $i = 1,2, \dots, n$ and $\sum_{i=1}^{n} \lambda_i \quad = 1 \; when \; \lambda > 0$

Navarro-Martinez et al. (2019) argues that decision-makers will be expected to choose a utility for which $\sum_{i=1}^{n} \lambda_i U_i(X_i)$ is higher. Determining the utility function is much like determining the value function in terms of the process. The relationship between the attributes, their consequences is illustrated earlier in *Figure 3-3*. In the utility space $u(.)$[13], attributes transform into utilities differently, e.g., $u(R)$ is smaller than the $u(S)$ yet in the consequence space, it is the opposite.

3.4.3.2 Interdependencies Among Attributes

In utility theory, the relationship of various factors actions is important in underscoring preference conditions essential for analysis. For example, 'organisation, portfolio or program' or rather the structure say Z, can be a utility, preferentially or additively dependent or independent of any stated benefits say $(x. y)$. Assuming a value of the structure, i.e.

[13] This is the von Neumann-Morgenstern (vNM) utility function see Navarro-Martinez et al. (2018)

'organisation, portfolio or program' z' in the Z space, for any benefits arising out of quantifiable lower-level attributes in the X, Y space, represented by a conditional preference structure $x.y$, at this given value of z' in the Z space, conditional preference observes that (x', y') will be preferred to (x'', y'') if and only if (x', y', z') is preferred to (x'', y'', z'). It further suffices that in conditional indifference, values (x', y') and (x'', y'') will be independent of z'. Essentially, the marginal rate of substation of (x', y') and (x'', y'') is independent of z' (Keeney & Raiffa, 1993).

The benefits set represented by low-level attributes x, y in the X and Y space is preferentially independent of Z if any conditional preferences set (x, y) at a given z' is independent of z'. Put simply, it matters for the project, portfolio or program or any causal agent for that matter as to a new need for new social housing design, rather the benefit of it fulfilling the effect (benefit) for which it was devised and that a user is at free will to substitute the benefits of the trap regardless of the 'organisation, portfolio or program'. Therefore if $x_1, y_1, z' \geq x_2, y_2, z'$ then it follows that $x_1, y_1, z \geq x_2, y_2, z$ for all z.

Of course, the implications of this extends further than this. For example, one would argue that surely organisations for instance, government entities have a role to play in determining the benefits of a social housing program. But another person could argue that surely a change of government does not stop one from extracting utility from that very same housing space. Both assertions are in fact are as indisputable as they are noncontradictory. The wider point being made by the foregoing is in how far conditions of independence go in the three or more-dimension space of actions/attributes, their consequences and utility. From the foregoing, conditions of utility independence can be defined to the point that $U(x, y)$ is independent of a given z'. This should not be taken to mean that attributes that are preferentially independent are necessarily utility independent. This also does not mean that independence conditions necessarily hold for the entire three or more-dimension space. Put more generally; independence conditions can hold for part or whole of any attribute/action space additively, preferentially or utility.

For Utility additive independence:
$$U(x, y, z) = k_x u_x(x) + k_y u_y(y) + k_z u_z(z) \equiv \sum_{i=1}^{n} k_i u_i(x_i) \qquad (11)$$

Which essentially means that utilities for x, y, z depend solely on their marginal probability distributions rather than their joint distribution.

Where the scaling constants:

Where the scaling constants: $k_x + k_y + k_y = 1 \quad \equiv \quad \sum_{i=1}^{n} k_i = 1$ (12)

A multiplicative case results if $\sum_{i=1}^{n} k_i \neq 1$ (13)

So that $(kk_x + 1)\ (kk_y + 1)\ (kk_y + 1)\ = 1 + k$ (14)

Utility, in this case, will be generalised as: $ku(\underline{x}) + 1 = \prod_{i=1}^{n} [k\,k_i u_i(x_i) + 1]$ (15)

Now for the case where Z is utility independent of $\{X, Y\}$ and $\{Z, X\}$ and $\{Z, Y\}$ are preferentially independent of Y and X respectively,

$$\begin{aligned} U(x,y,z) = \ & k_z u_z(z) \\ & = k_x u_x(x) + k_y u_y(y) + kk_z k_x u_z(z) u_x(x) + kk_z k_y u_z(z) u_y(y) \\ & + kk_x k_y u_x(x) u_y(y) + k^2 k_z k_x k_y u_z(z) u_x(x) u_y(y) \end{aligned} \quad (16)$$

A case can arise when all attributes $X, Y\ and\ Z$ are utility independent of their respective complements which means a multilinear utility function is as follows:

$$\begin{aligned} U(x,y,z) = k_z u_z(z) = k_x u_x(x) + k_y u_y(y) + k_{zx} k_z k_x u_z(z) u_x(x) \\ + k_{zy} k_z k_y u_z(z) u_y(y) + k_{xy} k_x k_y u_x(x) u_y(y) + k_{zxy} k_z k_x k_y u_z(z) u_x(x) u_y(y) \end{aligned} \quad (17)$$

The additional constant $k_{zxy}, k_z, k_x\ and\ k_y$ have to be determined in this case.

The final consideration is for when attributes/actions X and Y are utility independent of their respective complements $[Z, Y]$ and $[Z, X]$ in which case

$$\begin{aligned} U(x,y,z) = \ & k_z u_z(z) \\ & = + U(x,y,z) + f_x(z) u_x(x) + f_y(z) u_y(y) + f_{xy}(z) u_x(x) u_y(y) \end{aligned} \quad (18)$$

Where
$f_x(z)$ = u(z, x^*, y^0) - u(z, x^0, y^0)
$f_y(z)$ = u(z, x^0, y^*) - u(z, x^0, y^0)
$f_{xy}(z)$ = u(z, x^*, y^*) - u(z, x^*, y^0) - u(z, x^0, y^*) - u(z, x^0, y^0)
Considering normalisation so that z^*, x^*, y^* scaled to 1 and z^0, x^0, y^0 scaled to 0

The equations $2, 7, 8\ and\ 9$ provide most of the scenarios for utility, preference, and additive independence conditions in the assessment of benefits and objectives as would be needed in any Benefits Realisation process. This is particularly important for consideration of Benefits Realisation for FED where stakeholder and contextual dynamics and inherent uncertainty contributes to the complexity of FED processes. Utility theory can help explore overlapping attribute/action spaces through independence conditions and exploit them by defining and setting a preference and utility independence conditions (Keeney & Raiffa, 1993).

The conceptual basis from a Benefits Realisation perspective relates to how information that contributes to value generation can be modelled and transformed into activities that deliver tangible or intangible benefits. Outcomes like how, for example, a social housing program contributes to better livelihoods of the intended beneficiaries while also meeting the goals of the stakeholders like government policy become important focus areas. Information exchange is a key element in transferring the ideas across the broad spectrum of the Benefits Realisation cycle. FED equally is an information-intensive endeavour as perhaps in a reverse approach, transforms the user requirements (benefits) into design requirements through decision making. Information management is clearly a central feature in both approaches.

3.4.4 Summary

This chapter has explored and discussed current limitations to support an integrated Requirements Management practice and understanding to support design decision making in FED. Bias in current bodies of research towards some core requirements categories/groups (technical, economic, governance and environment) are revealed in subsequent analysis (see later in section 7.3); and also seen to constrain decision making (see later section 7.4). The conceptual model introduced in *Figure 3-1* serves an important role in highlighting the intricacies between Benefits Realisation and Requirements Management. The process of elicitation and definition, testing, modelling, and tracing is important for both Requirements Management and Benefits Realisation in the delivery of lifecycle project benefits. Ownership of requirements and benefits should be built on a participatory process, while any trade-offs during decision making have to be tested and accepted. All these important elements are important in the development and subsequent analysis using DESIDE. It is, therefore, important that DESIDE is informed by new research (e.g. as is presented in sections 7.3 and 7.4) bridges this gap and build an understanding of the vital role of Requirements Management in design decision making.

The change and control model (see *Figure 3-1*) is also important in the understanding of the inherent nature of FED as a dynamic process in the treatment of requirements for forecast modelling. AEC processes are under a constant state of change, particularly when it comes to changing user needs which presents opportunities for probabilistic assessments (Shieh & Wu, 2009; McKenney et al., 2011; Horkoff & Yu, 2016; Knauss et al., 2018). The Model suggests that the benefits stakeholders derive from built spaces starts with understanding their requirements. Requirements, however, are not static in space. Moreover, benefits derived from built spaces continue to change for the entirety of the project lifecycle. The changes can come from various influencing factors like a change in regulations or governments, changes in lifestyle and personal or family circumstances, socio-cultural changes or environmental changes to mention but a few; which in turn on lower-order requirements for instance constructability or choice of materials. Requirements forecasting is, therefore, becoming an increasingly important part of the design process (Shieh & Wu, 2009). Probabilistic approaches like HMM present the ability to derive constructions based on probability theory of potential future changes in requirements (Shieh & Wu, 2009)in the Benefits Realisation cycle. It follows that requirements that form the basis of decision making and trade-offs are adopted as the hidden parameters for the forecasting modelling and analysis, as demonstrated later in section 5.2. The probabilities of derived high-level focus factors/categorisations are derived through a combination of literature and documentary review (see later in section 5.2) as well as expert assessments as adopted (see later in chapter 6).

It also appears from the foregoing theory that utility theory provides a strong basis for an analysis of a decision maker's propensity to risk, which can affect their ability to make decisions in FED. The illustrations in Figure 3-2, *Figure 3-3* and *Figure 3-7* demonstrate that interdependences can be difficult to map in dynamic contexts basing in addition to the extra complexity they bring to the design process. As a result, they can heavily influence FED decisions, ultimately affecting value delivery. It is important to highlight that one of the central tenets of utility theory that of transitivity (Keeney & Raiffa, 1976; Keeney, 2002). Utility theory has been gaining wide appeal in practice e.g., in the Malak Jr et al. (2009) for improved FED processes, Georgy et al. (2005) study in engineering performance, Dong et al. (2003) and Min (1994) supplier selection studies and many others.

While utility theory successfully accounts for the decision maker's subjectivity in decision making (Min, 1994); it is argued that the method does have some issues of applicability in practice as highlighted authors like Machina (1987). This criticism is cited by Saaty (2005) in defence of the ANP-AHP approach to decision analysis. They both argue that transitivity may not necessarily be present in some real-world decision-making scenarios like expecting a housing model A to be better than B simply because housing model C is better than B. There are clearly issues around transitivity of decision making in many similar assumptions. Another issue is that which closely relates to the last. Authors like Navarro-Martinez et al. (2019), Di and Liu (2016) and Blavatskyy (2007) point to the inconsistency of the decision-maker in their expected utility assessment even with the same lottery if relayed more than once to them. This could be related to contextual uncertainty seen earlier or inherent biases during decision making (see Figure 3-7). This research adopts uncertainty modelling by Dempster Shafer theoretic of conditional probability (see section 5.5). Charles-Cadogan (2018) and Yearsley and Pothos (2016) have also recently highlighted that in fact during the analysis, it is possible that events which affect expected utility will keep changing, leading to preference reversal. This is something again important for DESIDE using HMM (see section 5.2). In a similar approach to Pergher and de Almeida (2018), a rank dependent utility approach is adopted for this research to support Benefits Realisation efforts to identify, model, test and trace requirements in facilitating benefits delivery (see *Figure 3-1*). In this approach, the developed decision system aims to represent the overall decision maker's preference structure on the basis of assessed consequences and trade-offs; that directly relate to specified design attributes, similarly derived from user requirements (Pergher & de Almeida, 2018).

4 RESEARCH METHODOLOGY

4.1 Introduction

The previous two chapters presented the literature basis for informing the research approach for this research by identifying gaps and reinforcing the research need. This chapter presents the research approach adopted. This includes the design, development, techniques, and strategy of implementing the research method to support the development of the proposed model. The chapter lays out the methodological approaches behind in developing the proposed model. This section also describes the research approach, including the methods used for data gathering and analysis that inform the theories behind it. It also describes the design and implementation of a validation and evaluation method adopted and how they contribute to understanding the effects of the artefact[14]-context interaction understanding and ultimately, the design theories. The general research methodology carries inspiration from Pettigrew (1990), who observes that:

"From time to time, there is a requirement for empirical researchers to make clear the theory of method which guides their inquiries (Pettigrew, 1990)."

4.2 The Philosophies Underpinning the Research Design

The research in part seeks to develop a mathematical model based on probabilistic algorithms as a basis for analysis of requirements and uncertainty modelling in the body of evidence that underlies design decision making. Algorithms complement the use of qualitative data to support validity a reflection of the pragmatist approach in this research (Schoonenboom & Johnson, 2017). In regards to applying mathematical algorithms, Lenhard and Carrier (2017) argue that best practice relies on well-founded theory; else research relies on a data iteration for its validity thus underscoring the epistemic nature of this research. However, research also shows that in understanding the world and devising solutions to its problems, two worlds have to meet; that of problem-solving and knowledge building (Wieringa, 2014). Research can have different philosophies that are sometimes multi-pronged based on a combination of multiple

[14] The artefact in this case is DESIDE applied first at a component level to establish validity of the components and second to the full case study for comparative analysis and evaluation.

ontologies, epistemologies[15] and axiology. Understanding of the world and a focus on the utility of research and its outcomes underscores the ontological[16] and axiological[17] approaches to this research representing a mixed philosophical approach at this level. On the other hand, the approach adopted in the methods of data gathering like *'questionnaires, interviews, observations, and documentary evidence, among others'* represents mixed methods. In addition to both the qualitative and quantitative methods of research employed in this research, the three elements amount to what Greene (2006) and Johnson et al. (2007) call a methodological basis for Mixed Methods Research (MMR). Essentially, the authors also presuppose an MMR methodology, a position that may be disputed by others.

The various philosophies at play in this research mean that the use of MMR allows the research to adopt and adapt them as highlighted by, Johnson (2017) to exploit both the empiricism and rationalism essential for validity and rigour in research. This suggestion is, however, noted to be rooted in a dialectical pluralist paradigm/philosophy in MMR. According to Johnson (2017), *'pluralism'* in dialectic pluralism emphasises the ontological nature of research discourse; where the multi-stakeholder nature of design means for instance that different parties come to the design process from different standpoints. On the other hand, through negotiation and dialogue, research epistemologies are realised through dialect to support the synthesis of artefacts (Johnson, 2017).

Design decision making is a significant part of FED, and therefore, individual and contextual influences on design present ontological, epistemological, and axiological issues that in turn require appropriate research inquiry. Secondly, in terms of the ontology, the reality in design practice is that design decision making is impacted by the social and individual influences something that brings the debate on *'agency and structure'* into the fore as considered in the social sciences, in research methodological practice. The two elements were seen in 2.2.4 as contributing to the subjectivity and preference structures in design decision making.

Axiological issues, on the other hand, relate to the values that influence in decision making e.g. in trade-offs in outcomes/utility, or uncertainty assessments because of the different constraining factors on design. The influences have to be balanced against the need for the

[15] Epistemology according to Schultz and Meleis (1988) lends to *" what human beings know, how they come to know what they think they know and what the criteria are for evaluating knowledge claims"*
[16] Brank et al. defines Ontology as *"as a structure capturing knowledge about a certain area via providing relevant concepts and relations between them".*
[17] According to Hartman (1967), Axiology relates to the *" the logical nature of meaning, namely intension, and on the structure of intension as a set of predicates"*

research and proposed decision system's capabilities to be useful in discerning any emergent influences during design (Johnson, 2017). As highlighted by Johnson (2017), ontologically, this research discourse in developing the system and validating it seeks to use (a) *'subjective reality'* (involving individual preference structures). (b) *'Intersubjective reality'* (e.g. socio-cultural influences on design decision making) (c) *'objective reality'* (e.g. physical, environmental attributes); (d) *'disciplinary reality'* (that which respects the multi-stakeholder preferences); and finally (e) '*paradigmatic reality'* (involving respect for the underlying philosophies in design decision making and those in probabilistic and other empirical approaches underlying the model). The realities reflect ontological pluralism considered in a dialectic pluralist space, and the many dialogues within the multiple ontological theories (Johnson, 2017).

Epistemologically *(regarding the theory of knowledge)*, this research discourse harnesses heterogeneity through thesis and antithesis after which it homogenises these epistemologies through synthesis, important for research methodologies as MMR; even with respect to divergence in multiple standpoints to support a model thesis that is built and validated in contexts in practice. Epistemology, therefore, helps discern aspects in the modelling of uncertainty and forecasting within design decision making. Together with the utilitarian principles, the multiple epistemologies this research takes inform the unified practical and theoretical standpoints; and interactions and interfaces in both the rational and empirical cycles relevant for representing the complex design process as illustrated in *Figure 4-1*.

Empiricism and rationalism, therefore, have relevance in both the ontological and epistemological spaces and are relevant in the research inquiry of the complex phenomena in FED processes. This research thus needs to adopt a methodology that conforms to the empirical and rational necessities for the modelling and evaluation of the various phenomena within it. It is also appreciated that there will emerge tensions between the empirical and the rational in practice requiring emic and etic approaches something that reinforces the role of dialectic pluralism as applied in MMR (Johnson, 2017). The role of the researcher in this thesis is, therefore, to act as an emic facilitator/mediator between the tensions/interactions of the various phenomena as is in FED decision making.

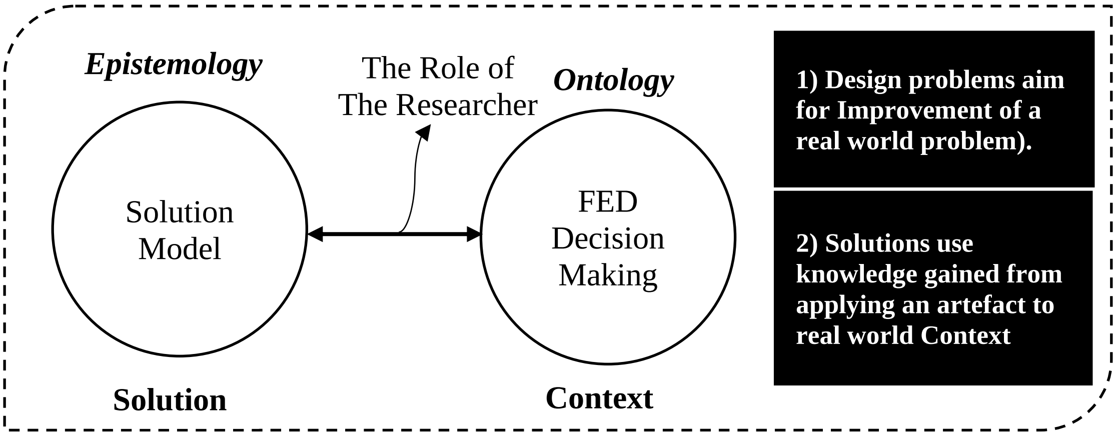

Figure 4-1 Role of the Researcher in Problem Solving adapted from: Wieringa (2014)

4.3 Mixed Methods Research (MMR)

Following on from the philosophical positions underpinning this research, a mixed methods research methodology (MMR) is adopted for this research. Bergman (2008) describes MMR as one that has *"at least one qualitative and at least one quantitative component"* within a research undertaking. MMR has been gaining broad appeal among research because of this unique combination of skillsets and hence the ability to add validity to research findings alongside adding to knowledge growth (Johnson et al., 2007; McKim, 2015). Using MMR, according to Schoonenboom and Johnson (2017) research gains added validity through a combination of qualitative and quantitative research approaches alongside improved knowledge of phenomena. This validity, however, depends on the explicit discussion of the paradigmatic research foundations (Shannon-Baker, 2015). This research seeks to devise a solution to the systemic problem in Benefits Realisation in projects during FED decision making in uncertain contexts from both a social construct (qualitative) and mathematical modelling (quantitative) approaches. Important in the qualitative-quantitative approach is the understanding of the appropriate integration of the two through dependence or simultaneity (which can be sequential or concurrent); such as levels of research purpose definition, method, methodology or paradigm, data collection, analysis or results (Guest, 2013; Greene, 2015; Creswell & Clark, 2017; Schoonenboom & Johnson, 2017).

The qualitative side utilises constructivist approaches that underlie the roles of stakeholders in design; while quantitative side is supported by the postpositivist approach to reflect the role of mathematical theory. Constructivism has been used widely in grounded theory as a paradigm that is based on the understanding that knowledge is shaped by experiences (Charmaz, 2020).

On the other hand, Gamlen and McIntyre (2018) demonstrate the use of Post-positivism in mixed methods research in which scientific inquiry seeks to validate in a methodical approach any conclusions. The complementary nature of both approaches is utilised in this research in supporting the *'structure and agency'* influences on design decision making and ultimately benefits realisation.

4.3.1 Justifying Use of MMR

The consideration for MMR followed an evaluation of not only the philosophical positions but also other methodologies like i) DSR, ii) action research, iii) grounded theory, iv) ethnography, v) archival research; that all proved not appropriate for this research in supporting its aims and objectives.

For example, while DSR allows for the investigation of phenomena within a bounded entity for the purpose of improving it, i.e. the possibility of artefacts to improve contexts, (Peffers et al., 2007). This was not considered enough for this research even though there is an overarching aim of understanding reality. This approach, therefore, appears limited in terms of adopting various methodologies as is allowed in MMR for instance those relating to axiology, ontology and epistemology in an integrated manner (Johnson et al., 2007; Schoonenboom & Johnson, 2017). Besides, this research's strategy was to progressively develop an artefact that us not present at the start as is required for DSR.

On the other hand, Action research would support the aims of this research as being in the context would inform improved data sets as a result of close action in context (Simon & Wilder, 2018). The requirements to be a part of the participating organisations was however an element not available to this research in part due to barriers in language in the first context but also owing to the wider health issues of 2019/2020 vis-a-vis Covid-19 pandemic. Strict non-disclosure policies and employment policy and compliance also meant this action research was not appropriate.

The approach in grounded theory and ethnography on the other requires that research is informed by the context from which theories can be drawn (Holton & Walsh, 2017; Ingold, 2017). This would not be appropriate for this research as the development of the decision support system hinged on the understanding of underlying theoretical and mathematical conceptions to support any subsequent formulations and adaptations. Archival research similarly would fall short of the basis required to support the level of rigour expected for this research on its own.

This research involves first establishing the theoretical basis to support the assessment of the appropriate mathematical elements of DESIDE. Together with the understanding and modelling of the subjective nature of decision-making iteration, flexibility, and basic foundations allowable in MMR makes it the most appropriate.

4.3.2 The Research Process and Iterative Approach in MMR

The MMR methodology, therefore, allows for different inquiry logics and complementary purposes in addressing the research objectives and support triangulation (Johnson, 2017). In facilitating this interaction, it may suffice, for example, that validation reveals some solutions in some contexts and not others, or even creating new barriers in some (Wieringa, 2014). In this case, Johnson (2017) argues that dialectic pluralism, as part of MMR can support research inquiry through dialogue, dialectics, and hermeneutics. In employing the three, research discourse can iteratively dispute and examine; continuously and in equal treatment of the parts and building on past interpretations to make new ones, exploiting the dynamic logic of *'thesis, antithesis and synthesis'* (Creswell & Clark, 2017).

Figure 4-2 represents a generic MMR approach adopted in this research, reflecting areas of ontology (design cycle) and epistemology (knowledge cycle) in an axiological perspective. In the ontological space, critical realism is allowed to exude so that the research can capture the real-world; balanced against constructivist and relativist epistemologies reflecting broader theories, constructions and perceptions of events influencing design decision making (Maxwell, 2012). It allows the designing of the problem and answering of the knowledge questions in an analytical/empirical cycle. Iterations over the design and knowledge cycles represent the coming together (nodes) of the qualitative and quantitative cycles respectively and aim to build understanding and underscore the applicability of the artefact to the context. In the design cycle, the research seeks to address any design needs for the artefact through defining and understanding of the design problem (Wieringa, 2014, p. 16).

MMR allows for both qualitative (rational cycle) and quantitative (empirical cycle) methodologies to run alongside each other in research (Schoonenboom & Johnson, 2017; Gamlen & McIntyre, 2018; Guetterman & Fetters, 2018). In this research, the cycles are reimagined to include the four goals of determining; i) the need, ii) the mechanism, iii) the proposed solution and finally iv) the end goal which is developing a decision support system for Benefits Realisation in FED processes. The first step is referred to as the problem definition, that involves investigation and establishing of the research rationale in supporting a subsequent rational process of data capture (Aken, 2004). The empirical cycle that represents the epistemological approach embodies two parts:- the analytical and the empirical domains for knowledge about the real world (Wieringa, 2014).

The typology for MMR adopted is the hybrid multiphase-multilevel sequential as part of a concurrent approach in which data from the qualitative research informs the quantitative parts in various phases and levels in the model to test, validate and inform the development and evaluation of DESIDE (Teddlie & Tashakkori, 2009; Schoonenboom & Johnson, 2017). In a multiphase approach, Delaney et al. (2017)and Schoonenboom and Johnson (2017) highlight that research employs an approach that connects data in phases and in a manner that meets the requirements of the research objectives.

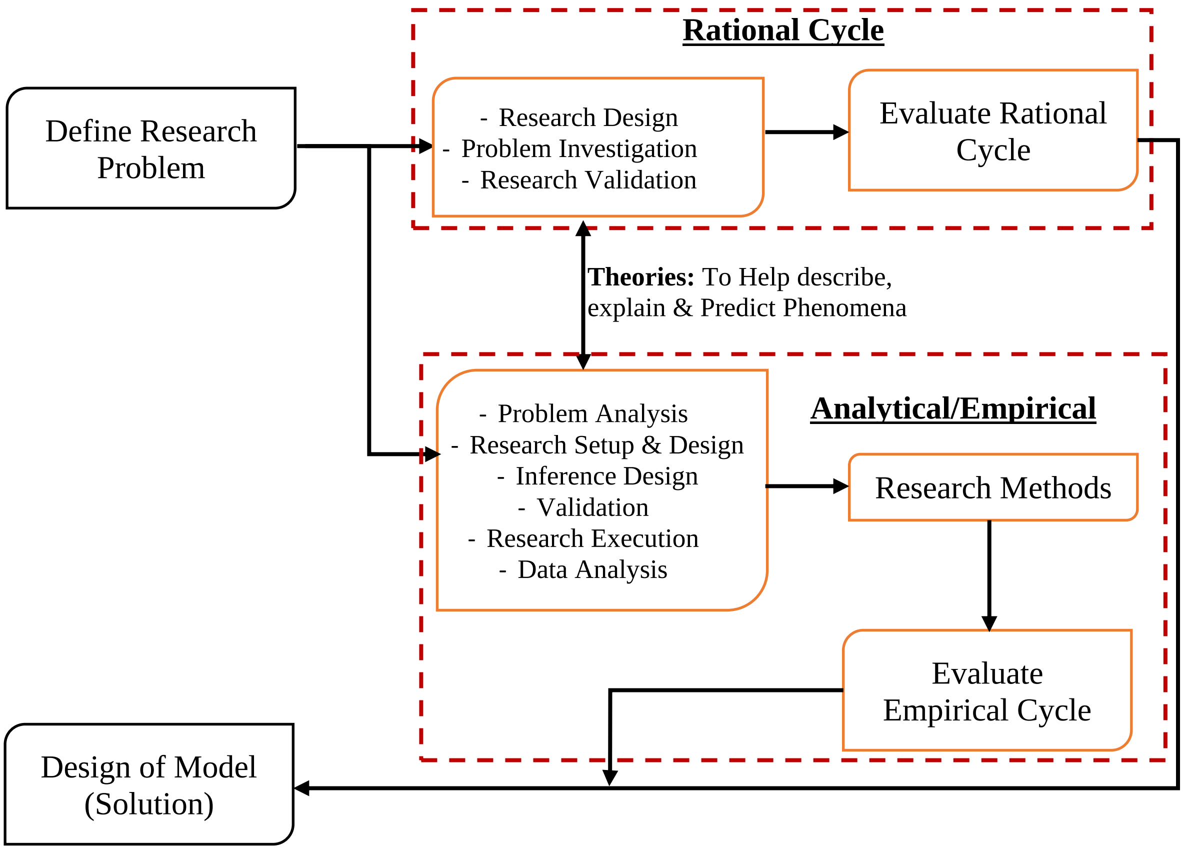

Figure 4-2 Generic Course of research in MMR adapted from: Wieringa (2014)

The first, addresses the epistemological aspects in the conceptual analysis, including the theories, maths and logic/ *priori* knowledge (Wieringa, 2014; Schoonenboom & Johnson, 2017). This includes the theories and mathematical concepts in probability theory, utility analysis and QFD HoQ. Knowledge in the analytical realms according to Aken (2004) can be

1) object knowledge – which is that relating to properties and setting of the model; 2) Realisation knowledge – one that relates to the subject domain like probability theory and finally 3) design knowledge – presented as an understanding and generalisations from processes dialogue, dialectics and hermeneutics through thesis, antithesis and synthesis.

The second is about data requirements to support the emergent questions. Adopting an empirical approach allows this research to build knowledge alongside qualitative data. It is important to stress the importance of setting precisely the knowledge questions, and this can be facilitated through the precise definition of knowledge goals through a goal hierarchy illustrated in *Figure 4-3* and as adopted by this research alongside the following knowledge questions underpinning the development of the decision support system (Wieringa, 2014, p. 21):

1) ***Effect Question:*** *Does the Decision Support System when tested in a context produce any results?*

   What effects are expected because of validating the model in the selected contexts? This sets the importance of observing the response of the artefact to context stimuli and how it performs.

2) ***Trade-off Question:*** *Do alternative decision support systems produce any results in the context?*

   The results from the phased research be it the sequential or concurrent strands or both; are important in highlighting differences and variations in approaches to the proposed model.

3) ***Sensitivity Question:*** *What are the results when the decision support system is applied to a different context?*

   This thesis undertakes two case studies to underscore and address the research objectives relating to variations in contextual dynamics during FED and any necessary modifications in required.

4) ***Requirement Satisfaction Question:*** *Are the stakeholder goals being met with DESIDE?*

   This lends to the results relating to the goals and objectives of the research. The proposed system aims to support an integrated and collaborative FED decision making by modelling requirements and forecasting. This has to be facilitated in practice.

In terms of the goal hierarchy in the knowledge questions domain, *Figure 4-3* illustrates how the two can iterate between instrument goals, knowledge goals (that links to the prediction goals) and the artefact goals (that relating to the decision support system). The goals have been espoused in the research aims and objectives seen earlier in section 1.4. They ultimately link to high-level goals in the research problem space, which are essentially stakeholder desires and goals supported through decision making. Prediction goals in this thesis relate to how the proposed model can contribute to theorising on the decision support in FED for the delivery of benefits in dynamics contexts.

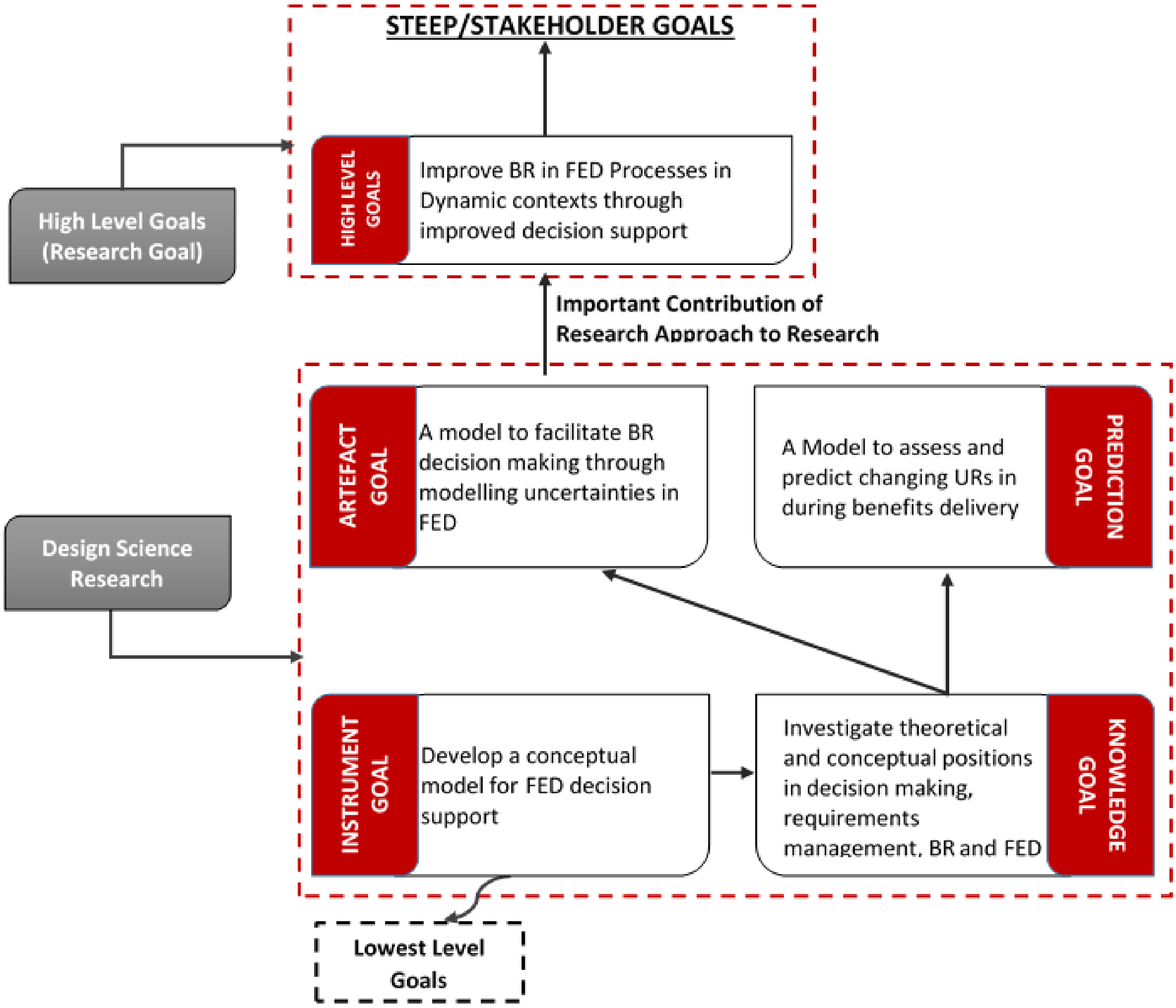

Figure 4-3 Goal Hierarchy - Characteristic contribution structure Adapted from Wieringa, (2014)

4.4 Developing the Research Design

4.4.1 Background to Research Design

The research design refers to the process of selecting and constructing a research method both for its process and artefact that represents the underlying research ontologies, epistemologies, axiology, methods, paradigms, methodologies as discussed in the previous section (Maxwell, 2013) and rules (Schoonenboom & Johnson, 2017) for research (see *Table 3*).

Table 3 Relating the World View to This Research

World view Element	The approach in this Research
Ontology	Ontology was applied in this research by capturing, integrating, modelling, and presenting views from multiple stakeholders from the perspective of FED in facilitating the delivery of project benefits
Epistemology	The systematic literature review and review of an extensive application of MCDM Utility Theory and QFD principles helped inform data collection necessary for modelling using the integrated decision support system.
Axiology	Integrating subjectivity of decision making is a key element of DESIDE and therefore provides a platform to evaluate objectively and considering all stakeholder values into modelling and analysis and ultimately decision making
Methodology	The application of various methodological approaches, including constructivist and post-positivist approaches alongside ontological, epistemological, and axiological perspectives reinforced the methodological mix in MMR.

Schoonenboom and Johnson (2017) discuss the primary design dimensions essential for MMR that are discussed throughout the preceding section to include; a) the importance of defining a research purpose that exploits the heightened knowledge and validity critical to the *'multiple validities legitimation'* in MMR (Johnson & Christensen, 2019). b) the theoretical drive, including identifying the research with such philosophies as inductive, deductive, abductive, dialectic, critical or otherwise (Johnson, 2017). c) the adopted typologies or rather the nature of the interaction, interface or integration within research discourse (Guest, 2013; Morse, 2016). d) defining the research design approach, whether that be emergent or planned. It can help the research cope with situations when the results from the modelling and analysis for instance are contradictory, unsatisfactory, or inconclusive in which case the model components may be revised or revisited. e) identifying the necessary points of integration in research discourse for the qualitative and quantitative methods. In this research, the points of integration are interactive and along the full process of the methodology from research purpose definition through to results and theories. f) lastly is the dimension of complexity, highlighting the inherently complex nature of MMR that can be characterised by multiple points of integration (Guest, 2013).

4.4.2 The Research Design

The preceding primary dimensions presented in the preceding sections are essential for MMR design and strategy alongside any secondary dimensions for instance any research-specific sampling methods, validity criteria and strategies, criteria for selection of research participants and, the complementarity or difference in adopted methods among others (Schoonenboom & Johnson, 2017). A research design for this research is illustrated in Figure 4-4. It takes the form of four important stages, namely: research definition, development and empirical stage, detail case study and evaluation stages. What is important to highlight here is the continuous integration of both the qualitative (design) and quantitative (knowledge) cycles throughout the research. In the two-pronged approach for both the defining of the design problem and answering of the knowledge questions, the research seeks to follow both an explanatory and empirical process at each stage (Schoonenboom & Johnson, 2017). In this approach, Schoonenboom and Johnson (2017) suggest that research undertakes a *"qualitative data collection and analysis process followed by the collection of quantitative data to test or generalize the initial qualitative results"*. The research iterates over the design problem and knowledge cycles and in the phases involving the development of the decision support system as well as the modelling.

The research in phase 1 starts with a literature review that informs the detailed understanding of the key concepts in FED decision making and Requirements Management for Benefits Realisation. The research first seeks to establish the current state of the art in FED decision making, highlighting any insufficiencies in current understanding and practice. The research also explores any modelling capabilities in practice that deliver improved Benefits Realisation with focus on the inherent and contextual dynamism in this stage through a systematic literature review. Concurrently, the research explores the understanding of design decision making and how it facilitates wider Benefits Realisation in FED. Essentially, in phase 1, the research seeks to identify the gap in theory and practice through systematic literature review in FED and how decision making and Requirements Management impact on Benefits Realisation. This is explored in chapter 3, and the results presented in sections 7.3 and 7.4. The FED stage also helps identify any specific tools, including those employing mathematical analysis that can address this gap. The purpose here is to provide a conceptual basis for the development of DESIDE for FED and identify the nature of data necessary for the subsequent modelling through any adopted data gathering techniques. Phase 1 is also important in aligning the research objectives with the process of validation required that is applied progressively through the research.

Phase 2 is the first stage of the development of DESIDE where identified components like those relating to utility assessments and cause-effect modelling and analysis, requirements forecasting, and uncertainty modelling are applied progressively using case study context one. Participants in this phase include end-users in the social housing sector in the city of Porto Alegre in Brazil, expert stakeholders including designers, academics in the sector, project managers, contractors, facility managers and other stakeholders. The data collected through questionnaires, interviews, observation, photos, and document review among others; and the modelling provided a preliminary validation and evaluation of the appropriateness of the component parts of the decision system. In this phase, therefore, the research seeks to establish how mathematical modelling can work in complementarity with qualitative and subjective data from stakeholders in addressing insufficiencies in Benefits Realisation through Requirements Management. Progressively modelling this data helps evaluate the applied tools in addressing complex modelling of utilities, uncertainty and changing requirements.

Phase 3 is the detailed case study in which the full decision support tool is applied to a case study in a U.K. case context, again in social housing. This stage is important not only to help draw on any differentiations in results but also establish coherence in data analysis. Participants followed a similar pattern as in case study one. This phase leads to Phase 4, which is the detailed evaluation process to establish rigour in the proposed system and link with earlier validation processes (through peer review publishing). The evaluation process also aims to establish consistency and coherency.

The data collection methods are detailed in figure 4-5, including explanations of their necessity. Phase 2 and 3 inform the discussion in chapter 6 and findings and discussion in chapter 7. While chapter 2 addresses the knowledge areas in conceptual understanding of the key elements in this research, chapters 3, 5, and 7 draw to the novelty of this research in establishing a decision support system for FED decision making for Benefits Realisation.

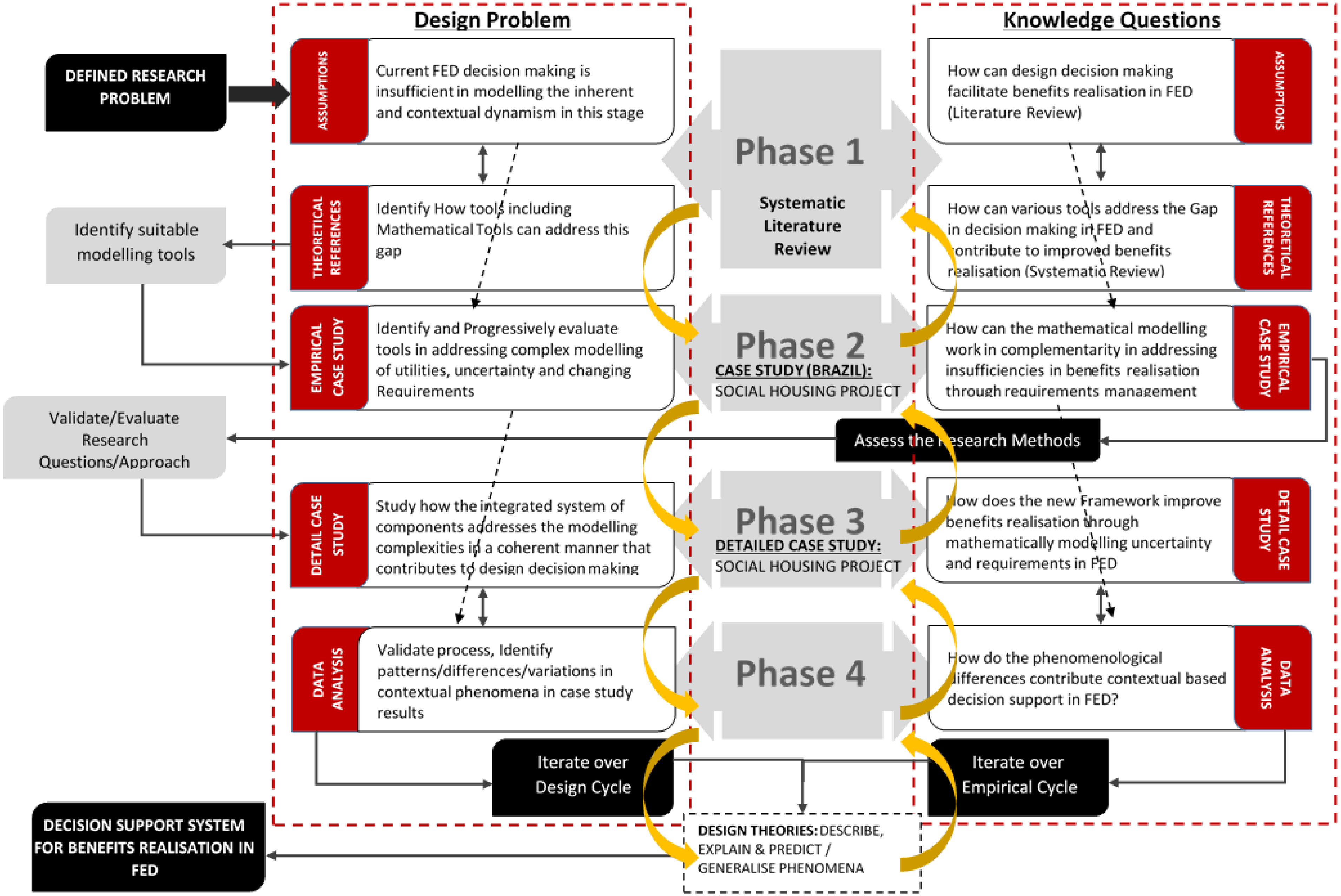

Figure 4-4The Research Design

A research design follows on from a systematic literature review (see results in sections 7.3 and 7.4). The systematic review informs the selection of the components parts of the proposed model that are progressively validated in case study one for their contribution to the overall model integrity in the development stage; ultimately forming part of the concept validation. A detail case study is used to validate and evaluate the full framework underpinning any theories and generalisations thereof by drawing to any differentiations through comparative analysis. Throughout, continuous literature review informs positions alongside the data collection methods adopted.

It, therefore, suggests that the research design is an essential determinant of the adopted research methods for supporting the data collection and analysis. According to Bellamy (2011), research methods principally refers to those sets of techniques employed in *'creating, collecting, coding, organising and analysing data'*. The research methods adopted for this research support simultaneously in MMR both qualitative and quantitative approaches through case studies. Moreover, Guetterman and Fetters (2018) highlight that in the case of case studies, various research methods can be adopted both qualitative and quantitative as part of perhaps a MMR approach; including data collection methods as interviews, questionnaires, surveys, observations, photography, and documentary evidence as qualitative; and requirements and forecasting modelling as a quantitative approaches in this case.

4.5 Data Creation and Collection Methods

Data collection and creation describes ways of creating raw data or sets of information as a basis for further research (Bellamy, 2011, p. 15). Raw data can be based on ethnography, observations, focus groups, questionnaire surveys, interviews, case studies, photography, or video recordings, among others. Following creation, data can be collected and captured in a way that makes sense to the research. This can be through counts or scanning texts for particular patterns or other fitting method. *Figure 4-5* indicates that a combination of methods was adopted for data collection. Guetterman and Fetters (2018) have highlighted that this way, research can exploit the strengths of multiple data collection techniques that ultimately, improves the validity and rigour of research in utilising the value added by a mixed-methods research approach.

4.5.1 The Research Data gathering methods

Figure 4-5 illustrates the methods and stages adopted for data collection in this research. The process iterates around project definition in case study A (see later in section 6.2) that takes on a full empirical approach in the detailed study. In the project definitions stage, *priori* knowledge together with literature review and case study context one, inform the basic structure of the conceptual model. The next stage is the development stage uses an empirical approach to research in establishing validity and flaws, reinforcing the key attributes in the modelling components and structure forming part of the decision support system. Empirical data is collected using questionnaires, interviews, observations, and documentary review. Analysis is carried out to validate the structure of the component of the decision system. The detailed case study (see later in section 6.3), applies the proposed decision system fully to case study two to inform the subsequent evaluation and validation process. Again, data is collected using questionnaires, interviews, observations, and documentary review. Cross case analysis and further literature review soon inform an improved model design following the evaluation. Cross-case analysis informs the discussions thereafter and the conclusions, including describing any generalisations. The processes are iterative in parts and methods used, for instance for data collection and literature review and not necessarily sequential but rather complementary, depending on the situation.

4.5.2 Literature review

According to Winchester and Salji (2016), literature reviews are an essential part of any research helping to not only guide constructive critical ideas but also be a source of rich information when setting a context. In so doing, Baker (2016) and Walliman (2017, p. 59) discuss that they reinforce and validate any hypotheses that may have been put forward previously; as well as helping identify gaps in existing research and any conceptualisations thereof. In other words, literature reviews are a diverse source of preliminary stage resource to reinforcing any arguments research is presenting argues Ary et al. (2018, p. 36). It is a continuous process that is engaged throughout this research and more especially so in confounding early research conceptualisations like constructing, justifying, and validating attributes included in the conceptual model. Perhaps more crucially, literature review continues to be important in developing the research idea and theory, confounding gaps in research Requirements Management and forecasting during FED and describing the research problem (Winchester & Salji, 2016). Gaps are reinforced by the limited nature of evidence and support tools with a focus on front end design processes. The extensive research has thus helped set the basis for:

- Understanding underlying concepts in design decision making including in Requirements Management in FED and dynamic contexts.
- Building an important base to augment *priori* knowledge of the research for arguing for constructs included in the conceptual model.

Sources of literature for this research ranged from print to digital media, including books, research papers and journals, academic texts and reports, review articles, reference databases and publicly available data sets. Based on literature review and *priori* knowledge, three high-level functional purposes of the research: i) Defining Design Parameters – as part of a requirements management process, ii) Interpreting Design Needs - in a process of decision making, and iii) Defining Design Processes. The systematic literature review analysis and results are discussed in sections 7.3 and 7.4.

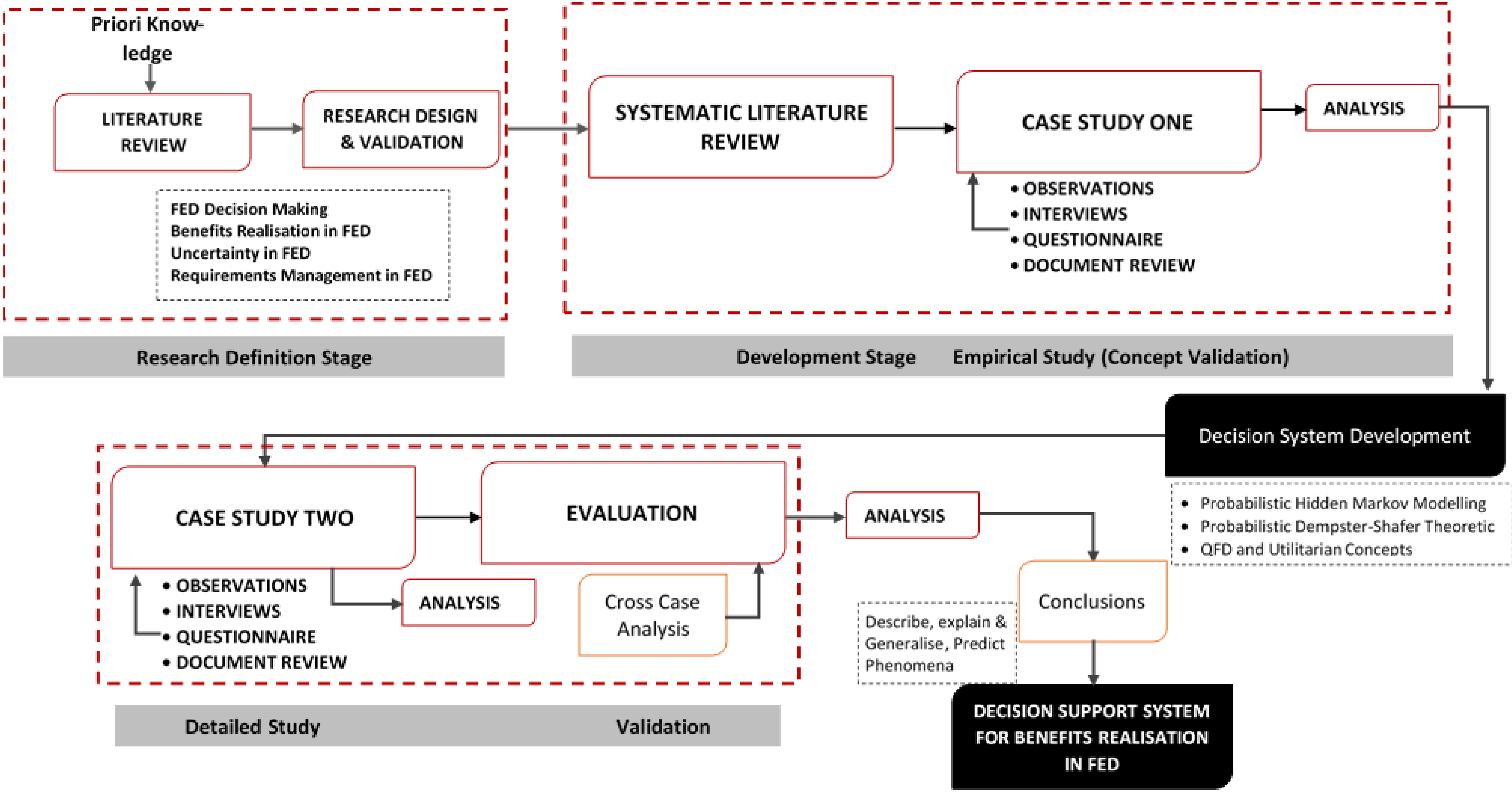

Figure 4-5 Steps adopted for Data Collection

4.5.3 Survey Research

Check and Schutt (2011, p. 160) define survey research as *"the collection of information from a sample of individuals through their responses to questions".* Surveys allow for several methods as possible data collection methods, including questionnaires (for instance for rated responses in a quantitative survey) or qualitative methods like using open-ended questions. A mixed approach can also be used in semi-structured interviews (Ponto, 2015). This method of data collection has been used widely in research (Straits, 2005); ranging from simple questions to more elaborated forms to enhance validity and rigour (Ponto, 2015). Using surveys, research can represent characteristics from a small group of individuals to a large sample like an entire community (Ponto, 2015).

Regarding sampling, this research engaged respondents with an association to the key research themes either as an end-user or as a stakeholder including designers, contractors, management, funding, academia, that all had experience with the social housing sector. Other stakeholders were chosen for their familiarity with decision support systems, particularly in MCDM. Also, regarding the extent of the sample, DESIDE relies on specific knowledge for input values for its integrity. This is so values can be correctly coded for the QFD initial HoQ matrix for the subsequent HMM, utilitarian and uncertainty modelling using DS-T. It was, therefore, more important that the right decision-makers made respondents rather than necessarily any number of them (Herath, 2004). For example, one funding agent in the MCMV program was sufficient to elucidate project delivery lead times from a funding/economic perspective.

The key elements in a survey are, therefore, how the research can define the sample, enlist participants and enact methodical ways of data collection, including any methods of administering the survey. Ponto (2015) adds that surveys can, as a result, be prone to biases. Author positions like Ponto's (2015) suggest that research ought to have in place mechanisms to guard against any biases for instance by applying methodical and explicit techniques in coding and analysis of data. It is also important to carefully consider the nature and design of the survey questions including paying attention to clarity, structure, simplicity and ease for coding and for respondents attention to questions and themes (Dillman et al., 2014). This is so surveys can address potential errors for instance by applying a multimode approach to survey alongside any effort to chase up nonresponse respondents. Literature and systematic literature reviews in Chapter 2 and Chapter 3 informed the basis of the questionnaire and semi-structured interviews for this research.

4.5.3.1 Questionnaire Survey.

Taherdoost (2016) has observed that questionnaire survey is one of the most used data collection methods. This is because questionnaires are effective and cost efficient particularly when research is across a wide domain. They also come with a layer of validity and reliability (Taherdoost, 2016). Three areas of inquiry informed the research – (i) relating to basic respondent bio particularly on demographics, (ii) relating to requirements both from a user and design perspective and (iii) relating to decision making in FED. Using a Saaty (2002) ranking approach users were asked to rate their preferences to questions in parts (ii) and (iii) from Not at all Important **(1)** to Extremely Important **(9).** It is important to highlight that while in the past mail order questionnaire surveys were dominant, the advent of the internet means they can now be applied increasingly electronically, cost-effectively, and efficiently. The questionnaire strategy was first to establish the role of the respondent in the social housing design process either as an end-user or other stakeholder like design. The next question regarded the level of occupancy stakeholders were involved in. The needs from both a user and design perspective can vary along with preferences in decision making with the level of occupancy, so this was important to be cast in perspective in the questionnaire.

The questions in the next section and indeed the rest of the questionnaire asked respondents to rate parameters starting with high order requirements through to low-level requirements first dealing with design and afterwards the user needs as influenced by a range of high and low order attributes. Question 7 relates to establishing a modelling basis for cause-effect analysis in utilitarian assessments, while question 8 establishes the rationale for complex modelling adopted for DESIDE. Questions 9, 10 and 11 seek comments as to practice in as far as design engages with structured decision making and Requirements Management more widely among respondents. Question 11 is the only open-ended in the questionnaire. The results are modelled using DESIDE using equations and algorithms adopted within excel first combined through a QFD analysis using the HoQ matrix. The next process in the modelling is the HMM followed by utilitarian modelling using COPRAS and MOORA that is followed by a cause-effect analysis. Finally, is the uncertainty analysis using equations in the DS-T all detailed in chapter 5.

Most questionnaires were distributed online through email to selected respondents. Three were by post while six were hand distributed following pre-arranged interviews (see *Table 4* and *Table 5*).

4.5.3.2 Semi-structured interviews

Semi-structured interviews are pre-set questions with the flexibility that they can be re-ordered or modified following the interviewer's assessment and judgement as to the appropriateness. The interviewer can change the wording of questions, and he/she can explain further the questions should it suffice that it is necessary. At the interviewer's discretion, inappropriate questions can be omitted or new ones added should this facilitate a better interview focus observes Bernard (2017, p. 165). Like Bernard (2017), many authors have pointed to the ease of organising semi-structured interviews as one of its greatest strengths. This can be through face to face, over the phone or using the internet with Skype or WhatsApp. They allow for some level of personal interaction between interviewer and interviewee. Telephones conversations may enable people to relax and feel able to disclose perceived sensitive information.

Expert opinion was important to this research as opinions brought grounded pragmatism to it. This qualitative approach to interviews was an essential part of this research with open-ended questions to enable unconstrained feedback from expert respondents. Semi-structured interviews contrast with structured interviews in which the same pre-set order of the questions is posed to all interviewees. They only differ to questionnaire surveys in their open-ended-ness (Van Teijlingen, 2014). They are less flexible and sometimes carry minimal interaction between the interviewee and interviewer who retains strict control over the process as compared to unstructured interviews. Unstructured interviews are a more informal approach to interviews. With this method, the interviewer goes into the interview with merely a general knowledge and interest in the subject matter and allows for the interview to progress freely in the course.

Powney and Watts (2018), like many authors in research methods, point to bias-related issues with interviews. Authors point out that semi-structured interviews and interviews in general still carry a degree of intrusiveness, however, that can create a level of bias in the type of information an interviewee is willing to divulge. Bias and subjectivity can also potentially manifest on the part of the interviewer in semi-structured interviews (Powney & Watts, 2018); including that stemming from any preconceptions and/or stereotypes, appearances and/or opinions (Van Teijlingen, 2014). As part of the questionnaire guided interview process, the research adopted a process of detailed interviews using an unstructured approach followed by a served questionnaire for the respondent to fill in their time. This process was important in establishing the background and preference structure that in turn, supported the data coding process in the QFD analysis stage. The robust data capturing process like recording devices enabled corroboration and coding from the transcription of information following the interview as relying on memory following interviews, can potentially corrupt data. The research was also alert to the danger of poor transcription, especially when constructing questions as poor questions would undoubtedly lead to poor quality data, something that ultimately affects the research rigour.

4.5.4 Summary nature of Interviewees

The case study context in capturing the important dynamics in the MCMV program elicited participation from twenty-two interviewees for case study one and U.K. social housing from twenty for case study two (see *Table 4* and *Table 5*).

Interviews were held with each of the participants for between 20 – 135 mins to capture their contribution to the programs from a Requirements Management perspective and their preferences to a range of requirements.

Table 4 Summary of Interviewee List for Case study One

Interviewee	Duration of Interview	Section 1	Section 2	Section 3	Section 4
Economics Professor	135	✓	✓	✓	
Architecture Professor	35	✓	✓	✓	
Architecture Professor	50	✓	✓	✓	
Project Management Professor	70	✓	✓	✓	
Local Council Planner	30	✓	✓		
Project Manager	70	✓	✓		✓
Site Manager	50	✓	✓	✓	
Architect on MCMV	80	✓	✓	✓	✓
Architect on MCMV	85	✓	✓	✓	✓
Project Manager	25	✓	✓		✓
Construction Manager	30	✓	✓	✓	✓
Funding Agent (Caixia)	40	✓	✓		✓
Researcher on MCMV	65	✓	✓	✓	
Researcher on MCMV	55	✓	✓	✓	
Resident 1	35	✓		✓	
Resident 2	35	✓		✓	
Resident 3	35	✓		✓	
Resident 4	35	✓		✓	
Resident 5	35	✓		✓	
Resident 6	35	✓		✓	
Resident 7	45	✓		✓	
Resident 8	35	✓		✓	

Table 5 Summary of Interviewee List for Case study Two

Interviewee	Duration of Interview	Section 1	Section 2	Section 3	Section 4
Chief Executive Officer Professor	115	✓	✓	✓	
Professor (Architecture)	35	✓	✓	✓	
Project Manager	135	✓	✓	✓	
Contracts Manager	70	✓	✓	✓	
Council Housing Officer	30	✓	✓		
Project Manager (contractor)	55	✓	✓		✓
Site Manager	50	✓	✓	✓	
Architect	20	✓	✓	✓	✓
Architect	25	✓	✓	✓	✓
Quantity Surveyor	20	✓	✓	✓	✓
Compliance Manager	25	✓	✓		✓
Construction Manager	20	✓	✓	✓	✓
Funding Agent (Homes England)	40	✓	✓	✓	✓
Researcher on Social Housing	65	✓	✓	✓	
Care Manager	55	✓	✓	✓	
Facilities Manager	55	✓		✓	
Training Manager	115	✓		✓	
Resident 1	30	✓		✓	
Resident 2	25	✓		✓	
Resident 3	20	✓		✓	

4.5.5 Documentary evidence

Documentary evidence is an important source of information in an unconstructive process that can be reviewed time and again by the researcher. It thus suffices that the information gathered can be rich in informing detail processes and dynamics during design decision making that would otherwise not be represented in other forms of data collection methods. Documents informed the HMM matrix in relating to high order factors and how they have changed over time (see example *Table 6*).

Documentation as shown in *Table 6* provided and corroborated expert data through expert reports, in both print and online. Photographs also form a great part of the array of documentary evidence. Documentary evidence is, therefore, that essential link between other methods of data gathering for instance in interviews or observation considering ethnographic and anthropologist approaches can be constrained by political, legal, economic, cultural, social and personal circumstances Madden (2017, p. 4); sometimes leading to disparities between what is said or seen to be done with what people actually end up doing.

Table 6 Example of Documentary Review

Requirement	Nature of Documents Reviewed in this Research
Sociocultural, Economic,	UN Reports on World Economic and Social Affairs (https://www.un.org/development/desa/dpad/publication/world-economic-situation-and-prospects-2020/)
Community, Governance, Geopolitics	Transparency international.
Health and Safety	Health and Safety Executive (https://books.hse.gov.uk/)
Occupancy	Office for National Statistics (https://www.ons.gov.uk/searchpublication?q=social%20housing).
Environment, Life Cycle Performance	DEFRA (https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs/services-information)
Sociocultural, Economic, Geopolitics	Case Context funding Proposals
Technical, Health and Safety, Environment	Floor Plans, Site plans, elevations, sections and other documentary evidence
Geopolitics, Health and Safety, Technical	Planning standards

Walliman (2017, p. 94) however cautions on potential pitfalls in the rigour associated with documentary evidence, i.e. that relating to reliability and authenticity. Walliman (2017, p. 97) also discusses the importance of objectivity and rigour on the part of the researcher in collating and analysing documentary evidence some of which may be biased, outdated, non-contextual or altered in some form. None the less, some documentary evidence has been explored to inform the stages of data collection.

4.5.6 Observations

Observational studies are quite an important method for data collection as they are unobtrusive and less intrusive, at least not intentionally (Carter, 1999). Observations can be both of a qualitative or quantitative nature (Mulder et al., 1985). Qualitative observations are the less intrusive of the two; attempting to merely record patterns of phenomenological information and are flexible in what information can be gathered (Coiera & Tombs, 1998). For example, trends in and record of the nature of the context can be captured by this method. Quantitative observations on the other hand can be useful in instances as recording the number of instances of information exchanges between stakeholders. The case studies hinge on data collected through observations for this research as a form of collaboration of any other data source e.g., in documentary and photographic evidence (see sections 6.2.1 and 6.3.1) i.e. through attending meetings and site visits. In the observations study in Case study one, the aim was to understand, assess and correlate the dynamic nature of the context, for instance the economic and family factors that influence MCMV. This involved observing how design and professional teams interpreted real-life lived experiences of potential and current residents and how requirements like site/physical management were implemented in design for compliance. Meetings were held at the local planning authority offices and in Caixa bank with a funding agency, and interactions here were recorded too. In the case of observations, the aim was to understand (see *Figure 6-1* to *Figure 6-15* and *Figure 6-23* to *Figure 6-28*):

- How contextual factors like socio-cultural, geo-political technological and economic impacted on requirements.
- To understand and corroborate the role of understated stakeholders and goals and desires in influencing Benefits Realisation in FED (constructability requirements was a key issue here).
- How interdependences between stakeholder goals and contextual dynamics impacts on FED processes.
- How an understanding of changing user needs impacts on Benefits Realisation (observation of how users changed their homes and connecting to the what they changed).

The same approach is adopted in the second case study as its effective in revealing related albeit different and subtle facets of Benefits Realisation from a FED decision making perspective; reflecting the contextual dynamics that bear on projects (see a summary of collaborated requirements in *Table 7* and *Table 36*).

4.6 Justifying Case-based Research as Part of MMR

Bellamy (2011) defines case-based research as:

> *"one that is defined and bounded by the researcher to answer a question about a particular phenomenon either empirically and inductively or theoretically and deductively."*

The case study approach allows this research to study in detail case context-specific influences, dynamics and mechanisms/phenomena in Benefits Realisation as comprehensively as possible (Bellamy, 2011, p. 102). Meyer (2015) is among a number of authors to draw to the constructivist approach in case studies where reality is taken to be a *'socially constructed'* endeavour; that to understand it requires examining tacit knowledge. Bellamy (2011, p. 102) on the other hand describes case study mechanisms and phenomena as patterns of interactions between and among component systems which can occur on a reflective cycle/exploratory study or the detailed study/problem-solving cycle.

Understanding of case study research is as varied as its definitions (Yin, 1989; Merriam, 2009). Merriam (2009, p. 40) for example defines a case study as *"an in-depth description and analysis of a bounded system"*. Yin (2009, p. 18) on the other hand views case study as *'an empirical'* investigation into *'a contemporary phenomenon'* in its context more so in the absence of a clear relationship between the two. The latter definition appears to relate more closely to and support use of MMR, and it is on this basis that this research considers a case study research.

Dul and Hak (2009, p. 25) and Baxter and Jack (2008) observe that the case study approach to research is appropriate when the research is 1) faced with a complex and broad scope, 2) limited in the amount of background information available to it and 3) context-dependent. A case-based study was adopted in Design Science Research (DSR) – an alternative research methodology by Kao et al. (2016) to successfully develop an intelligent system for a hospital case while a similar approach was adopted by Arnott and Pervan (2016) for decision support. In terms of MMR, case studies, therefore, allow for a detailed and understanding of context-artefact interaction as well as allowing for detailed development for empirical based analysis alongside it; and descriptions of phenomena of the interactions and ultimately theory that can be developed and evaluated (Hughes & McDonagh, 2017). There are, therefore, many possibilities in case study approaches as illustrated in *Figure 4-6* according to (Wieringa, 2014) some of which are applied in this research, including:

Observational case studies: in this approach, detailed knowledge of phenomena is built around a specific case study with little consideration for wider differentiations. Some data gathering in case studies in this thesis is in part observational. While on its own this would be inappropriate for this research, elements of observational studies were incorporated as part of a corroboration process for other data gathering methods.

Single case study mechanisms experiments: this extends the observational case studies approach by research gaining detailed knowledge from parallel single case studies through establishing differentiations between or among them. The contextual approach in this thesis means each case is treated independently as a single case study. A single case would be inappropriate for this research as it would fall short of the necessary empirical stages required for the development and evaluation of DESIDE.

Understanding Case Study Research: where research seeks to apply case study research as part of the methodological approach, *Figure 4-6* is a guide to the developing methods as part of the process. Two case studies are adopted for this research to keep within scope and have rigour in the research.

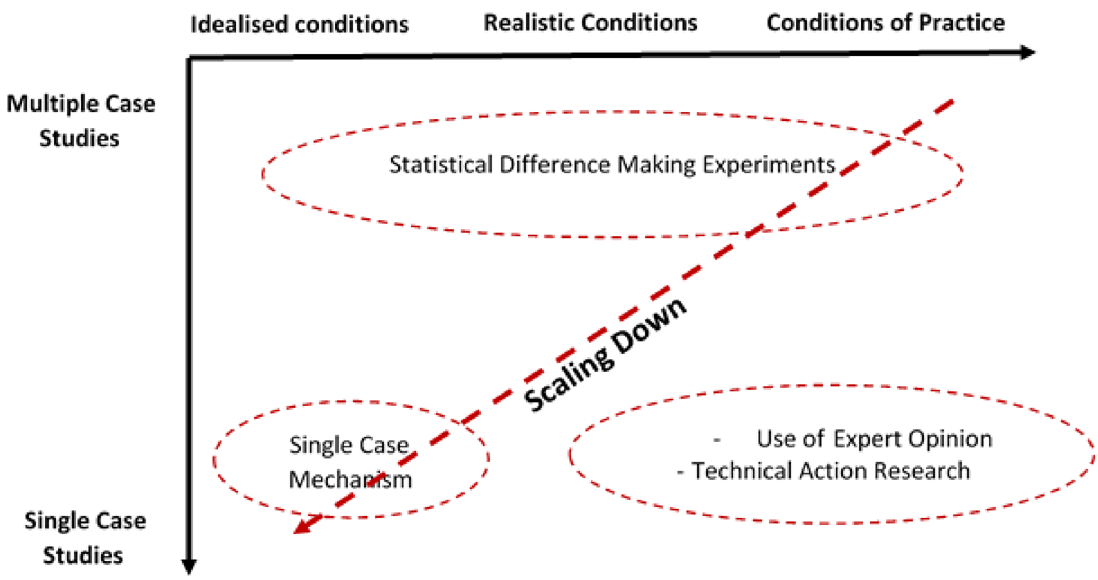

Figure 4-6 Scaling up in Treatment Validation in Case-Based Research – Adapted from: Wieringa (2014)

Statistical difference-making experiments: statistical differentiations in this approach among several solutions applied to several cases are the basis for the study. These differentiations may exist in part or fully across the analysis. This is not adopted for this research as the full decision system is applied to only one context for evaluation and validation.

A mixed-methods as adopted in this research can employ multiple case studies and approaches allowing context(s) of related conditions to facilitate generalised theory following evaluation and validation of the model in the problem-solving cycle (Wieringa, 2014). Multiple case studies can be important in presenting an understanding of *'insight in the indications and contra-indications'* arising from data gained from cross-case analysis. While also helping support the development of boundaries of any eventual theory. The relationship between the study participants with their cases while generating data for the model is an important process for this research (Crabtree & Miller, 1999).

4.6.1 Selection of Case Studies

The number of case studies required for the research to be rigorous is not something literature converges on. While some authors like Eisenhardt (1989) have advocated for 4-10 case studies, others like Yin (1989) insist that it is much to do with the researcher's desired limit of replication than the number. At the centre of this debate is the notion of integrity that a structured and objective case selection process brings to the rigour of the research (Baxter & Jack, 2008). However, this has been noted to be a persistent weakness in 68% of research that fails to adequately and explicitly state their case selection criteria, something that erodes the integrity of any research in terms of its rigour (Dul & Hak, 2009, p. 26).

The approach to case selection is that fronted by Pettigrew (1990) and reinforced by Eisenhardt (1989) who suggest that sometimes case selection of extremes is a sufficient basis of research. The authors argue that the phenomena to be studied are clearly defined in extremes. This is more particularly important when faced with limitations like the number of cases or time the research can undertake. The case selection for this thesis was therefore so that it could support the research objectives and questions and be representative of a dynamic context where outcomes were by large uncertain at this stage of design (Small, 2009). Case one is selected to inform the initial empirical research and two for the detailed research. A detailed designer stakeholder level study is used in case study one to help explore how dynamic contexts influence decision making in FED and support a component level analysis. Case study one is a social housing project-level case in Brazil. It is chosen to be representative of a dynamic context from a Benefits Realisation process level. This is so it helps in observing how the contextual dynamics in decision making and end-user perspective affect Benefits Realisation processes both target and derived. Case study two is project implementation level detailed social housing study representing real world context in the U.K. context.

4.6.2 Limitations of Case Study Research

The value of research goes beyond more than just a handful of cases, Hughes and McDonagh (2017) observe. The quality and validity of research of the research, therefore, hinges much on the nature of the selected cases, the researcher's skills in analysis and data gathering and in part their experience and that of their wider network that contributes to the initial knowledge base but this is open to bias however objective the research is. Meyer (2015) observes that because case studies are a constructivist approach, research is unable to control many variables. Meyer (2015) also points to the limitation on the number of cases that can be undertaken as part of this research strategy. The author argues that the number should be set against the need for an adequate array of results (Bellamy, 2011, p. 104), in a robust case selection process. Secondly, generalisations from just the limited number of cases can be insufficient, bear little relation and limited to apply on a wider scale both authors observe. The other drawback of case study research is its potentially heightened intrusiveness in cases that may constrain the quality of information gathered (Bellamy, 2011, p. 104). This research, therefore, addresses these drawbacks potentially ameliorating the rigour of the results in part by employing various methods, each of which complements and improves on the case-based research approach.

4.7 Data Management - Coding, Analysis and Evaluation

In the realms of intelligent data analysis, Runkler (2012) highlights four important stages in data management, i.e. Pre-preparation, Processing, Analysis and Post Processing stages. Within these stages are all the steps necessary for data management including planning, collection, and selection of data; cleaning, filtering, standardisation, and transformation all the way to analysis, interpretation, and evaluation, summarised in *Figure 4-7*.

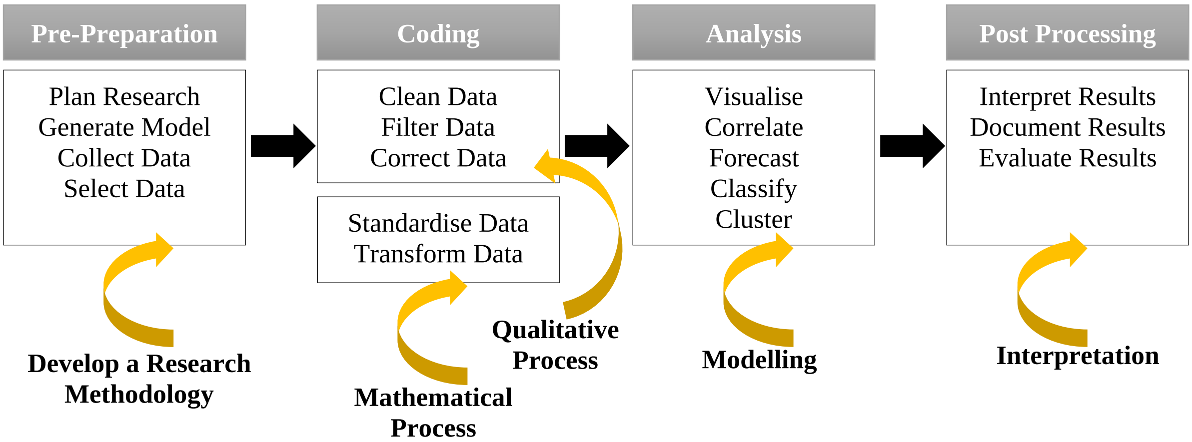

Figure 4-7 Stages of Intelligent Data Analysis from: Runkler (2012)

4.7.1 Data Organisation Methods

Organising data provides a basis for logical data structuring through graphs or tables. Whether data is from secondary sources or primary sources, this research understands the importance of organising the data in a manner that aids easy analysis. Microsoft Excel is used in structuring data; capturing the different mathematical concepts that underlie the model.

4.7.2 Data Coding Methods

When coding data, the purpose is to establish whether the particular set of data presents the presumed information in a manner that makes sense and that meets the required standards or thresholds or bounds of the research questions and hypotheses (Bellamy, 2011, p. 15).

When coding data, the purpose is to establish whether the particular set of data presents the presumed information in a manner that makes sense and that meets the required standards or thresholds or bounds of the research questions and hypotheses (Bellamy, 2011, p. 15). Blair (2015) avers that data coding should be reflexive to the need for the research. Runkler (2012) and Berthold et al. (2010) highlight some important elements of coding processes including cleaning, filtering, correcting standardising and transforming data. While Faherty (2009) observes that there is indeed no *'hard-and-fast'* rules on coding, this research takes an intelligent data coding and analysis approach in assessing the numerical data gathered for inference. Moreover, Stemler (2001) has suggested two data coding techniques, the emergent type typical with grounded theory methodology and the *Priori* approach that relies on a predetermined template and can ensure consistency in data sets. The research is, therefore, in the main takes an *interpretivist* approach to data coding and analysis. Berthold and Hand (2007) describe data analysis as a process by which a given set of data is computed for a set of derived values. The intelligent data coding and analysis technique adopted aims to set a coherent basis for comparison of data sets based on contextual factors and capture changes in user requirements over time using probabilistic algorithms[18] (Berthold & Hand, 2007). The tools adopted for coding, including QFD, ANP, DS-T, and HMM while with complex interrelationships can support analytical inference on phenomena under study in this thesis. This approach addresses research objectives 2, 3 and 4. The tools are important in analysis through facilitating visualisation, forecasting and classifying data on a case by case basis so as to contribute to cross case analysis (Runkler, 2012). While Berthold and Hand (2007) observe the convenience in numerical data coding and analysis owing to ease and effortless manipulation of data; they caution on data sets potentially having missing values, distorted, miss recorded or from inadequate samples. The authors advise that research undertakes a comprehensive examination of any data ahead of the analysis, a strategy adopted in this research.

4.8 Research Approach to Validation

A significant part of research outcomes is achieved through demonstrating credibility (Groesser & Schwaninger, 2012). Validation, in this case, aims to build confidence and rigour in the research and the proposed system (Groesser & Schwaninger, 2012). Regarding DESIDE, the key element here is the consistency of the component elements – in as much as how they contribute to the overall systems performance and modelling capabilities. The component systems for instance, utilitarian MOORA and COPRAS assessments and modelling (see section 5.4.1.1) are widely applied in modelling complex decision settings (Chakraborty, 2011; Patel & Maniya, 2015; Arabsheybani et al., 2018). Similarly, DS-T (see section 5.5) is at the

[18] Algorithms are described as the computational basis to enable data analysis Berthold and Hand, (2007)

centre of wide application in uncertainty modelling (Beynon et al., 2001; Altieri et al., 2017; Serugga et al., 2019c). HMM (see section 5.2) for requirements forecasting is also considered widely in the prediction of trends in attributes (Lethanh & Adey, 2013; Liu et al., 2017; Pino et al., 2018). Moreover, the application of the tools in complementary solutions with QFD (see section 3.3); demonstrates the contribution of both theory and operational validity. Using the tools as a basis for the proposed decision system also demonstrates the requirements of accuracy (Anastasakis et al., 2008) to ensure that the system is built right (O'Keefe & Preece, 1996); in as much as it represents the reality of the research together with its aims and objectives, something that is central to the construction of the proposed system.

Regarding the general research, it is vitally important that careful thought is given as to the level at which it is appropriate for the validation process. This remains a matter of debate with perhaps the only agreement that the more testing, the better the validation. Yet it is accepted that only so much testing may be feasible. Popper (2005) suggests that scientific theories can be merely tested but sometimes difficult to prove. In this case, validity can be understood sometimes to be when there is corroboration or agreement in results and observations with those previously; and that if there is a departure, then validity may not be supported. While the former may not necessarily be an indicator of efficacy, the latter may support invalidity (Babuska & Oden, 2004). The foregoing suggests that validity in a system/model cannot merely be founded, but rather that insufficiency in the evidence to support it does significantly contribute to its invalidity. Popper (2005) thus suggests further that until the moment when new evidence to the contrary comes to the fore, the validity of a system holds.

4.8.1 Structured Approach to Validation and Evaluation

Steinke (2004, p. 184) observes that the quality of research is dependent on the replicability and validity of the research criteria. Validity in MMR will require that any evaluation and validation process establishes these criteria for both the qualitative and quantitative elements of the research. Quantitative approaches to validity that in the main are argued in research to carry a level of *'objectivity and reliability'*, therefore, have to run alongside the qualitative aspects that will be *'subjective'*. Miles and Huberman (1994), also argue that credibility should be added to the process of validity. For credibility and validity, therefore, research should carry through its process an enhanced layer of transparency, reliability, and dependability to build the necessary rigour. Just like a clear and explicit general research methodology is necessary, the methodology behind any validation process should carry the same rigour in linking theory, methods and data collection and analysis that is *'replicable'* the authors highlight.

Validity can be internal or external but in all cases should be credible and plausible in adopting, in a careful manner, methods of data investigations with an awareness of any potential for irregularities in data sets, respondents and rigour in information (Miles & Huberman, 1994). Some approaches suggested ensuring validity maintains its rigour include:

i. Research carries out a comparative analysis with similar research.
ii. Research to be reflexive in the sense that active efforts should be made to identify and account for the role of the researcher in impacting on the results.
iii. Research explores relevance and generalisability – where research establishes boundaries to extend the underlying research paradigms and conceptualisations drawn from the results to wider application settings.

4.8.1.1. Reflexivity

Flick (2004), suggests that regarding reflexivity, subjectivities, and influences of the researcher on research processes are integral to research. This position ties in with Rooke et al. (2010) positions of unique adequacy (that which the researcher's competence is allowed to contribute to research results in a controlled and accountable manner). Together with the argument in Hesse-Biber (2010), the understanding from this body of research is that the researcher's previous experience can count as a contributing element for the research as long as accountability for this is explicit and that mitigating factors are in place not to unduly impact on the results through a heightened level of awareness of the researcher's involvement. The researcher's involvement could owe to their sociocultural, academic or research background, all of which can have an influencing role on the research results.

In keeping to the themes and concepts in validation processes, this research has adopted an explicit methodological approach for both for the wider research and its approach to evaluation and validation. The underlying paradigms have been pursued in a controlled and ethical manner with contribution from three other researchers and the research team; in addition to contributing regularly throughout this research to high-quality peer-reviewed conferences and journals as part of extant works of this research. The guidance and contribution have ensured an enhanced level of transparency, reliability, and dependability of not only the data collection but also that the methods of analysis are verifiable. In the process of data collection, at all times the research was in accompaniment with other researchers either as part of this or related research or a member of staff in the host organisation to ensure not only that ethical standards were upheld but that the process yielded data with integrity.

Experience from various contexts, including Uganda and the U.K. in both design and academia and Research in Brazil, place this researcher in a situation that can be regarded influencing on this research. The researcher's experience has extended from design environments in public service to the private sector – working on projects in health care, rural telephone infrastructure and housing design and implementation. As a result, biases may come in the form contextual influences from the various work and research scenarios alongside any academic idealism. This background may come up against that of participants in the validation and evaluation process whose own backgrounds may equally impact on their judgements and beliefs to either reinforce the researcher's own inherent positions or run conflict with them to the detriment of the research. Biases from participants may similarly be influenced by their socio-cultural, professional academic or other influence from their lived experiences.

The preceding illustrates the intricacies in both researcher backgrounds and the research that can translate into biases that in turn, may influence and impact on the validity and rigour of research. Biases are, therefore, demonstrably unavoidable in the main (Pope & Mays, 2006) and that reflexive awareness in research and validation is imperative (Green & Thorogood, 2018). This awareness should extend to contextual nuances, including any sociocultural economic, political, or other influences across the full spectrum of the research strategy in the development of a rigorous methodology.

Regarding generalisability and relevance, emergent themes and concepts form an important element of research alongside any patterns linking to theory. Only then can research demonstrate replicability and practical applicability, either in specific or bounded contexts (Yin, 2009). Replicability and validity are, in part, demonstrated in this research through the evaluation process of individual expert feedback and peer-reviewed published works.

While the concept of validity and its importance for research may be widely accepted, debate and complexity still surround some of the processes through which it should be carried out (Carley, 1996; Groesser & Schwaninger, 2012); more importantly in regard to any interpretations thereof (Anastasakis et al., 2008). This places high the need for the correct nodes of interaction between the qualitative and quantitative elements in MMR, perhaps integrated or in independent frameworks or set of results.

The validation process in this research is one that takes on a multi-pronged effort, ensuring that the best techniques can be applied at the best suitable time of the decision system's development process. The separate components of the system are in part first validated using

Case study A, while the full model is validated and evaluated using Case Study B. Both steps are essential in assessing the rigour of the selected mathematical and utilitarian processes together with the components against real-world context data and thereafter for consistency.

Regarding the validity of the methodology for the development of the decision system, while there are no generally defined validation criteria, Gass (1983) suggests theoretical, data and operational validity as fitting criteria. Creswell and Clark (2017) add transparency, simplicity, and flexibility as additional criteria. The research strategy (see figure 4.4) demonstrates a clear and *replicable* research process for the research methodology adopted. Data collection (see figure 4.5) including questionnaires, interviews, and literature review on the different research conceptualisations in FED decision making demonstrate structure, transparency, and theoretical grounding of DESIDE. The various data sources, as well as being important for modelling, are additionally, a result of a multi-pronged data collection effort. Operational validity is demonstrable in this approach as well as in the system's ability to exploit the best strengths of each of the component systems for instance in DS-T for uncertainty modelling or HMM for requirements forecasting where a mere utilitarian model assessment would be unable to sufficiently account for some elements quantitatively.

The simplicity of the model more generally, however, cannot be demonstrated. With the prospect of the use of computational methods like coding and programming, this can potentially be achieved. At the processes level, however, simplicity in methods like the simple pair-wise comparisons and rakings based on Saaty (1999) ANP/AHP methods provides a clear, systematic and transparent approach. Transparency is further demonstrated by a systematic and traceable approach to modelling. Sensitivity can be assessed at the DS-T modelling level. However, this could still be expanded as part of the future development of the decision system set at various nodes of qualitative and quantitative interaction. The logical connection among the multiple components also adds to the transparency of the whole system. Flexibility is demonstrable both at the application and modelling levels. The system can be applied in different contexts and for different decision problems (based on the extensive requirements taxonomy it employs (see later in section 7.3.1).

4.8.1.2. Triangulation

As part of an MMR methodology, it has argued that triangulation forms a central part of the methodological validation. Methodological triangulation was, therefore, achieved through complementary data gathering techniques (see section 4.5) where the aim was to run triangulation alongside the requirement for complementarity in methodological research development; as a way of enhancing the credibility of research results. Data were collected from participant sources with similar roles within contexts and across the two contexts (Flick, 2004), underpinned by an extensive but complementary literature review. This meets the requirement for theory and methodological triangulation. Findings from the extensive literature review on the key research conceptualisations of Requirements Management and decision making in FED Benefits Realisation sense are presented in peer-reviewed journals highlighting gaps and biases in current practice and theoretical positions. In terms of data triangulation, the various cross-context, multiple and complementary stakeholder teams engaged, alongside extensive documentary data sets served to reinforce this validation process.

The results from the of individual expert feedback in case study context one were also essential in reinforcing the triangulated data sets on how the results from modelling using DESIDE conformed to and corroborated existing theory and practice.

4.8.2 Validity, Generalisability, Reliability

Validity is affected in many ways not least that; it is possible for the mathematical computations to result in different answers to those of qualitative analyses (Lenhard & Carrier, 2017). This is especially the case in cases where there is an erroneous application of the computations. At other times, however, the result needed to support the decision lies in between discrete results and not readily accessible so that only results before and after it are accessible. In this case, decision making relies on mathematical results, not truly reflective of the right one. Similarly, Lenhard and Carrier (2017) argue that mathematical models only give *"an idealised version of the real world target system"*. The simple mathematical models adopted are, in other words, far from the complex phenomena in the real world, which means that models as is proposed ought to have the capacity for some parameter adjustments as a pragmatic approach. The ability to adjust parameters including adjusting parts of the mathematical equations (if the central tenet does not require new reasoning and reformulation), presents opportunities for simulating design complexities that closely match those needed in any FED analysis.

Validity can also be enhanced by running alongside any mathematical approaches with real-word methods or methodologies (Lenhard & Carrier, 2017).

Research approaches, as in this research allow for levels of some idealised conditions had to be assumed, certain particulars removed, and simplifications made to obtain a research fit model and system. However, the purpose of the model and the fact some real nodes in the problem are satisfied make the system a fit approach for the complex analysis of FED. Research should support the development of the theory that is of practical importance to FED processes through generalisation. More importantly, however, is the meta-epistemological effects of the proposed system. The decision support system's novel approach can be at the centre of a new dialectic dialogue within the design community by invoking discussion hence new understanding of processes complexities that need to be discerned; and new paradigms for improved project performances in the wider AEC.

In the treatment validation, stage-specific context conditions should be bounded. For example, a treatment T in Y conditions performing an action Z can achieve a situation X. X is the embodiment of the stakeholder goals while T bounds a class of context cases upon which to achieve X.

Lastly is the implementation and evaluations stage in which problem investigation may also be carried out to identify any new requirements arising from results. The new requirements feed into the treatment design stage again through iteration. The evaluation process aims to reconcile the goals of the research with the research problem as a basis for design theory. Wieringa (2014, p. 31) describes design theory as those properties of the artefact espoused in a set of descriptions of phenomena, mechanisms or underlying reasons from the results of an artefact context investigation and how they contribute to the goals of the specific research and any generalisations. Aken (2004) refers to it as technological rules. Aken (2004) similarly argues that in a *'reflective cycle,'* technological rules have to be tested and grounded in their context. This is so as to obtain a level of validity of the proposed model's *'effectiveness under the influence of even less well-known factors'* (Aken, 2004). It thus suffices that design theory or technological rule follows a belief that there is a pattern in observed phenomena (Wieringa, 2014). According to some authors, theories can be important in exploring, framing, describing, explaining, predicting, specifying, designing, controlling and organising phenomena (Voordijk, 2009; Wieringa, 2014). It is a predicate of causality between independent or interdependent phenomena (Voordijk, 2009).

At the level of validation, with no real world context, validation models are considered sufficient to carry out any validation processes of the model and the context to support the development of any design theories (Wieringa, 2014, p. 31). In this case, models create a level of simplicity that affords model-context investigations and in scaled and sometimes controlled conditions. This step is particularly important in this thesis to validate parts of the proposed model with results published in peer-reviewed journal papers and conferences. Based on these theories, theoretical predictions were made of some real-world phenomena to be investigated further in the full model; essentially forming a basis for any generalisations and scale-ups into real-world conditions from the idealised model based conditions (Wieringa, 2014, p. 31).

It has also been suggested in other research that any evidence underlying any new proposed scientific systems as is proposed in this research reinforces its ability to integrate any criticisms to it (Sargent, 2010). It is, therefore, essential that research can take any criticisms onboard drawing out any limitations both within them and the proposed system alongside any capabilities and bounding them in a manner that adds confidence to the validated system (Gass, 1983). Groesser and Schwaninger (2012), however, warn that any validity is only to the degree supported by any corresponding criticisms and never in absolute terms as opposed to that gained through operational validity. The authors highlight that during operational validity, validation can identify any errors in processes for instance those relating to modelling for their significance and impact on the overall results. The validity of the results from any system component analysis is, therefore, dependent on the outcome of this further analysis. The proposed model aims to build a utilitarian ranking system alongside highlighting and predictive capabilities for high order requirements for FED decision making and this is validated in the full model in case context two.

Any assessment of system validity arising from the component performance is what Gass (1983) describes as operational validity of that system. While some research has argued that theoretical validity may be a sufficient basis for system validity (Eden, 1995), others argue for additional validity, like experimental validity (Finlay, 1998). Without this further validation process, it is argued, systems like the one proposed in this research would fall short of a threshold for validation. The several validation and evaluation techniques are, therefore, adopted for this research and are discussed in Chapter Eight aimed at assessing consistency and wider applicability and generalisability of the systems modelling and results across contexts (Gass, 1983). The mathematical modelling and qualitative assessments represent objective and subjective validations, respectively.

4.9 Summary and Conclusions

In this chapter, the various philosophies underpinning this research have been discussed. The philosophies have informed the basis for choice of MMR as a best fit methodology for this research. Among the key influencing elements identified are adaptability to different philosophies that support both empirical and rational views in an integrated manner alongside

MMR's complementarity with multi/sequential case study research. This has informed the basis for consideration of ontology and epistemology as key influences on this research. Adaptability in research discourse identifies MMR as a formidable approach to realise the research goals as introduced in this chapter. Regarding he research design, the approach adopted is iteration over the knowledge questions and design problem as a way of progressively supporting the research to fulfil its objectives. Data collection again aim to support the objectives of the research to include progressive literature reviews alongside case studies and observations, surveys, and review of documentary evidence. The sequential case study approach chosen is important in drawing understanding within and between cases on. The cases have been selected to be representative of the research goals based on the research objectives as set out at the start. By investigating the system modelling capabilities in the different contexts, it is possible to validate and draw conclusions from the emergent patterns in phenomena observed. The chapter has also shown how the intelligent data analysis technique is uniquely placed to form a basis for drawing the required results and the steps to be employed. The choice and nature of the selected case studies is, therefore, critical to this research. Considerations for limitations to this data collection method are important in any research. Limitations can range from the lack control over some variables in the study context to the appropriateness and number. It is this knowledge of the strengths and limitations of case-based research that has informed the careful selection of the research methodology and design. Data management and coding has also been highlighted to be crucial in any subsequent modelling. The pre-preparation and processing, of raw data are thus crucial in any subsequent analysis and post processing stages. Another important aspect discussed in this research though explored in more detail in Chapter eight is validation and evaluation. The research design had to explore appropriate validations both DESIDE constituent components and the results. This meant that this process was vital to this research particularly as part of an MMR approach. The key element identified here is consistency both at the system and research levels. This again has to support the objectives of the research. Appropriateness of the process of system validity may be established as highlighted while that of the general research is debatable. This again casts the importance of judgement and efficacy during research in focus both operationally and in modelling and analysis. The research's proposed decision support model is presented and discussed in the next chapter.

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5 THE DECISION SUPPORT SYSTEM

5.1 Overview

The last chapter established the methodological strategy for this research including the various philosophical underpinnings, the research design, and data collection methods. This chapter presents the development of the decision support system DESIDE. Serra and Kunc (2015) and Breese (2012) postulate that at the heart of successful projects is a Benefits Realisation approach hinged on a Requirements Management process. This appears true in view of the various process strategies seen in the foregoing literature stipulating the role of lean methods, information, knowledge and stakeholder management and Benefits Realisation in FED processes. This chapter also presents the conceptual model based on the key conceptualisations of requirements and information management supporting the decision-making analysis and modelling in FED processes to ensure successful Benefits Realisation. The chapter presents the probabilistic mathematical computations of QFD, HMM and DS-T underpinning the computations in the model.

5.2 Requirements Forecasting

Changing user requirements have been a subject of research in many sectors of industry including signal processing (Xu et al., 2011; Yu, 2012; Lethanh & Adey, 2013) and IS/IT (Shieh & Wu, 2009; Bolar et al., 2017) among others. This is because various factors can influence value perceptions or benefit derived from use of a product/service not least those relating sociocultural, geopolitical, economic, environmental or technological influences (Bolar et al., 2017). As a result, there is an emerging need for automation in prediction based on changing user requirements and adopting HMM allows just this. Change in customer preferences can automatically be updated in the QFD’s HoQ as part of a core computation process. Seamless update of parameters is important when benefits should be forecast into future space-time in the midst of change. However, capabilities as this are yet to be explored in Benefits Realisation literature, research and practice. This is particularly important when viewed in the perspective of FED where integrated and collaborative decision-making aims to capture and define processes for later stages of the project cycle. The inherent process complexity in construction resulting from the many stakeholders that have to be engaged can mean a wide range of parameters to be considered for the HMM and QFD analysis (Bolar et al., 2017). Given states have to be defined in a prior assessment in an HMM analysis e.g., capturing the important probabilistic states of social housing use e.g. when a family goes through fluctuating income cycles of low, medium, high, and very high all of which influence the benefit derived from their housing space. The given states $1,2, \dots, m$ can be captured and recorded at different times t for a HMM. Let the medium income a state at time t be represented by X_t for a condition state j. The condition state i for low income at $t-1$ is represented by X_{t-1}. This essentially means that at any given time t, i or j can exhibit one state among $1,2, \dots, m$. Conditional probability can be applied to define transition probability given that the probability of X_t being in state j given that $X_{t-1}$was in i so that the transition probability matrix (TPM) is defined as follows (Asadabadi, 2017):

$$P[X_t = j | X_{t-1} = i] = P_{ij}^t \quad (19)$$

The condition states set is so that $S = \{s_1, s_2 \dots, s_n\}$ with the corresponding observed parameters $O = \{o_1, o_2 \dots, o_k\}$, $1 \le i \le n$ and $1 \le j \le k$. If $\{X\}$ is the representation of the Markov chain $P_{ij}^{(0)}$is defined as the absolute probability so that $s_1$is in t_0. The transition probabilities so that s_i transits to $s_1$is then represented by:

$$A = \begin{bmatrix} P_{s_1|s_1} & P_{s_1|s_2} & P_{s_1|s_3} & \cdots & P_{s_1|s_m} \\ P_{s_2|s_1} & P_{s_2|s_2} & P_{s_2|s_3} & \cdots & P_{s_2|s_m} \\ P_{s_3|s_1} & P_{s_3|s_2} & P_{s_3|s_3} & \cdots & P_{s_3|s_m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{s_m|s_1} & P_{s_m|s_1} & P_{s_m|s_1} & \cdots & P_{s_m|s_m} \end{bmatrix} \quad (20)$$

The corresponding emission matrix for the output o_j given that the current state is $s_i$is:

$$B = C_{re} \begin{bmatrix} P_{o_1|s_1} & P_{o_1|s_2} & P_{o_1|s_3} & \cdots & P_{o_1|s_m} \\ P_{o_2|s_1} & P_{o_2|s_2} & P_{o_2|s_3} & \cdots & P_{o_2|s_m} \\ P_{o_3|s_1} & P_{o_3|s_2} & P_{o_3|s_3} & \cdots & P_{o_3|s_m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{o_m|s_1} & P_{o_m|s_1} & P_{o_m|s_1} & \cdots & P_{o_m|s_m} \end{bmatrix} \quad (21)$$

Where the probabilities $P_{s_1|s_1}$and $P_{o_1|s_1}$are empirically determined and C_{re} is the credibility factor applied to represent confidence in the empirical sets and $\sum_{j=1}^{m} P_{s_j|s_i} = 1$ and $\sum_{k=1}^{m} C_{re} P_{o_k|s_j} = 1$. An HMM is thus the transition matrix A along with the probability $P_{ij}^{(0)}$ associated with the s_j state while the emission matrix B is that with the probability $P_{ij}^{(0)}$ associated with the observed outcome o_j.

The transition of all i states through j states means that the sum of all transition probabilities sum to unity represented as $\sum_{j=1}^{m} P_{ij}^{t} = 1 \; \forall i$ and iterating over several time-steps the probability at n steps is so that $P^{n} = P^{(0)} P_{ij}^{n}$ where $P^{(0)}$ is the initial probability. It thus follows that given an initial probability and a transition probability as TPM, proceeding probabilities can be computed through raising the initial probability to the power n representative of the nth time state (Shieh & Wu, 2009).

Now assume X_{tn} observation is dependent on the probability $P_{ij}^{t} = P[X_t = j | X_{t-1} = i]$, then it follows from conditional probability that $\left[P_1^{(i)}, P_2^{(i)}, \dots, P_k^{(i)}\right] = [a_1^{(i)}, a_2^{(i)}, \dots, a_k^{(i)}]B$ for $i \in N \cup \{0\}$. Similarly, $[a_1^{(n)}, a_2^{(n)}, \dots, a_k^{(n)}]$ and $[a_1^{(n-1)}, a_2^{(n-1)}, \dots, a_k^{(n-1)}]$ relations for each $n \in N$ are summarised as below:

$$\left[a_1^{(n)}, a_2^{(n)}, \dots, a_k^{(n)}\right] = \left[a_1^{(n-1)}, a_2^{(n-1)}, \dots, a_k^{(n-1)}\right] A \text{ for each } n \in N \tag{22}$$

$$\left[P_1^{(i)}, P_2^{(i)}, \dots, P_k^{(i)}\right] = \left[a_1^{(i)}, a_2^{(i)}, \dots, a_k^{(i)}\right] B \text{ for each } i \in N \cup \{0\} \tag{23}$$

From equations (22) and (23),

$$\begin{aligned}\left[P_1^{(n)}, P_2^{(n)}, \dots, P_k^{(n)}\right] &= \left[a_1^{(n)}, a_2^{(n)}, \dots, a_k^{(n)}\right] B \\ &= \left[a_1^{(n-1)}, a_2^{(n-1)}, \dots, a_k^{(n-1)}\right] AB \end{aligned} \tag{24}$$

Over n steps iterations, using equation (22), the relationship is redefined as

$$\left[P_1^{(n)}, P_2^{(n)}, \dots, P_k^{(n)}\right] = \left[a_1^{(0)}, a_2^{(0)}, \dots, a_k^{(0)}\right] A^{n} B \tag{25}$$

The matrices A and B are obtained from documented evidence or expert input and can continuously be refined to represent the changing reality of events.

When B is a square matrix, it is invertible and at $i = 0$, Equation (23) yields

$$\left[a_1^{(0)}, a_2^{(0)}, \dots, a_k^{(0)}\right] = \left[P_1^{(n)}, P_2^{(n)}, \dots, P_k^{(n)}\right] B^{-1} \tag{26}$$

Computing through equations (25) and (26) yields:

$$\left[P_1^{(n)}, P_2^{(n)}, \dots, P_k^{(n)}\right] = \left[P_1^{(0)}, P_2^{(0)}, \dots, P_k^{(0)}\right] B^{-1} A^{n} B \tag{27}$$

So that when n=1, equation (27) becomes:

$$\left[P_1^{(1)}, P_2^{(1)}, \dots, P_k^{(1)}\right] = \left[P_1^{(0)}, P_2^{(0)}, \dots, P_k^{(0)}\right] B^{-1}AB$$
$$= \left[P_1^{(0)}, P_2^{(0)}, \dots, P_k^{(0)}\right] YZ \quad (28)$$

Where YZ represents $B^{-1}AB$, the transformation matrix for observed outcomes after one-step transition at $t = 1$. Also, at $t = 1$, equation (28) becomes

$$P_j^{(1)} = P_1^{(0)} YZ_{1j}, P_2^{(0)} YZ_{2j}, \dots, P_k^{(0)} YZ_{kj} B^{-1}$$
$$= \sum_i P_i^{(0)} YZ_{ij} \text{ for } 1 \leq j \leq k \quad (29)$$

The two-step transformation becomes:

$$P_j^{(2)} = \sum_i \left(\sum_k P_i^{(0)} YZ_{ki} \right) YZ_{ij} = \sum_k P_k^{(0)} \left(\sum_i YZ_{ki} YZ_{ij} \right)$$
$$= \sum_k P_k^{(0)} YZ_{kj}^{(2)} = \sum_k P_k^{(0)} (B^{-1}A^2B)_{kj} \quad (30)$$

It, therefore, follows that for $n\ steps$ the transformation matrix $YZ_{kj}^{(n)}$ can be represented by

$$YZ_{kj}^{(n)} = \sum_k YZ_{ij}^{(n-1)} YZ_{kj} = B^{-1}A^n B_{kj} \quad (31)$$

5.2.1 Applications of HMM in AEC

Unlike rational/explanatory and model-based decision-making techniques whose futility in modelling complexity in requirements was discussed in section 3.3 and 7.4, probabilistic HMM has been instrumental in capturing and predicting the same (Mallya et al., 2012; Liu et al., 2017; Pino et al., 2018). It has gained wide applications in the fields of electronic and telecommunications engineering and recognitions technologies. There are however limited applications of HMM in AEC, particularly in FED. Bolar et al. (2017) proposed its application in infrastructure maintenance, while Lethanh and Adey (2013) used it to model pavement deterioration. Mallya et al. (2012) used the HMM for drought characterisation to account for uncertainty in the prediction of weather systems. Xu et al. (2011) meanwhile proposed an HMM-based driver *'misbehaviour and errors'* recognition system through predicting their intentions while the Shen and Bai (2006) model was for processing images for vehicle recognition. Other applications can be found in the field of maintenance, as highlighted by Yu (2012) and Bunks et al. (2000) among many others.

5.2.2 Model for HMM for Requirements Forecasting

The important elements in HMM, as discussed in the foregoing, inform a model for the analysis of requirements changes in FED processes. Requirements elicitation and transformation is an important element of HMM, which involves the structuring of the decision hierarchy (Gotzamani et al., 2018b). An overview of an eight-step requirements forecasting framework for a generic process is summarised in *Figure 5-1*. Step one involves the definition of the scope of the project that informs the requirements elicitation and transformation processes in step two. The requirements should at the same time be tabulated in high level categories in step three in iteration with the previous step. This process is then followed by the modelling process through both computation of the emission matrices in a stepwise manner; followed by normalisation in steps five and six respectively. The process then gives way for the analysis process that informs any subsequent decision making or further data processing as may be required.

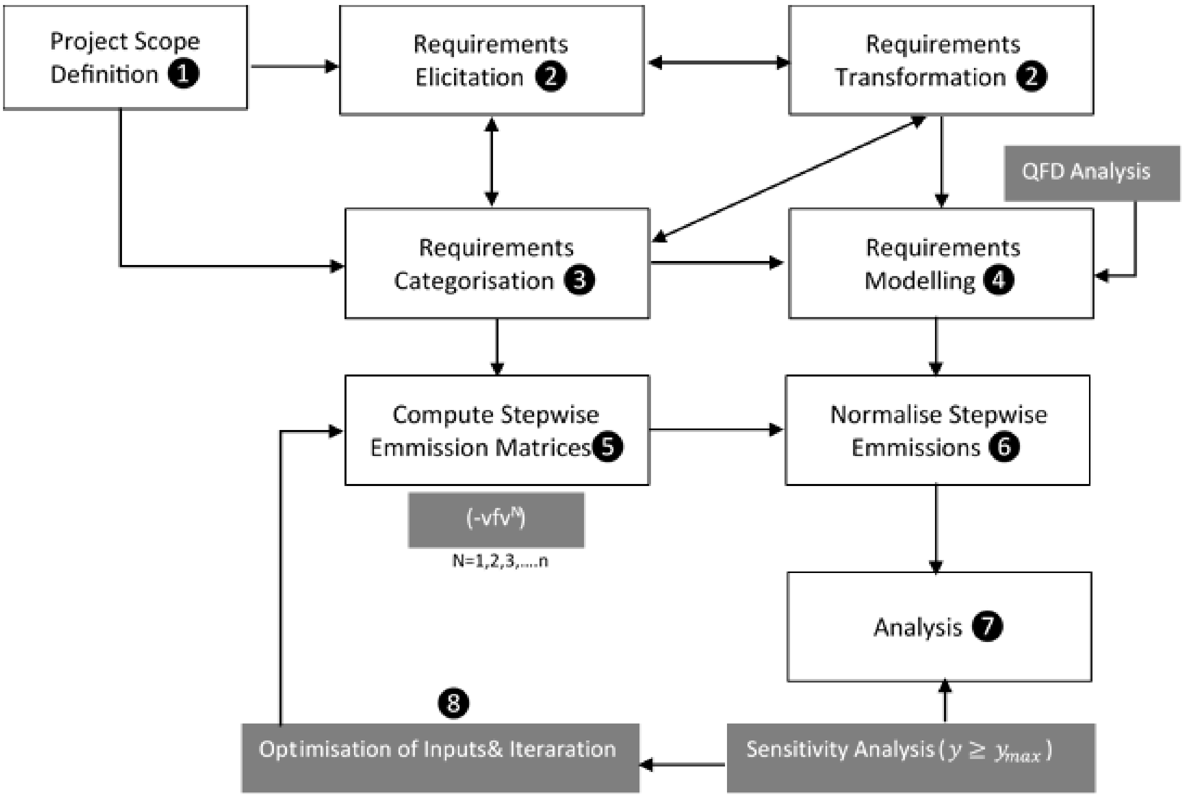

Figure 5-1 Process for Requirements Forecasting Analysis

5.2.3 Requirements Forecast Modelling in DESIDE

In adapting and adopting HMM in the proposed system, a nine-step approach is presented in Figure 5-2. Step 1 involves identifying an appropriate user to elicit user needs from as part of a Requirements Management process. The needs/requirements are then tabulated in categories if appropriate in step 2 (see section and 7.3). Stakeholder and expert groups are also identified to elicit corresponding design requirements followed by probabilities for the transition and emission matrices and thereafter capture the interdependences between design requirements in steps three, four and five, respectively. Documentary evidence can also be used or any factual data that updates any requirements for the probability and relationship matrices. Requirements are then computed in an HMM analysis over the time-space required in step six. The rating results feed into the HoQ user requirement for computing the relationship matrix in step seven. Then the HoQ matrix is computed for results in step eight. A sensitivity analysis and further data processing can be undertaken in step nine. The whole process is as part of a QFD process of defining the 'WHATs' and 'HOWs' of the decision problem, including defining high order requirements categorisations. The QFD process involves the elicitation of input data to support pair-wise comparisons among lower-level transformed attributes in Steps two and three. The process of modelling takes the steps four, five and six. This involves defining data sequences in the data sets, calculating for, and constructing transition matrices and finally computing for initial transition matrices all using HMM equations 46-58.

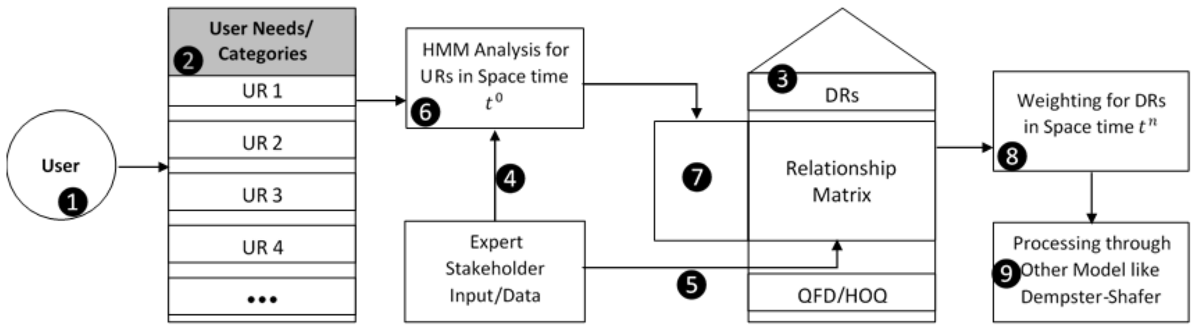

Figure 5-2 Hidden Markov Analysis of User Requirements using QFD

5.3 Quality Function Deployment

One other often applied method for Requirements Management also introduced in section 1.4.4 and adopted in this thesis for analysis is the QFD. QFD has been recently applied quite extensively in the transformation of user desires and goals into the design requirements (Chen & Ko, 2010; Zaim et al., 2014; Yazdani et al., 2017; Babbar & Amin, 2018). QFD has gained broad appeal in many sectors of industry including manufacturing (Kwong et al., 2011; Vinodh & Chintha, 2011), procurement and supply (Lima-Junior & Carpinetti, 2016; Yazdani et al., 2017; Babbar & Amin, 2018), construction (Ignatius et al., 2016; Bolar et al., 2017), product design (Liu, 2011; Zaim et al., 2014), and energy use (Akbaş & Bilgen, 2017); and in sectors such as IT/IS, and business processes (Mallon & Mulligan, 1993; Akbaş & Bilgen, 2017; Yazdani et al., 2017; Babbar & Amin, 2018).among others. QFD is used by Dinçer et al. (2018) for instance to assess the European energy investment policies and performance in a decision-making setting. They describe a process that allowed them to apply the strengths of QFD with the subjectivity and fuzziness of the decision-maker, i.e. the end-user in defining their goals and desires. QFD deployment, therefore, not only provides a strong basis for supporting decision making in benefits management but has done so quite strongly in many sectors away from design and construction (Cristiano et al., 2001; Lager, 2005).

Generating end-user benefits is a key element in Benefits Realisation management, particularly in FED processes. This can mean building an understanding of these processes from an end-user perspective (Sweeney et al., 2018). The QFD approach allows for capturing of User Requirements, modelling, and refining them a process also often referred to as managing the voice of the customer (VOC). Ultimately, the process plays an essential role in aligning the organisational aims with its Benefits Realisation management program and ultimately contributing to enhanced end-user value. However, QFD benefits have yet to be realised in AEC apart from occasional and limited applications seen in the Eldin and Hikle (2003) pilot study among a handful. This is more so for FED during which robust user requirements capture processes are required to set a strong basis for Benefits Realisation throughout later project processes. A robust requirements transformation process can only, therefore, be realised based on the right user requirements. A key process in FED is user Requirements Management including capture, definition, and transformation into design requirements through a trade-offs process. Current literature and support tools are still however limited in both the knowledge base and in practice particularly in FED. Current practice in FED is mainly prescriptively resulting in a disconnect between designers and end-users. QFD, on the other hand, builds on this strong integration between designers and end-users (Karsak, 2004; Hoyle & Chen, 2009).

Thus Karsak (2004) describes QFD as an integrated and customer-oriented process carried out with the sole aim of increasing satisfaction among end-users across many processes in design, marketing, manufacturing processes, among others. In building that intricate relationship between User and design requirements Ignatius et al. (2016) and Yazdani et al. (2017) separately argue that QFD is also able to establish a basis for selection criteria.

The transformation of the qualitative user requirements into quantitative requirements through pairwise comparisons using the HoQ helps define the 'WHATs' and 'HOWs' of a benefits delivery process by using the VOC (Zhang & Chu, 2009; Kassela et al., 2017). The benefits of QFD are documented between process and organisational levels (Zare Mehrjerdi, 2011; Kassela et al., 2017). Vinodh and Chintha (2011) observe that this is much in compliment to Benefits Realisation practice that seeks to work at the same interface. Both complementary processes, therefore, while presenting opportunities for Benefits Realisation through a robust requirements management processes do ultimately present opportunities for supporting decision making. QFD for instance has a strong basis of Requirements Management while Benefits Realisation emphasises the delivery of the same to the end user. At the centre of both approaches hinges a trade-offs process of the consequences of any requirements and the structural and inherent project constraints. It suffices to mention that this as already highlighted in this thesis is a central element of the dynamics of FED processes that gives rise to uncertainty at various levels and ultimately, complexity.

Figure 5-3 is an adapted design house of quality being applied with nine rooms in DESIDE. Room 1 is the **first stage** in the process of applying the DQFD in decision support. It is the user requirements capture stage which is immediately followed by weighting their relative importance. In **room 2**, is a correlation matrix of the user and design requirements.

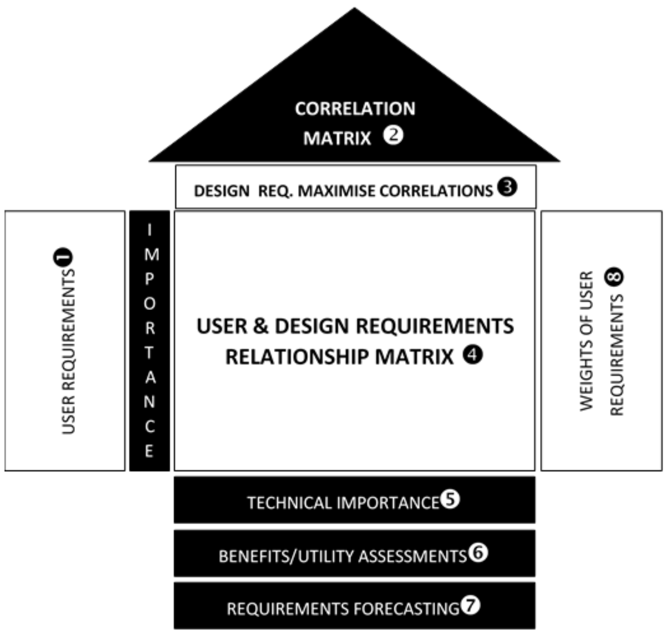

Figure 5-3 Framework for Utilitarian Design QFD (DQFD) source: Serugga et al. (2019a)

Stage 3 is identifying the design requirements and development of pairwise comparisons. This allows for capturing inner interdependences between them in **Room 3,** including establishing their target utility maximisations. **Room 4** is the relationship matrix between the user requirements and transformed design requirements. The technical importance of the requirements is assessed in room five while rooms 6, 7 and 8 are where benefits are defined, utilities of the attributes are assessed, and requirements forecasted, respectively. Finally, is the value assessments with knowledge of alternative value propositions. **Stage 4** is the QFD analysis process of assigning priority weights to the Design requirements. A nine-point scaling is adopted as Extremely not important (1), Not Very important (2), Not important (3), less important (4) important (5) more important (6) Very Important (7) Extremely Important (8) and Most Important (9). **Stage 5** is the establishing of the impact matrix between the WHATs and the HOWs pronouncing on the degrees of that relationship of how one affects the other based on a four-point scaling of Weak (1), moderate (3), Strong (6) and very strong (9). **Stage 6** is the last of the steps in which the derived matrix is computed and normalised for weights to be applied in the initial alternative models' evaluation. In the DHOQ/DQFD approach, the assessment of attributes is easily captured in a quantifiable way. However, the reflection of these assessments in view of the alternatives is difficult to assess. Rooms 5, 6, 7, 8 and 9 are important in extending the conceptual basis of QFD to a utilitarian assessment that looks at the alternative utilities and value judgements.

5.3.1 Applying the DQFD in DESIDE

First, a QFD assessment is applied to the data to ascertain the interdependences among attributes and their *importances* using the 'HOWs', as outputs of a stage that result from the inputs 'WHATs to form inputs in proceeding stages as illustrated in *Figure 5-4*. This is especially essential in reflecting the iterative nature of FED processes.

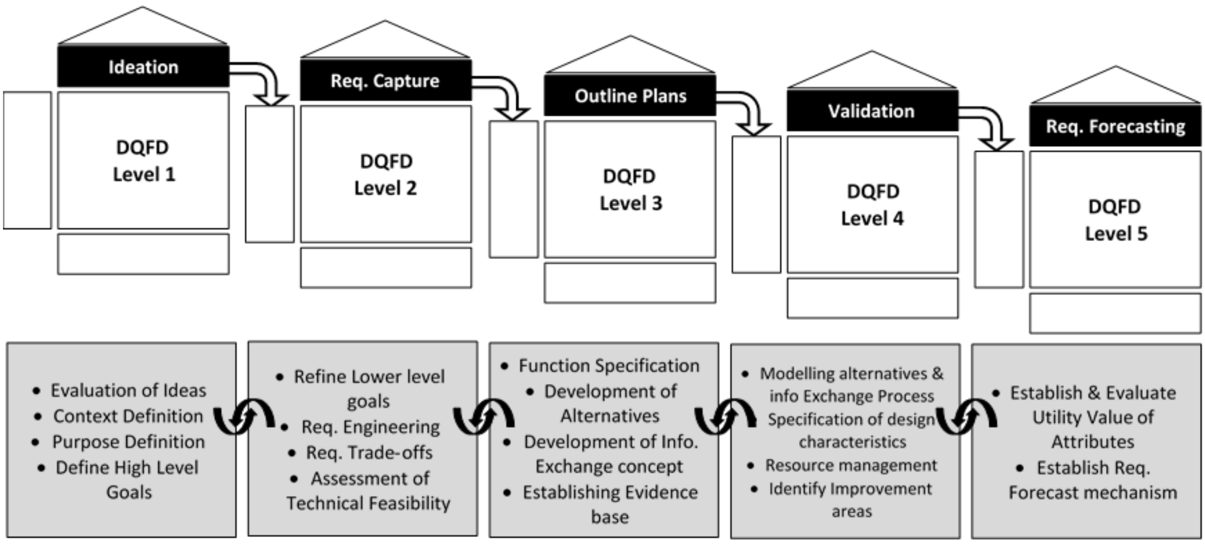

Figure 5-4 Processes in FED Utilitarian DQFD (source: Serugga et al. 2020d)

In **level 1,** the DQFD process establishes the basis for the project idea, including evaluation of all alternative ideas on the way to defining the project purpose, including capturing the project context and defining any high-level goals. In **level 2**, the goals and methods are embedded in the design process. This is a process of defining lower-level goals and capturing user requirements. It also means defining the importance of requirements and assessment of any trade-offs against any technical feasibility.

In **level 3** involves deriving the function specification and development of alternatives. An integrated and collaborative approach ensures a wider evidence base to support decision making at this stage. However, it is important that a mechanism for this information exchange is present so that information does reflect contribution to value generation.

Level 4 explores the modelling alternatives and mechanisms for information exchanges among stakeholders. Also, important to consider in the DHOQ at this point is the specification of design characteristics and resource management mechanisms including for materials, people, finance, and the site. By considering alternatives, this can form a basis for identifying any improvement areas based on the shared information from the various stakeholders.

Finally, in **level 5,** the DQFD process evaluates the benefits and utilities of the implemented design requirements against the user the requirements captured in the initial stages. Also important at this level is how the design can integrate any emergent requirements through requirements forecasting. This ensures the DQFD takes a life cycle approach.

The strength of QFD is in its complementary nature to other tools as ANP/AHP by Saaty (1996) and probability theory for mathematical modelling of uncertainty and changing user requirements among the many other extensions (Shieh & Wu, 2009; Zare Mehrjerdi, 2010; Kwong et al., 2011; Kukulies & Schmitt, 2018).

5.4 Extending Utility Theory with wider MADM methodology

Utility theory was introduced in section 3.4.3, including a detailed discussion of its underlying principles. This section discusses utility theory as adopted in DESIDE based on the adaptations and extensions. The adaptations have been chosen to be complementary and support a comparative modelling (see later in Chapter 8) with other modelling techniques.

5.4.1 General application of Utilitarian Assessment

The project scope underscores the preliminaries of the analysis, including the project purpose and any high-level/order goals (see *Figure 5-5*). User requirements are elicited based on their importance determined on a scaling using DHOQ. This forms the basis for the initial weighting of the design requirements during the analysis. This follows a process of trade-offs during which consequences are determined to define the states both known (for utilities) or not fully known (borne out of uncertainty in decision making). Beyond the design requirements domain, the analysis can use projections e.g. based on time costs today of future benefits in determining requirements forecasting using cost/benefit or cost/effectiveness analysis.

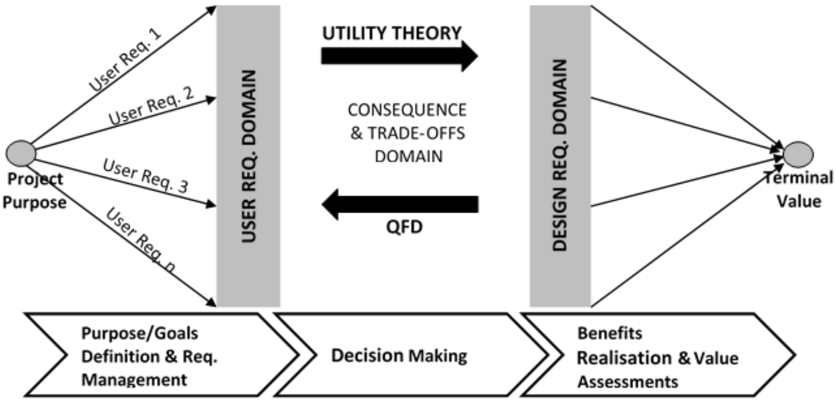

Figure 5-5 QFD Utility Theory Design Interface – Source: Serugga et. al (2020d)

5.4.1.1. Utilitarian MOORA and COPRAS Analysis

Many MADA adaptations of decision support methodologies with a utilitarian basis have contributed to its robustness including MOORA (Chakraborty, 2011; Akkaya et al., 2015); COPRAS (Liou et al., 2016; Mondal et al., 2017); ANP/AHP (Saaty, 2001; Cheng et al., 2005; Saaty, 2005; Dağdeviren & Yüksel, 2010; Zaim et al., 2014; Senturk et al., 2016); and DEMATEL (Ranjan et al., 2015). A MOORA analysis is important in the simultaneous optimisation of conflicting criteria under certain constraints or uncertainty (Yazdani et al., 2017). A COPRAS analysis, on the other hand, is a utility analysis ranking criteria based on their utility (Ignatius et al., 2016; Yazdani et al., 2017). The combined methodology of the steps agrees with the fundamental utilitarian principle that a decision-maker will act in a way that maximises their expected utility from a lottery so that for two alternatives Z, W

$$Max\ E[U(x)] = U(y_1x, y_2x, \dots, y_lx)$$
$$Min\ E[U(x)] = U({y'}_1x, {y'}_2x, \dots, {y_r}'x) \quad (32)$$

$$\text{For } x \in X = [x \geq 0]$$

Where l is objectives to be maximised, and r is those to be minimised.

5.4.2 The COPRAS Analysis

Step 1

The process starts by capturing the user requirements and their interrelationships through a direct relationship matrix U using the COPRAS method based on pronounced user requirements (Patel & Maniya, 2015; Arabsheybani et al., 2018; Sahu et al., 2018) so that :

$$U = \begin{bmatrix} 0 & y_{12} & \cdots & y_{1j} & \cdots \\ y_{21} & 0 & \cdots & y_{2j} & \cdots \\ y_{31} & y_{32} & \cdots & y_{3j} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{nj} & 0 \end{bmatrix} \quad (33)$$

Step 2

This is then normalised by (Yazdani et al., 2017):

$$X = k.a \quad (34)$$

Given

$$k = \frac{1}{\max\limits_{1 \le i \le n} \left(\sum_j^n a_{ij} \right)}, (j = 1,2, \dots, n) \quad (35)$$

Step 3

The DHOQ is the basis for establishing the weighting for the different trade-offs between the user requirements and the design requirements. The decision-making process aims to pronounce itself on the relationship between the sets of paired attributes to establish the direct effect that each ith attribute exerts on each jth attribute, using a scoring range to underscore the varying influences (Yazdani et al., 2017). The computation of the total relation matrix T to capture all the dynamics of each element (t_{ij}) and how indirectly its ith criterion is influenced by its jth; and is derived as follows according to Ranjan et al. (2015):

$$T = \left[t_{ij} \right]_{nxn}, i, j = 1,2, \dots\dots, n$$

$$T = X + X^2 + X^3 +, \dots \dots, +X^k$$

$$T = X(I + X + X^2 +\dots, +X^{k-1})[(I - X)(I - X)^{-1} \quad (36)$$

$$T = X(I - X^k)(I - X)^{-1}$$

$$T = X(I - X)^{-1}T, \text{ when } k \to \infty, X^k = [0]_{nxn},$$

$$T = X(I - X)^{-1}$$

The process then aims to rank the design requirements through a series of normalisation and transformation of the T matrix. FED only forms part of a wider and protracted design and implementation lifecycle. Decision-makers are in the main unable to pronounce themselves on a given state independently. This introduces the understanding of subjective utilities and probabilities that underpin subjective value judgements, particularly in dynamic contexts (Karni & Schmeidler, 2016).

Step 4

In this step, the vectors D and R representing the sum of the rows and columns respectively are derived as follows;

$$D_i = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} = [t_i]_{nx1}, (i = 1,2, \dots, n) \quad (37)$$

$$R_j = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn} = [t_i]_{nx1}, (j = 1,2, \dots, n) \quad (38)$$

Step 5

Step 5 is the visual stage of the decision modelling in which the conflicting criteria are mapped graphically to provide insight into their causal relationships. It involves the development of the causal diagrams among criteria through a plot of $D_k + R_j$ vs $D_k - R_j$ so that $k = i = j = 1$ to support the importance of one criterion over the other so as to establish the cause and effect groups among criteria separated by a relation axis. A positive value assigns the criterion to the causal group, while a negative one assigns it to the effect group.

Step 6

The last step is the ranking stage in which criteria weights are calculated through normalised $D_k + R_j$ values.

The pairwise comparison matrix for the design criteria is of the form:

$$G = \begin{bmatrix} 1 & x_{12} & \dots & x_{1j} & \dots \\ x_{21} & 1 & \dots & x_{2j} & \dots \\ x_{31} & x_{32} & \dots & x_{3j} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nj} & 1 \end{bmatrix} \tag{39}$$

5.4.3 MOORA Analysis

The MOORA analysis takes the form of the following equations:

Step 1 uses the Eq (40) to compute a normalised decision matrix of dimensionless numbers.

$$x_{ij}^{*} = \frac{x_{ij}}{\left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{\frac{1}{2}}} \text{ , } (j = 1,2, \dots, n) \tag{40}$$

And x_{ij}^{*} is a dimensionless number in the interval [0,1], the normalised performance of ith alternative on jth attribute

Step 2 is to weight the matrix using the following equation:

$$v_{ij} = x_{ij}^{*} \text{ x } r_{ij} \text{ , } (i, j = 1,2, \dots, n) \tag{41}$$

Step 3 involves computing for the benefit/dis-benefits is S_j^{+} and S_j^{-} values of the matrix using the Equation below:

$$S_j^{+} = \sum_{i=1}^{n} v_{ij} \text{ , } (i \in J^{Max})$$

$$S_j^{-} = \sum_{i=1}^{n} v_{ij} \text{ , } (i \in J^{Min}) \tag{42}$$

The Step 4 process determines the overall impact as the difference between the benefits and dis-benefits in the operation of Eq. (43) followed by computation of the utility ranking as a percentage of the best highest utility. The equation below is used to obtain the overall performance index by mutually subtracting the overall ratings for beneficial and cost criteria:

$$S_j = S_j^{+} - S_j^{-} \tag{43}$$

It is therefore important that considerations for the evolution of value judgements are taken in in account in the process through forecasting or accounting for changing awareness (see next section) in the decision making (Karni & Vierø, 2017). In terms of requirements forecasting (seen earlier in 5.2), the consequences c_{ij}ci are defined at progressive times t against the benefits/value b_{ij} in a matrix A (Yazdani et al., 2017). Subjective probabilities and state-dependent utilities are drawn and extended from fully known consequences at the time of decision making and allowing for these to anchor the states the decision-maker is not fully aware of using the general matrix A below:

$$A = \begin{bmatrix} c_1 & c_2 & \dots & c_t & \dots \\ b_{11} & b_{12} & \dots & b_{1t} & \dots \\ b_{21} & b_{22} & \dots & b_{2t} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{r1} & b_{r2} & \dots & b_{rt} & \dots \end{bmatrix} \quad (44)$$

This step is also important in assisting decision making in establishing relationships through pairwise comparisons among the requirements sets. Using this utilitarian approach, the decision maker weights in a trade-off between the cost $(c)$of an attribute today vs its benefit (b) in the future time (t) (Keeney & Raiffa, 1976). This utilitarian approach adds robustness to the process of decision making by allowing for uncertainty and rationality of decision making in FED but in a quantifiable manner. This allows for an accurate account of utilities and Benefits/outcomes of design decisions. The complementary approach with QFD and other tools forms a powerful decision support mechanism over traditional approaches to FED as it brings a robust structure to decision making to allow for life cycle thinking while decision-makers gain a sense of accountability of their decisions.

5.5 Uncertainty Modelling

Design is a problem-solving endeavour creating solutions in responding to the contextual problems (Lawson, 2005, p. 138). The introduction to FED in section 1.4.1 and its detail theoretical conceptualisation (see section 2.2) drew to the intensity of decision making in FED processes. The concept of uncertainty and its intricate relationship with decision making was also introduced in section 1.4.3. What emerges from both these positions is that design processes in AEC projects are faced with uncertainty (Böhle et al., 2016); both epistemic - that relating to knowledge; and stochastic - that relating to context-specific events (Kukulies & Schmitt, 2018). User needs may change just as much as contextual events evolve, all of which directly affects FED processes. Pich et al. (2002) say that complexity of which uncertainty is a form, in projects can be intractable thus proposing that learning or *selectionism* be adapted to cope with uncertainty. In a FED perspective, uncertainty can run across various domains as illustrated in *Figure 5-6* both as a result of the project context and at a systems/operational level. The choice of the IDEF0 in *Figure 5-6* representation and modelling is to support the multi-level nature of discernment of the intricate dynamics in a graphical way that the tool is powerfully renown for.

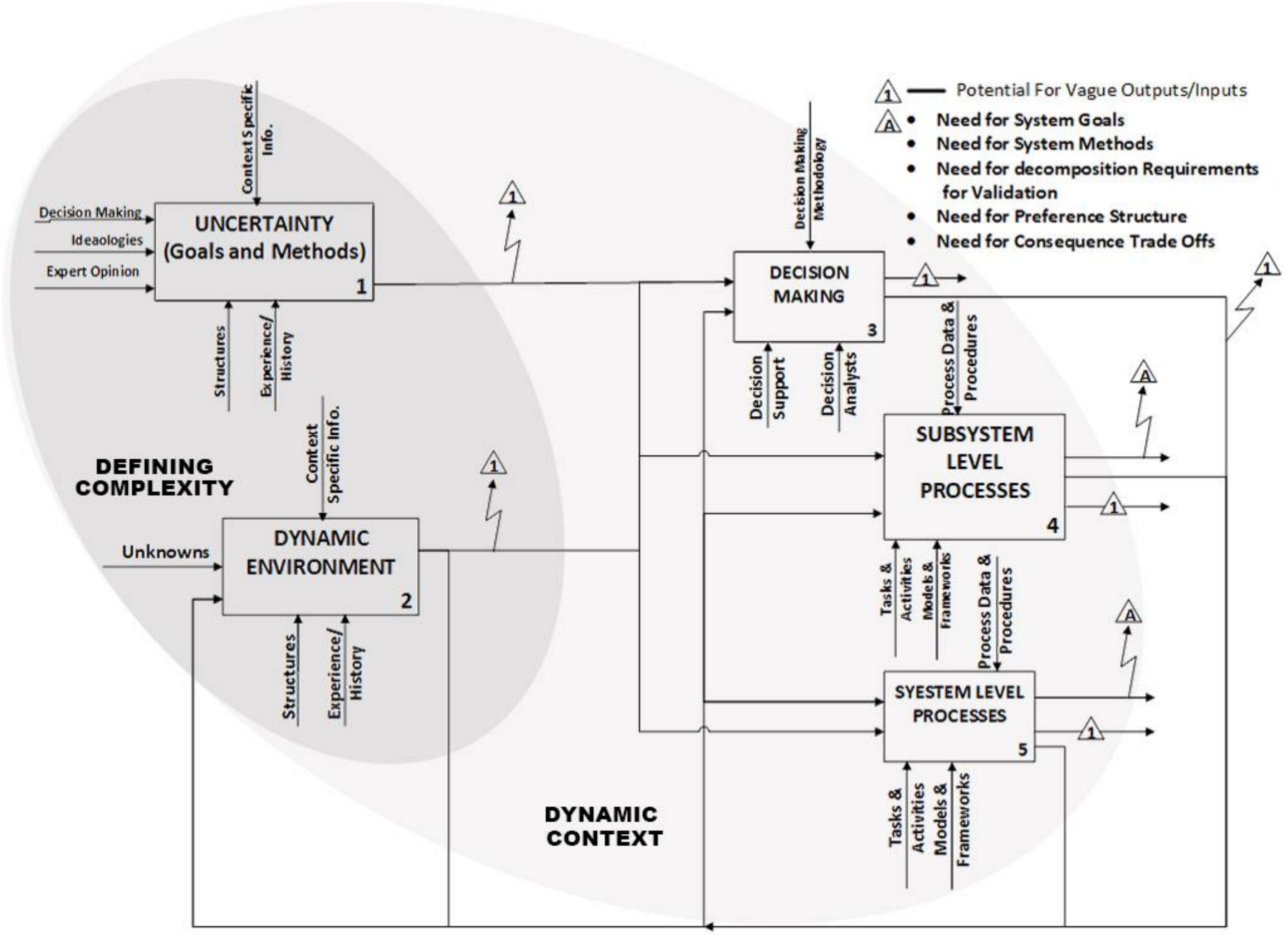

Figure 5-6 Sources of Uncertainty in FED Processes

In *Figure 5-6*, it is illustrated that the general project context has an over bearing influence on FED processes *'structure'* and in subsystems within the context e.g. in influencing the cultures and microcultures that ultimately impact on design decision making within the wider stakeholder environment. This ultimately influences the goals and methods (Turner & Cochrane, 1993) in projects definition in FED. Similarly, in this specific design environment, processes do become dynamic as a result, all of which requires design decision making to be supported by tools able to decipher the complexity at this process level. The tools can support the decomposition of user and design requirements and the modelling of the key interdependences among them to reflect project goals and user benefits in design decision making.

5.5.1 Uncertainty in Model Space

It is thus conceivable from the foregoing that not all scenarios, outcomes and therefore benefits may be captured during design and that project environments are not static. Yet most project design proceeds within set parameters and based on achieving set objectives. It is important that processes have a structure through which necessity for ambiguity does not ignore focus on benefits to maximise expected utility. *Instructionist* approaches based on assumptions of system stability (Pich et al., 2002); assumed in current Benefits Realisation models perhaps ought to be updated. This section draws on the science and mathematics of the system interdependences between *'knowns, known unknowns and unknown unknowns'*. Hill (2010); Dietrich (2018) and Karni and Vierø (2017) call it the changing awareness during decision making. This understanding is important in the dynamics of uncertainty and decision making. The decision maker's certain or uncertain world is espoused in the decision maker's preference structure that considers lotteries, probabilities consequences and expected utilities that satisfy the decision maker's assumptions.

The decision-making process cannot in the main anticipate all the preference structure or all the benefits for that matter – and therefore cannot definitively pronounce itself on all utilities and ultimately on value across the entire state space. Analysis of this, therefore, creates a three-part structure see *Figure 5-1*. (Karni & Vierø, 2017). The fully known and describable part of the outcomes, the partially describable parts, and the indescribable part.

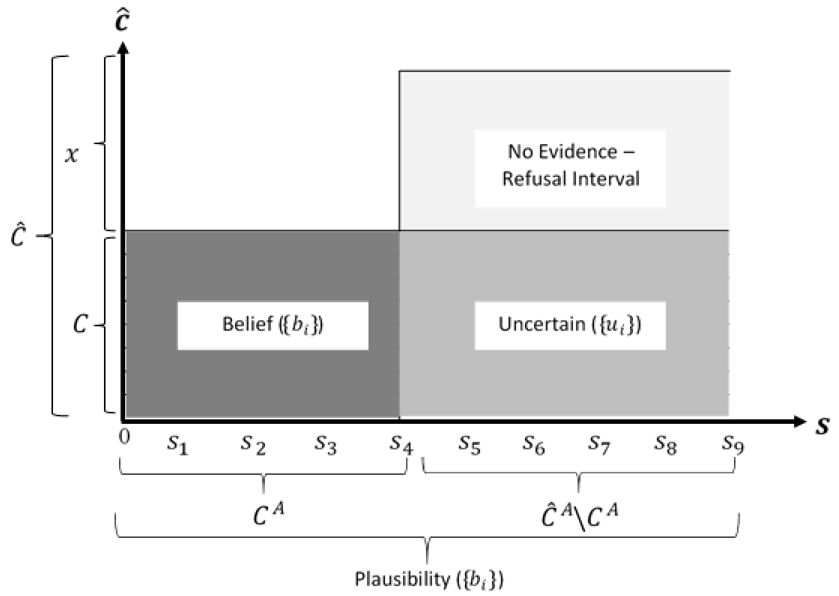

Figure 5-7 Illustrating the Knowledge Spaces (adapted from Karni and Vierø (2017)

The fully describable part embodies all revealed preferences. To underscore the partially describable part, the decision-maker basing on the now revealed preferences anticipates and appreciates the existence of some unknowns and be prepared to review their preferences should these come to light. In the *unknown-unknowns* outcomes space, the decision-maker appreciates there are consequences they might not be aware of altogether and that they might or might not affect their decision when revealed.

As the uncertainty resolves, three results are possible: first that the decision-maker feels in position based on the new information to now pronounce themselves on a decision, second that even with the new information, the decision-maker feels indifferent from before than they are now; or thirdly and ultimately that with the new information, the decision-maker feels even more inclined to await further information having discovered they knew little than they thought they did at the start.

So, the big question for the analysis is how decision making can understand and establish dependencies based on the describable states and use this to predict the nature of the partially describable states while accounting for boundary events. The following demonstrates the approach based on Savage's Theorem as discussed by authors as Dietrich (2018), Anscombe and Aumann (1963), Keeney and Raiffa (1993) and Karni and Vierø (2017).

Assume a non-empty space of lotteries, outcomes and consequences, i.e. $A, S\ and\ C$ respectively so that $A > 0, S > 0\ and\ C > 0$. Also, assume an abstract space of unimaginable outcomes $x = \urcorner C \ \equiv non\ of\ the\ above$. Let $\hat{C} = C\ \cup \{x\}$ be the set of all imaginable and unimaginable consequences and $\hat{c} \in \hat{C}$ otherwise called the Frame of Discernment (FOD); together, these sets define the extended conceivable outcomes so that: $\{\hat{C}^A = S{:}\, A \rightarrow\ \hat{C}\}$. Now, assume two actions a_1, a_2 resulting in corresponding consequences C_1, C_2, the following matrix captures the nine-state resultant space as captured in Eq. 45.

$$\begin{array}{cccccccccc} A/S & s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 & s_8 & s_9 \\ a_1 & C_1 & C_2 & C_1 & C_2 & x & x & C_1 & C_2 & x \\ a_2 & C_1 & C_1 & C_2 & C_2 & C_1 & C_2 & x & x & x \end{array} \tag{45}$$

C^A - Belief $\quad \hat{C}^A$ – Uncertain

$$F = \{\text{f}{:}\, \hat{C}^A \ \rightarrow\ C\}$$

Each consequence becomes an event so that when a new consequence thus is revealed $\left(C_i, C_j\right) = i, j = 1{,}2$, there is a resultant expanded consequence space $(C_1, C_2, C_i), \left(C_1, C_2, C_j\right)\ and\ \left(C_i, C_j, x\right) = i, j = 1{,}2$; with a corresponding expanded $F^*$of conceivable outcomes.

$$F^* = \ \{\text{f}^*{:}\, \hat{C}^A \ \rightarrow\ \hat{C} \mid f^{*-1}(\text{x})\ \subseteq \hat{C}^A \backslash C^A\} \tag{46}$$

$\nabla F^*$is the probability distribution over F^*.

For any new information with a consequence say C_3, that contributes to a new awareness, there is a corresponding extended outcome-consequence space summarised in the matrix below

$$\begin{array}{ccccccccccccccccc} A/S & s_1 & s_2 & s_3 & s_4 & s_5' & s_5 & s_6' & s_6 & s_7' & s_7 & s_8' & s_8 & s_9' & s_9'' & s_9''' & s_9 \\ a_1 & C_1 & C_2 & C_1 & C_3 & C_3 & x_1 & C_3 & x_1 & C_1 & C_1 & C_2 & C_2 & C_3 & C_3 & x_1 & x_1 \\ a_2 & C_1 & C_1 & C_2 & C_2 & C_1 & C_1 & C_2 & C_2 & C_3 & x_1 & C_3 & x_1 & C_3 & x_1 & C_3 & x_1 \end{array} \tag{47}$$

Karni and Vierø (2017) suggest a transform φ that maps the extended conceivable outcomes into Anscombe and Aumann (1963) outcomes so that if $\nabla(F^*)\ \rightarrow\ (\nabla\hat{C}))^{\hat{C}^A}$ and for all $s \in \hat{C}^A, \hat{c} \in \hat{C}$ and $\mu \in \nabla(F^*)$ is summarised in equation 48 below:

$$\varphi_s(\mu)(\hat{c}) = \sum_{\{\text{f} \in \text{supp}(\mu) = \hat{C}\}} \mu(f) \tag{48}$$

$\varphi_s(\mu)(\hat{c}) \in\ \nabla\left(\hat{C}\right)$ assigns $\varphi(\mu)$ to each $s \in \hat{C}^A$.

More detailed assumptions, axioms and proofs can be found in Karni and Vierø (2017) and Dietrich (2018). The utilitarian approach is able to assign a subjective expected utility and therefore allow for benefit realisation even in the partially perceived outcomes or even unknown and unknowns to improve decision making by applying a subjective expected utility (Karni & Vierø, 2017). But more importantly the foregoing elucidates new fundamental understanding of uncertainty that runs counter to general application in AEC and FED decision making in particularly.

5.5.2 A Dempster-Shafer Approach to uncertainty

When faced with uncertainty or situations of incomplete information as in the foregoing, MADM methodology on their own would be insufficient to account for actions spaces of partially or completely indescribable consequences (Beynon et al., 2001; Hua et al., 2008). Many approaches have used the Bayesian theoretic and its derivatives like the DS-T (Shafer, 1976; Dempster, 2008); and related adaptations to account for this uncertainty in decision making (Beynon, 2005; Hua et al., 2008; Awasthi & Chauhan, 2011; Wang et al., 2016a; Altieri et al., 2017). One of the benefits of the DS-T in MADM, according to Chen et al. (2018) is in reducing indeterminacy in decision making. The main strength of the DS-T according to a lot of other authors including Denœux et al. (2018), Zhou et al. (2017), and Tang (2015) among others, however, is its effectiveness in accounting for uncertain and unknown information through providing the Frame of Discernment (FOD) and the basic probability assignment (bpa) to facilitate information modelling. Using the DS-T, it is possible for decision analysis to assess a body of evidence (BoE) even with incomplete information by assigning a bpa to describable, partially describable and indescribable focal elements in an action space as DS-T mass functions (Denœux et al., 2018). The DS-T approach has been adapted in a manner that first uses QFD for user requirements capture and transformation. The user requirements are then transformed using the utilitarian approach into design requirements upon which spaces, the knowledge matrix is drawn. The proposed approach builds on the utility assessment to reinforce the preference relations among user and design requirements and alternatives to support the belief and plausibility structures in FED decision making.

5.5.3 Identifying the focal elements

The DS-T approach considers a finite set of alternatives say $\Theta = b_1, b_2, \dots, b_n$, which is called the frame of discernment (FOD). For a *bpa* function across this set, a mass function $m: m: 2^{\Theta} \rightarrow [0,1]$ should satisfy the following statement.

$$m(\emptyset) = 0 \; and \; \sum_{B \subseteq \Theta} m(B) = 1 \quad (49)$$

Where $\emptyset$ is an empty set and A, any subset of Θ and 2^{Θ} a power set of Θ consisting of all the subsets of Θ so that;

$$2^{\Theta} = [\emptyset, [b_1], \dots, [b_N,], [b_1, a_2], \dots, [b_1, b_N], \dots, \Theta\,] \quad (50)$$

In assigning a bpa, (also called the probability mass) $m(B)$, the decision analysis assesses the belief there is in a BoE (B); which is a set of all focal elements. The empty set $\emptyset$, therefore, represents no belief while all bpa in a set sum to unity. A bpa to $m(\Theta)$ represents the uncertainty, i.e. the ignorance while a subset $B \subseteq \Theta$ so that $m(B) > 0$ defines the focal element m. The defined decision matrix $S = [f(x_i, C_j)]_{nxm}$ is a representation of the BoE from which focal elements are defined. It thus follows that $f(x_i, C_j)$ evaluates the alternative b_i, $(i = 1,2, \dots, n)$ for the jth attribute C_j, $(j = 1,2, \dots, m)$. The DS-T approach is underpinned by this concept in the following six definitions.

<u>*Definition 1*</u>

It is stated that for $\forall b_i, b_k \in \Theta$ and $b_i \neq b_k$, $b_i \; and \; b_k$ belong to the same element if $f(b_i, C_j) = f(b_k, C_j)$. In the absence of the full set of information, the DS-T approach still allows for decision analysis and with the emergence of the new evidence comes an expanded consequence space that can still be considered in the FOD Θ. This is on the basis that any emergent new evidence will still allow for equal evaluation of decision alternatives. All decision alternatives are a set of Θ, the FOD, and it, therefore, follows that $p(\Theta) = 1$ (Beynon et al., 2001). For all focal elements on the jth attribute C_j, $(j = 1,2, \dots, m)$ denoted by B_j^k $(j = 1,2, \dots, m; k = 1,2, \dots, s; s < 2^n;$); a pairwise comparison can be adopted from **definition 1** to obtain a decision maker's preference weighting so that for $b_i \in B_j^k$, the preference on B_j^k i.e. $p(B_j^k)$ is represented by $w_j f(b_i, C_j)$ where w_j is the weighting of attribute C_j; thus .

$$p(B_j^k) = w_j f(b_i, C_j). \quad (51)$$

<u>*Definition 2*</u>

The bpa of each focal element B_j^k can then be represented as a standard normalised preference so that

$$m_j\left(B_j^k\right) = \frac{p\left(B_j^k\right)}{\sum_k p\left(B_j^k\right)} \tag{52}$$

$\forall b_i \in \Theta$ and $\forall B_j^k \in 2^{\Theta}$ for all $b_i \in B_j^k$

While definition 2 yields the $m_j\left(B_j^k\right)$, bpa of each focal element is obtained using the Dempster rule of combination (Jiao et al., 2016). In this, its argued that for two attributes j_1, j_2 $(j = 1,2,\dots,m)$ with two focal elements $B_k^{j_1}, B_l^{j_2}$ respectively with intersection E, $j_1 \neq j_2$ the Dempster rule of combination is so that

$$\left[m_{j_1} \oplus m_{j_2}\right](E) = \begin{cases} 0, & for\ E = \emptyset \\ \dfrac{\sum_E m_{j_1}\left(B_k^{j_1}\right) m_{j_2}\left(B_l^{j_2}\right)}{1 - \sum_{E=\emptyset} m_{j_1}\left(B_k^{j_1}\right) m_{j_2}\left(B_l^{j_2}\right)}, & for\ E \neq \emptyset \end{cases} \tag{53}$$

<u>*Definition 3*</u>

This accounts for the belief function a measure $m: 2^{\Theta} \rightarrow [0,1]$ for each bpa in a $FOD\ \Theta$ (Jiao et al., 2016), So that

$$Bel\ (B) = \sum_{X \subseteq A} m(X),\ \forall B \epsilon 2^{\Theta} \tag{54}$$

The $Bel(B)$ is a representation of the support there is in B while B and X are subsets of Θ.

<u>*Definition 4*</u>

Similarly, plausibility (Pls) is a measure of how plausible each bpa is across the space $m: 2^{\Theta} \rightarrow [0,1]$ in a $FOD\ \Theta$, So that

$$Pls\ (B) = 1 - Bel\ (\bar{B}) = 1 - \sum_{X \cap B \neq \emptyset} m(X),\ \forall B \epsilon 2^{\Theta} \tag{55}$$

The $Pls(B)$ is a representation of the possible support there is in B including the certain support $Bel(B)$ while B and X are subsets of Θ and $\bar{B}$ is the full set of B.

It, therefore, follows from equations (52) and (53) that $Bel(\{b_i\})$ and $Pls(\{b_i\})$ can be determined across the decision setting a_i $(i = 1,2,\dots,n)$ so that

$$Bel\ (\{b_i\}) = \sum_{E=\{b_i\}} m(E), \tag{56}$$

$$Pls\ (\{b_i\}) = \sum_{b_i \in E} m(E),\ \forall i \in (1,2, \dots, n)$$

Across a set of uncertain information, equation (56) yields the belief interval $[Bel\ (\{b_i\})$ and $Pls\ (\{b_i\})]$ for the entire decision alternatives set. In this context, the points $Bel\ (\{b_i\})$ and $Pls\ (\{b_i\})$ in the overall bound $[Bel\ (\{b_i\}), Pls\ (\{b_i\})]$ indicate the lower and upper bounds of belief based on the incomplete BoE of b_i available to the decision maker. A bound $[Bel\ (\{b_i\}), Pls\ (\{b_i\})] = [0,0]$ indicates absence of any evidence in support of the alternative a_i. A refusal probability of 0.2 on the other can be expressed as $[Bel\ (\{b_i\}), Pls\ (\{b_i\})] = [0.4,0.8]$ which essentially means that the $Bel\ (\{b_i\})$ is 0.4 while $Pls\ (\{b_i\})]$ is 0.8. By now the analysis would have established the belief interval of each alternative from the uncertain decision set. This same belief interval can now form a basis for ranking of the beliefs based on their preference relations. For two alternatives a_i and a_k with corresponding intervals $[Bel\ (\{b_i\}), Pls\ (\{b_i\})]$ and $[Bel\ (\{b_k\}), Pls\ (\{b_k\})]$ respectively, $b_i > b_k$ i.e. alternative , b_i preferred to b_k when $Bel\ (\{b_i\}) > Bel\ (\{b_k\})$ and $Pls\ (\{b_i\}) > Pls\ (\{b_k\})$.

Definition 5

The degree of preference of one alternative to other denoted by, $P(b_i > b_k) \in [0,1]$ can thus be defined as

$$P(b_i > b_k) = \frac{\max\left[0, Pls\ (\{b_i\}) - Bel\ (\{b_k\})\right] - \max\left[0, Bel\ (\{b_i\}) - Pls\ (\{b_k\})\right]}{\left[Pls\ (\{b_i\}) - Bel\ (\{b_i\})\right] - \left[Pls\ (\{b_k\}) - Bel\ (\{b_k\})\right]} \tag{57}$$

Equation (57) yields the following conclusions

i. $P(b_i > b_k) = 1$ if and only if $Bel\ (\{b_i\}) \geq Pls\ (\{b_k\})$
ii. $P(b_i > b_k) = 0$ if and only if $Pls\ (\{b_i\}) \geq Bel\ (\{b_k\})$
iii. $P(b_i > b_k) = 0.5$ if and only if $Bel\ (\{b_i\}) + Pls\ (\{b_i\}) = Bel\ (\{b_k\}) + Pls\ (\{b_k\})$
iv. $P(b_i > b_k) > 0.5$ if $P(b_i > b_l) > 0.5$ and $P(b_l > b_k) > 0.5$
v. Also, that
vi. $P(b_i > b_k) > 0.5$ if $Bel\ (\{b_i\}) > Bel\ (\{b_k\})$ and $Pls\ (\{b_i\}) > Pls\ (\{b_k\})$
vii. $P(b_i > b_k) > 0.5$ if $Bel\ (\{b_i\}) < Bel\ (\{b_k\})$ and $Pls\ (\{b_i\}) > Pls\ (\{b_k\})$ and $\frac{Bel\ (\{b_i\}) + Bel\ (\{b_k\})}{2} > \frac{Pls\ (\{b_i\}) + Pls\ (\{b_k\})}{2}$

Definition 6

The final definition thus captures the last five in setting the basis for an alternative ranking mechanism based on the belief interval so that the preference relations between the various decision alternatives are so that:

i. $b_i \succ b_k$ i.e. decision alternative b_i is superior to $b_k$if $P(b_i > b_k) > 0.5$
ii. $b_i \prec b_k$ i.e. decision alternative b_i is inferior to $b_k$if $P(b_i > b_k) < 0.5$
iii. $b_i \sim b_k$ i.e. decision alternative b_i is indifferent to $b_k$if $P(b_i > b_k) = 0.5$

The above preference relations also confirm transitivity among alternatives so that if decision alternative b_i is preferred to b_k and b_k to b_l then it follows that b_i will be preferred to b_l.

Uncertainty according to Altieri et al. (2017) can be established by the relation

$$u(\{b_i\}) = Pls\ (\{b_i\}) - Bel\ (\{b_i\}) \quad (58)$$

5.6 Underlying Concepts to the Decision Support System

This section to seek to highlight important elements in FED introducing key conceptualisations of Benefits Realisation, FED processes dynamic contexts and uncertainties and tools currently employed in facilitating value delivery in construction design. The key lessons from literature that inform the decision system are (a) current Benefits Realisation approaches have focussed less on FED processes and more generally lack a quantitative way of contextualising the dynamics on benefits delivery generally; (b) that current approaches are great at focussing on value delivery through collaboration and integrated approaches but do not reflect the changing dynamics of project contexts and their modelling; (c) decision support tools currently available in design largely focus on steady-state project environments and ignore the reality of dynamic contexts and users, and finally (d) that conditional probability can enhance Benefits Realisation in FED processes to account for the dynamic project contexts.

The preceding chapters have also highlighted the influencing role of decision making in Benefits Realisation, including a look at various decision support tools e.g. CBA, ANP and Utility theory. The utilitarian approach is considered a solid basis for the proposed decision support model. In combination with ANP, utility theory offers a unique way to focus decision-making processes on utility and outcomes while drawing context to the dynamics of the trade-offs processes.

Finally, the preceding chapters also sought to explicitly explore Requirements Management and how they can be forecast in a dynamic context in delivering the project benefits. QFD is seen in its diverse and complementing way it can quantitatively facilitate Requirements Management. Using QFD, it is possible to integrate utilitarian approaches, the ANP and uncertainty modelling using the DS-T. Probability theory using HMM has also shown great strengths for requirements forecasting and is again seen to complement the selected tools.

DESIDE embodies those strengths and addresses weaknesses in current dispensations as highlighted in research such as Samset and Volden (2016). Laurent and Leicht (2019) and Almqvist (2017) point out that FED design should be collaborative and integrated to help facilitate focus processes on benefits delivery. DESIDES approach facilitates this endeavour in embedding these tools. Horkoff and Yu (2016) and Yang et al. (2015) emphasise the importance of Requirements Management in the process of Benefits Realisation. Laurent and Leicht (2019), Boukhris et al. (2017) Halttula et al. (2017) and Exner et al. (2016) argue for integrated early customer engagement in order to embed flexibility in capacity in FED processes. Basing on the highlighted positions, the proposed model can therefore:

(a) Facilitate value co-creation through early stakeholder involvement making use of their knowledge and capabilities in supporting benefits delivery (Fuentes & Smyth, 2016).
(b) Embed processes that leverage individual skills to support understanding and shared response to changing needs of projects so as to minimise process constraints (Laurent & Leicht, 2019).
(c) Embed processes that integrate contextual specific parameters in design processes e.g. in important factors that impact design processes (Markou et al., 2017; Sousa-Zomer & Cauchick-Miguel, 2017).
(d) Support early decision making through shared information and knowledge modelling in reinforcing project goals (Nielsen et al., 2016).

The focus of the proposed system is on Benefits Realisation from a FED standpoint. Current dispensations are in the main qualitative and therefore, lacking in the necessary quantifiable basis to facilitate benefits delivery (Farbey et al., 1999; Reiss, 2006; Balta et al., 2015). It does this by:

(a) Embedding a flexible, consistent and scalable method of integrating various contextual parameters in a single approach (Doherty et al., 2012).
(b) A focus on project benefits in the utility assessments to address ambiguity in current approaches thereby improving accuracy in representations and design thus forming a strong basis for decision making (Reiss, 2006; Gomes et al., 2017a).

(c) A new model that emphasises integration and participatory FED linking organisational goals to the user and stakeholder goals and ultimately link them to target and derived project benefits (Lin & Pervan, 2001; Balta et al., 2015; Kpamma et al., 2017).

(d) A model that facilitates ongoing benefits evaluation and forecasting through allowing ongoing updates in parameters such as probability assignments in HMM to reflect current contextual reality and how this affects future derived benefits in a quantifiable approach (Remenyi et al., 1998; Yates et al., 2009; Bolar et al., 2017).

Three key processes pertinent to the proposed model identified from literature for FED; processes and summarised and represented in the process model seen earlier in part in *Figure 5-6* are:

Defining Use Parameters: in this process, inputs like organisational goals, end-user, and stakeholder input information, including any feasibility and business case studies are considered alongside the project objectives.

Interpreting Design Needs: in this process, inputs like outline plan of works, stakeholder feedback, defined project benefits and alternative solutions are developed collaboratively; among stakeholder decision making and trade-offs feed into concepts derived so far alongside other outputs from the previous process.

Defining Design Processes: in this process, outline plans and planning resources inform wider decisions in the perspective of the project life cycle iteratively.

5.6.1 Model for The Decision Support System (DESIDE)

Figure 5-8 is the proposed uncertainty-based decision support system for Benefits Realisation for FED. What is intended in the model is for the methodology to draw on the link between Benefits Realisation processes in FED and related uncertainty and modelling using the DS/ANP and requirements forecasting with HMM. The seven Step strategy employs the various tools discussed in the foregoing sections for information/requirements capture, management, modelling, optimisation, and iteration using the following steps:

In the first process, a requirements forecast analysis is carried out using HMM. The process starts with identifying appropriate users/stakeholders to elicit needs from. They are then tabulated in categories if appropriate in step 1. Stakeholder and expert groups are also identified to elicit corresponding design requirements followed by defining probabilities for the transition and emission matrices and thereafter capture the interdependences between design requirements in steps 2, 3 and 4, respectively. Documentary evidence as seen earlier can also be used or any factual data that updates the data for the probability and relationship matrices that are subsequently computed in an HMM analysis over a time-space. The rating results feed into the HoQ user requirement for computation of the relationship matrix in step 6. Then the HoQ matrix is computed for results in step 7. Sensitivity analysis and further data processing can be undertaken in step 8.

In the second process, a utility and uncertainty modelling process is carried out as follows. **Step 1** – Defines both refine-able and raw data, target benefits and related information. In this step, it is important that information able to support a Benefits Realisation process is gathered relevant to the specific analysis. Some of this data can be refined using pre-analysis modelling tools seen earlier while other information can be treated as raw data. Multiple variables can be dealt with even with varying lower-level attributes. The project core purpose is perhaps the starting point in the definition of potential benefit variables and progressively, the higher and lower-level goals. Benefits Realisation is focussed on change management at the organisation-portfolio-program interface where some of the goals will already be defined. Stakeholder input is just as important so a collaborative approach can best serve this process in defining scope, lead times or any high/low order requirements while end users can be invaluable in guiding on user desires. Any approach to Benefits Realisation has first and foremost to set parameters that define the degree to which benefits can be achieved and how they can be planned and optimised. Secondly, risks to achieving such benefits have to be defined in the same light, including identifying critical non-value-adding processes. FED processes aim to manage user requirements and transform them into design requirements and, therefore, it is important that in this stage, QFD as a suggested useful tool is used in transforming the VOC and corresponding design requirements based on the expected benefits of the project.

Step 2- Involves Modelling Input data as refine-able and uncertain variables ready for DS/ANP modelling. This is a part cleaning process where some data can be pre-modelled prior to input into the DS/ANP model. The proposed model suggests the use of QFD, Utility analysis employing the COPRAS and MOORA to refine and rank user and design requirements e.g. a QFD analysis first that yields ranking for user requirements and subsequent comparison with identified design requirements. Data can be captured and pre-modelled, as user benefits information. This is adopted through the use of HoQ importance weighting for the matrix (Yazdani et al., 2017).

However, their combination contributes to the refined set of data to run alongside the uncertain data from other raw sources. Rankings for user and design requirements basing on a weighting can be obtained, and the utilities established among alternatives. Decision-makers are adjudged to have a propensity for maximisation of their Utility. For a utility to be maximised or minimised, equation 59 represents the eventual relationships when l is the objective to be maximised and r is to be minimised for $x \in X = [x \geq 0]$:

$$Max\ E[U(x)] = U(y_1 x, y_2 x, \dots, y_l x),\ Min\ E[U(x)] = U({y'}_1 x, {y'}_2 x, \dots, {y_r}' x) \qquad (59)$$

The matrices U and G in Equation 60 represent the user requirements interdependences (Sahu et al., 2018) and design requirements pairwise comparisons, respectively.

$$U = \begin{bmatrix} 0 & y_{12} & \dots & y_{1j} & \dots \\ y_{21} & 0 & \dots & y_{2j} & \dots \\ y_{31} & y_{32} & \dots & y_{3j} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{n1} & y_{n2} & \dots & y_{nj} & 0 \end{bmatrix}, G = \begin{bmatrix} 1 & x_{12} & \dots & x_{1j} & \dots \\ x_{21} & 1 & \dots & x_{2j} & \dots \\ x_{31} & x_{32} & \dots & x_{3j} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nj} & 1 \end{bmatrix} \qquad (60)$$

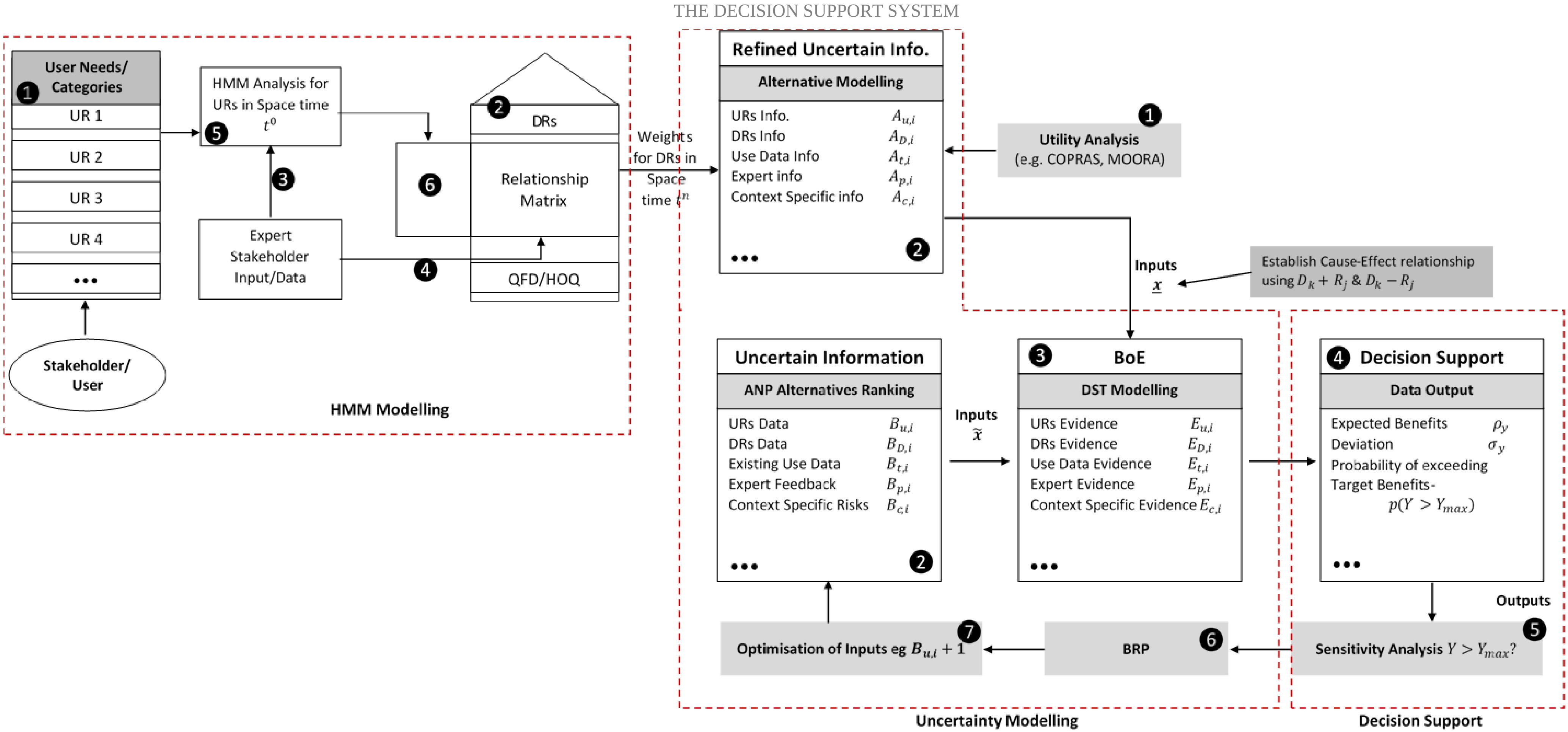

Figure 5-8 The Model for DESIDE For Benefits Realisation in FED

G is normalised by $X = k.a$ where $k = \max_{1 \le i \le n} \left(\sum_j^n a_{ij}\right)^{-1}$ $(j = 1,2, \ldots, n)$ and thereafter through matrix transformation computation for the total relation matrix $T = X(I - X)^{-1}$ to establish each criterion as to how its ith criterion is influenced by its jth (Sahu et al., 2018). Rankings are obtained by $D_k + R_j$ where $D_i = \left[\sum_{j=1}^n t_{ij}\right]_{nx1} = [t_i]_{nx1}, (i = 1,2, \ldots, n)$ and $R_j = \left[\sum_{i=1}^n t_{ij}\right]_{1xn} = [t_i]_{nx1}, (j = 1,2, \ldots, n)$. At the end of this step, two sets of data in step 2 should be defined forming the BoE.

Step 3 – Define the Uncertainty Modelling parameters and compute for the variables in the DS/ANP model. This step is the application of the DS/ANP modelling process outlined briefly in section 5.5.2. The process establishes firstly uncertain information from the previous step from the various sources about the now determined benefit(s) as model input variables. Secondly, the process draws the relation between the benefit(s) information and inputs quantitatively. Third step is to establish and analyse the uncertainty using one of the various methods like $u(\{b_i\}) = Pls\ (\{b_i\}) - Bel\ (\{b_i\})$ or more elaborate methods of dissonance, the Generalised-Hartley method or Average Width within the BoE. Lastly is to develop decision rationale basing on the results to attempt to reduce the uncertainty or validate the conditions for the benefit(s). Boundary values can be set upon which results may be accepted or refused.

Step 4 – Produce and Analyse Preliminary Results perhaps with aid of graphical representations. This phase involves using the threshold parameters for the analysis of the results. Combined evidence from the BoE is collected alongside their uncertainty calculations from the FOD. Rankings can, for example, aim to define Expected Benefits (ρ_y), deviation (σ_y), and defining the probability of any assessed parameters of exceeding Target Benefits- $p(Y > Y_{max})$. This step is important in the definition of a Benefits Realisation based on results from the DS/ANP modelling.

Step 5 – Carry out Sensitivity Analysis: In this step, depending on how far the uncertainty in an alternative is from the threshold, a sensitivity analysis can be carried out to establish the key contributor is to the uncertainty. By identifying the intricate information about a specific uncertainty, it is possible to iterate the model for the best fit results. It might suffice that more reliable information is needed in which case uncertainty in a benefit will be reduced. Alternatively, new data as evidence on a given specification can have the same desired effect. Benefits Realisation through this modelling process can thus engage with the process of reducing uncertainty to influence the true utility of benefit.

Step 6 – Define the Benefits Realisation program based on the results from the sensitivity analysis as part of a feedback process with information about modelled uncertainties. The Benefits Realisation process established benefits to be analysed from a set of alternative parameters. It might suffice that uncertainty modelling reveals irreconcilable results to the level that data from data sources cannot be refined any further to support uncertainty reduction. In this case, it is prudent that the Benefits Realisation strategy has room to take account of this data and consider redefining the benefit in question. Conversely, if the data supports the BoE in the benefit(s) then the strategy can adopt the results as is.

Step 7 – Iterate over uncertain information for results that do not meet criteria as new input variables. These results can then form part of a new iterative analysis as additional input variables that will yield a higher value-weighted BoE regarding the benefit. The whole analysis process can thus be updated, potentially leading to improved values of uncertainty about the benefit. Should the results improve to meet or exceed the threshold, they can be adopted in the Benefits Realisation. If they do not, then the process can iterate over the previous steps again.

5.6.2 Summary

The quest for increased focus on benefits delivery in AEC design continues to grow. Design management provides new opportunities and more particularly in decision making in FED. To help draw a better understanding of the various process uncertainties and dynamics, and their influencing role to delivery of project objectives of this stage, new quantitative methods have been argued. An extensive literature review revealed solutions in probabilistic approaches using such as the DS-T and HMM for uncertainty modelling and requirements forecasting, respectively. The two approaches alongside a utilitarian and Requirements Management modelling approach using QFD and ANP have informed the proposed model. The model is tested in chapter six using social housing case studies in two contexts following which the findings of the are presented in chapter seven.

The literature review has also revealed three areas of high-level functional process interdependences in FED that merit contextual consideration for benefits delivery in design processes: 1) Defining Design Parameters, 2) Interpreting Design Needs and 3) Defining Design Processes. The three constructs firstly espouse the central role of FED processes in Benefits Realisation. Secondly, basing on these constructs, it is possible to underscore areas of potential value creation in FED. Thirdly, they form a basis for proposed modelling providing a way that enables identified problems initially in Benefits Realisation cycle to be tracked and traced as the design evolves, through design, use and across the entire project time-space. Perhaps Hertzberger's (1971) assertion that *"What we should make (in* Benefits Realisation*) is the wall on which everyone can write whatever he/she wants to communicate to others"* rings so true now. The next chapter presents the case studies.

6 CASE STUDIES

6.1 Introduction

The last chapter discussed the conceptual model adopted in this research for decision making analysis and modelling. In this chapter, the two case study contexts are discussed together with the data collected and subsequently modelled and analysed. Both case studies are discussed in the context of the research objectives. The first case study context One is in the Brazilian city of Porto Alegre, Rio Grande Do Sul and represents opportunities for validating component parts of the DESIDE components. Two cases are considered A, from the implementation side and B from the design perspective. Parts of the data and analysis has been presented in the Journal paper (Serugga et al., 2020e). The detail validation is presented in journal papers in the appendix for cases A and B. For this case study, a narrative is presented to give the context and the underlying attributes modelled in DESIDE. The detail case study context is in the U. K and discussed with the aim of evaluating and validating the full proposed decision system. The detail case study captures the integrated dynamics of Requirements Management and forecasting as well as modelling uncertainty with the full integrated model.

6.2 Case Study Context ONE – Brazil

Context 1 is set in the Brazilian state of Rio Grande Do Sul in the main city Porto Alegre. The choice of this context is to capture the essential dynamics that impact on the delivery of social housing in the Minha Casa Minha Vida (My House- My Life) program. Data in this context case is captured from both a design and implementation perspective supplemented by other stakeholder interviews for instance from funding, community, and users. The Minha Cas-Minha Vida (MCMV) social housing scheme is a government-backed and funded program delivered locally by each state in Brazil. The program is the predecessor of the City Entrance Integrated Program (Programa Integrado Entrada da Cidade - PIEC) that subsequently also replaced a previous public social housing program the Residential Leasing Program (Programa de Arrendamento Residencial – PAR). The difference between the previous programs and the current one relates to the involvement of the private sector in the delivery of the housing schemes as opposed to the local or federal state previously. Funding mechanisms have also been revised in MCMV just as much as the legal frameworks and delivery processes for the new scheme. Social housing is now funded through Caixa Bank (a state backed bank in Brazil) that currently evaluates the viability and provides a supervisory and management role on behalf of the central government. New regulations now stipulate many conditions on the developer, including target financial, environmental and energy performance of the new developments, among others. The approach in this context is to investigate the '*structure and agent*' issues relating to Requirements Management from different perspectives among stakeholders, analysing designs, production control and other documents, carrying out semi-structured interviews with design and production professionals, and finally analysing data on user satisfaction.

6.2.1 Case Study A

This is a two-bed residential development program part of MCMV undertaken and led by an engineering and project management operation in the city of Porto Alegre in Rio Grande Do Sul that has for a considerable time been involved in similar developments as part of the scheme in mostly Band 2 – the Medium Low to Medium social Housing sector. The firm operates as a fully-fledged engineering and construction entity including project managers, specialist and trade engineers, cost estimators and construction teams among other technical teams. It collaborates on the MCMV with other stakeholders

Its current developments include:

The Santa Isabel – 2 Bedroom apartment development in Santa Izabel in the outskirts of Porto Alegre in the suburb of Viamão. The development comprises of 11 blocks of four floors each. The wider development also includes a communal children's play centre, a social centre for activities, a swimming pool, a health facility (gym), party facilities and various small party BBQ places that are a mainstay of the state's social life. Also included is a parking slot for each apartment. The blocks of apartments are in various stages of development; Six of the blocks are in advanced stages of implementation; one at the foundation level and the last one at the time was yet to be started while the remainder were in development.

The Paseo Citta - 2 Bedroom apartment development; comprising of two-bed apartments and The Solar da Estancia - 2 Bedroom apartment development. Both these have been completed.

The projects' selection represents a typical development program in the MCMV program in the city of Porto Alegre and in terms of other contextual issues like compliance, target users, funding, and implementation regime. In Paseo Citta and The Solar da Estancia the are units mainly two-bedroom apartments blocks in condominiums over more generally four floors each. The condominium is typically gated with a staffed main entrance. The developments also have shared facilities like health and fitness suites, social and entertainment centre, a swimming pool, staffed security, parking, and shared open spaces; and geared towards medium-income earners. Each block and the units are identical comprising of a laundry room, kitchen, living room, bathroom and two bedrooms each of around 42sqm. Each block shares a lobby and car parking spaces around it one for each apartment. The blocks are in various stages of implementation but mostly in post commissioning stage; all project are of structural masonry with each development led by an engineer from the Engineering Management company based. The firm has over 26 years of real estates development portfolio in Rio Grande Do Sul and engages in execution of a broad range of developments including commercial, industrial, residential, high standard, popular housing, and infrastructure schemes. The three locations are in the suburbs on former green sites. Typically, the neighbourhoods are run down, and other amenities e.g. transport, schools, shopping are still in infancy. Some of the factors for modelling using the various components of the proposed decision system are drawn from *Figure 6-1* to *Figure 6-15* and summarised in *Table 7*.

Figure 6-1 Option one Floor MCMV Plan

Figure 6-2 Option two MCMV Floor Plan

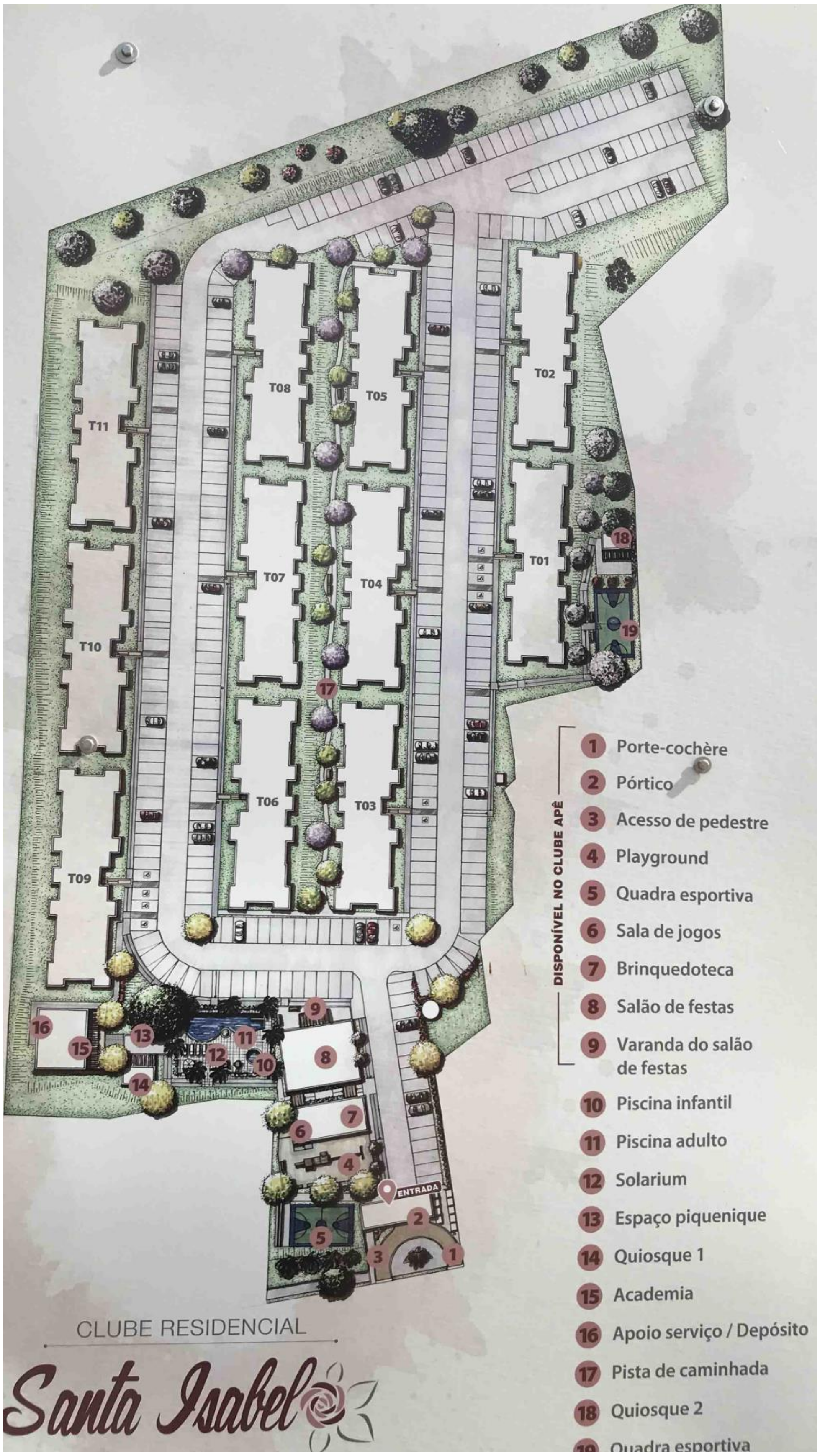

Figure 6-3 Santa Isabel Site Plan

Figure 6-4 Foundations and Ground Works

Figure 6-5 Preparation of Footings

Figure 6-6 Mechanical and Electrical Works

Figure 6-7 Internal Finishes and Installations

Figure 6-8 Plumbing Works and Installations

Figure 6-9 External Building Envelop

Figure 6-10 Kids Day Care Centre and Play Facilities

Figure 6-11 Junior Pool Facility

Figure 6-12 Arial view of development

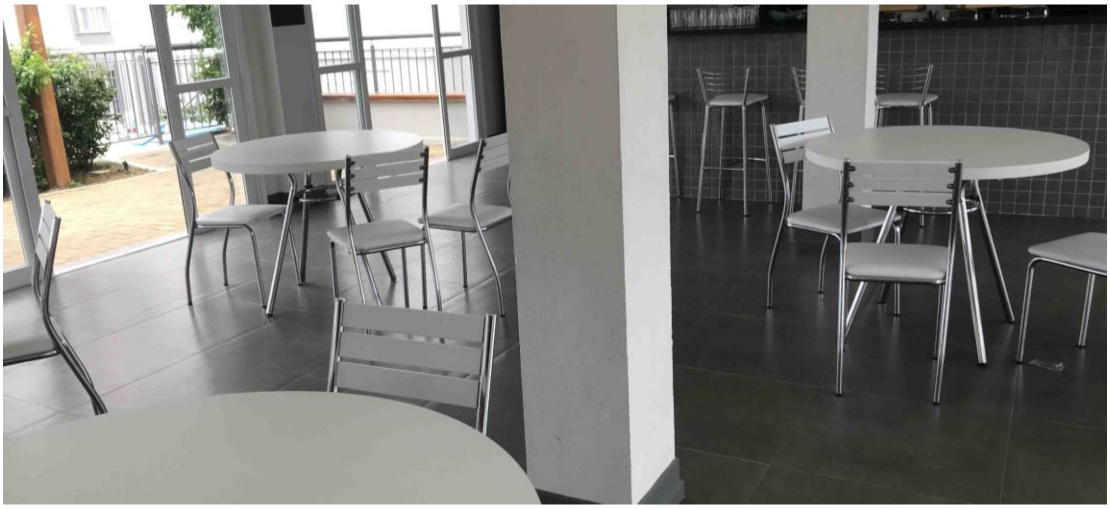

Figure 6-13 Cafeteria and Small Party Venue

Figure 6-14 Swimming Pool Facilities

Figure 6-15 Landscaping and Site Design

Table 7 Identification of Potential Modelling Parameters

Figure	Requirements Identified	Associated Potential Uncertainties
Figure 6-1 and Figure 6-2	Technical	Space and functional performance in the MCMV programme are a major element of the requirements with space and size constraints from the funding agency and federal authority. Uncertainties abound because of the constraints.
Figure 6-3	Physical and Site Planning	Impact on the immediate environment and associated services of development of this size
Figure 6-4 & Figure 6-5	Technical, environmental, technical, energy performance	Constructability is a key element for the MCMV developments, and locally available materials and construction systems (masonry and precast columns for footing piling) that support local expertise in terms of contractor teams are a natural choice. Materials performance is a key element that together forms an important source of uncertainty for design processes.
Figure 6-6	Economics, Technical	The quality of mechanical and electrical design, materials and services is important for many users and therefore a potential source of uncertainties.
Figure 6-7	Technical, Environmental	The requirements for materials performance can be high in developments and therefore, an important consideration for designers. The choice and characteristics of materials can, therefore, be a particular source of uncertainties.
Figure 6-8	Environmental, Economic, technical	The design of restrooms can place particular requirements on a dwelling alongside the choice of fittings and design of works. Functional and space requirements can also present or relieve some particular pressures for users alongside related waste management systems
Figure 6-9	Physical planning, technical, environmental	The external building envelop can present particular challenges in shared housing facilities like in these developments. Related costs of maintenance, choice and characteristics of materials or access to parking facilities can all quickly contribute to emergent uncertainties.
Figure 6-10	Technical, sociocultural, health and safety. economics	Related and shared facilities present some uncertainties relating to health and safety of users, maintenance costs and related cost pressures as for replacement of equipment alongside the technical uncertainties relating to functional and space performance. Also important are uncertainties in terms of integration in case of any emergent wider sociocultural shifts
Figure 6-11	Costs, health, and safety	Junior facilities are an important and potentially essential facility. However, there could be emergent uncertainties relating to health and safety among this vulnerable group of users alongside any emergent costs relating to maintenance and replacement of any fabric.
Figure 6-12	Environment, sociocultural	This and many similar developments are sited on previous green sites. This can place particular pressures on the neighbourhood in terms of access to local services and amenities like schools, health, and transport services, among others.
Figure 6-13	Economics, technical requirements like functional and space design	Uncertainties relating to accessibility to facilities and impact on residents' economics and financial performance
Figure 6-14	Economics, maintainability, sociocultural impacts	Environmental performance and sociocultural shifts can create uncertainties in maintenance regimes for the delicate facilities impacting on family life
Figure 6-15	Environmental Impact, maintainability, maintenance costs, occupancy, economic, geopolitics	Change in requirements both for local and national authorities and maintenance & management teams and sociocultural shifts can have an impact

In this case study context, the overall aim was first to draw onto specific parameters in user and design requirements that impact on derived benefits through observations and direct interviews. Questionnaires and documentary evidence were also employed to further explore factors as: Occupancy structure, economic performance, environmental, governance, among others. The modelling first explores the utility of design decision-making in supporting user requirements relating mobility, Health and Safety, Lifecycle performance and Maintainability, the role of Geopolitics – in how stakeholders perceive the influencing role of the general political environments in impacting on design outcomes; and finally Environment – in terms of the general environmental factors are integrated in design decision making from a stakeholder perspective.

A retrospective questionnaire survey with residents of recently occupied apartments, was essential to capture all the above as well as an understanding of current and potential future influencing changes in the use of their home. This was regarding understanding if any of the home features they would need changing, including any rearrangements or identification of uncomfortable design features or material choices. Ranking the level of satisfaction among requirements users and other stakeholders hoped to derive from any potential new design or after any desired changes further informed a sense of users' and stakeholders' preference structure. This research has adopted the Saaty (1999) scaling of 1-9 with 1 representing the least and 9 the most preferred for modelling interdependences among requirements. This processes also elicits any trade-offs using the same scale for the QFD analysis among the preferences reflecting the utility analysis. Evaluation of the stakeholders' degrees of preferences via a stakeholder-focussed questionnaire aimed to address the following high order requirements categorisations for forecasting modelling using DESIDE.

6.2.2 The Role of Design - Case Study B

This is a design firm in Canoas, a suburb of Porto Alegre in Rio Grande Do Sul. It is engaged in the development of social housing schemes as part of the MCMV program. The firm operates on a mission of providing *'creative and functional solutions'* for accommodation for both living and workspaces. They emphasise the design for comfort and safety while also ensuring value and satisfaction to end-users. The firm also prides in its transparent practices and operations; while also being responsive to the impact of its activities on the environment, an issue the company says it understands is central with its client base. It works with the medium to high-end income housing. The firm takes the lead in design and development of the condominiums liaising with stakeholders including contractors, design teams, financing, local authorities, compliance teams and facilities management teams, among others. The following is a list of the general approach to development as part of the firm's services:

- Analysing of development documentation including any site plans and funding mechanisms for the potential development.
- Preparing and monitoring/supervising and ongoing management of project documents including feasibilities, outline designs, compliance, funding, and contractual documentation.
- Ensuring compliance through all competence bodies that have an interest in a development.
- Liaising with stakeholders in the management and sales of properties.
- Post-commissioning inspection checks to ensure compliance and development of management plan.

The Design Process

Figure 6-16 is a representation of the FED process for typical social housing development. The firm maintains a list of potential sites including assessments and analysis of the size, location, and any specific additional information important in the development of a feasibility business case. The next step in the development is the analysis of the information, including outline costings and bills of quantities after which a feasibility study is carried out. Following this, the team proceeds to liaise with stakeholders including wider design teams, local authorities in planning, environment, leadership, fire department, contractors, management companies and others. Outline and scheme designs are developed at this time.

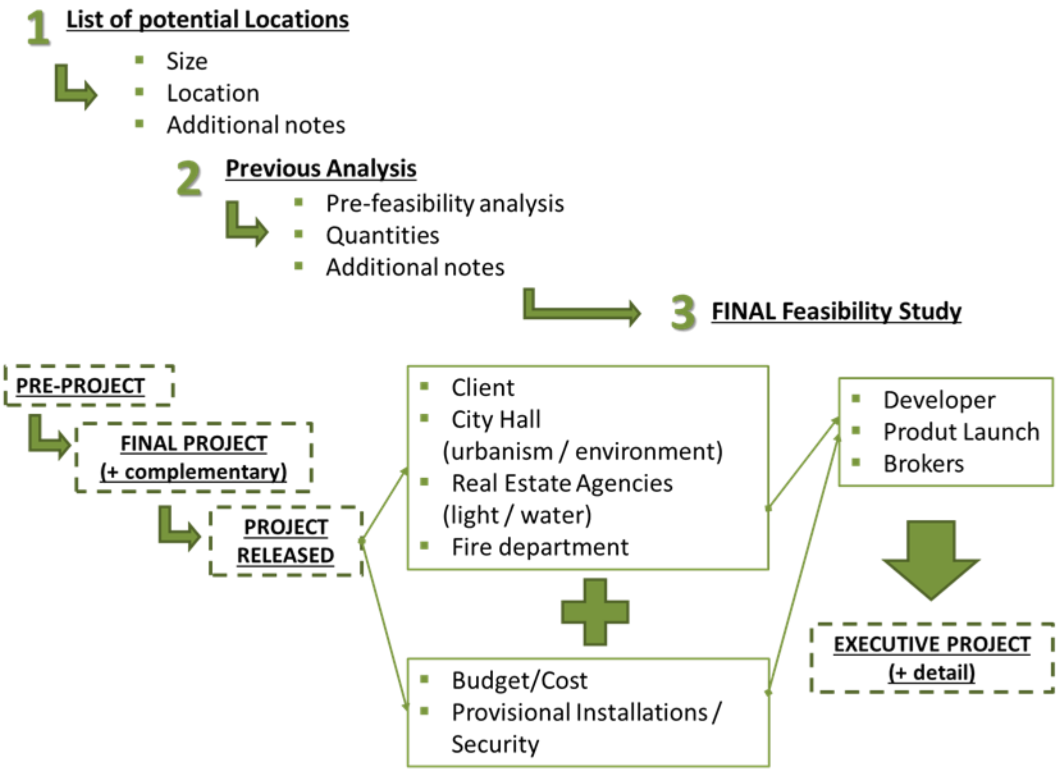

Figure 6-16 Process of Design in Case Study one

6.2.2.1 Key Notes from Case

The firm reports of active efforts in understanding and integrating end-user information into its design process. The firm engages actively with new residents in a feedback process and analyses the data proactively, both current and previous, to take this into new developments. However, there are no support tools over and above the basic that support rational decision making as widely adopted in practice. There is also no suggestion that the firm actively engages with potential end-users ahead of any development. The interviews, document reviews and questionnaires with the designers help elucidate the process of requirements management from user to design. In terms of the project design process, family structure, including any individual or family-specific requirements, do play an essential role in requirements transformation. The same applies to other factors for instance the local or national economy, socio-cultural factors that determine use and issues like mobility and the Health and Safety that is now a requirement in every planning and implementation of MCMV projects. The designers' perspective of health and safety in supporting users' general wellbeing is also important to understand just like the influence of factors as physical, environmental, constructability, Maintainability, and Geopolitics on design decision making. DESIDE in this case is used in part to underscore the confidence level in the BoE that designers use in implementing projects in the specific contexts.

6.2.3 The Data

The data from both case A and B are aggregated into a unified form to inform a single case context narrative. The idea is to assess whether decision making based on the various parameters supports the design models adopted in the MCMV process by various entities. The data was first analysed for utility across various attributes in Sociocultural, Health and Safety, Technical, Life-Cycle Performance, Occupancy, Geopolitics, Environment and Governance factors. The extended decision system draws and relies on the steps and rigour of evidence gathering, the process of development of alternatives, including outline designs, and any steps and considerations for analysis of conflicting requirements and alternatives. In later and future analyses, decision-makers can build and reuse this knowledge base and evidence for similar or related analyse.

In stage 1, the participants assign a weighting to housing user requirements. The weightings are checked with expert participants to again underscore the correlation matrix considering the design alternatives. In stage 2, the weights are normalised for the respective user requirements and adopted for the QFD analysis and ultimately in the weighting the design requirements. In stage 3, a Utility assessment of the utilities is carried out. The utility assessments are based on the adopted design requirements and the utilities they yield over the design model rankings considering the appropriate levels. Utility Theory assigns a utility to each level of attributes or attribute clusters and attributes themselves so that the most desired out is assigned a value of 1 and the least 0. The levels are assessed from expert participants on seven attributes and form the basis for attribute comparison.

6.2.4 How Data is Processed

The data were analysed using the proposed system's components independently first by defining the *refinable* and non-*refinable* data sets from the information to inform both the utility and uncertainty assessments. HMM analysis based on a set of transition and emission probabilities was then carried out to discern any impact on and interdependence among the parameters because of changes in events. These events, in this case, could be from Economic performance fluctuations as understood within the context, considering the current state, past state and anticipated future state. The same is done for the social-cultural, Health and Safety, Technological changes, and geopolitics. Additional considerations are also made for the maintainability of the home, any family-specific factors, and finally environmental and physical aspects.

6.2.5 Utility Assessment of Social Housing Alternatives

First, a QFD assessment is applied to the data to ascertain the interdependences among attributes and their *importances*. This follows the approach to using the 'HOWs', as outputs of a stage that result from the inputs 'WHATs to form inputs in proceeding stages as illustrated in *Figure 5-4*. This is especially essential in reflecting the iterative nature of FED processes. The starting Utilitarian-QFD phase of the proposed decision model is a basis for robust requirements trade-offs in accounting for contextual influences as highlighted throughout this thesis.

Table 8 is a summary of the design and user requirements elicited from the interviews together with their corresponding annotations. The corresponding annotations, as adopted in the analysis, are also listed. Also presented in Table 8 is the derived utility assessment and the identified maximisation or minimisation goals of the outcomes. From this table, first, a direct relationship matrix captures the interdependences among user requirements (see Table 9). This is the basis of the normalisation following the Yan and Ma (2015) and Kwong et al. (2011) approach. Normalisation uses Eq. (34) and the results presented in *Table 10*. The normalisation reveals a strong influence from *'comfort'* (0.1404), *'low energy'* (0.1316) and *'safety'* (0.1228) of the desired home/design while *'low maintenance'* (0.0614) ranks least in terms of user benefits analysis.

Table 8 Elicited User and Design Requirements and Utility Assessments for MCMV social housing Design

Design Requirements			**User Requirements**		**Utility Assessments**		**Rating**
Constructability	Co	increase	Low Energy	LE	Maintenance Costs	MC	low
Compliance	Cp	increase	Low Maintenance	LM	Construction Costs	CC	low
Functional Space	FS	increase	Security	SY	Accidents & Illnesses	AI	low
Materials Use	MU	decrease	Comfort	C	Time off Work	TW	low
Design Form	DF	increase	Durable Materials	DM	Cost of Changes	CoC	low
Costs	C	decrease	Ample Space	AS	Time in Home	TH	high
Service Areas	SA	increase	Ventilation	V	Equity	E	high
Site	Si	decrease	Safety	S	Running Costs	RC	low

Table 9: The initial direct-relation matrix (A) for URs

	LE	LM	S	C	DM	AS	V	S
LE	0	2	2	2	3	2	2	2
LM	2	0	1	1	1	1	1	1
SY	4	3	0	3	2	3	2	2
C	3	3	2	0	2	2	2	2
DM	2	1	1	1	0	2	2	1
AS	3	2	1	2	1	0	1	1
V	3	3	2	2	2	3	0	2
S	3	3	2	2	3	3	2	0
	20	17	11	13	14	16	12	11

The total influence matrix in Table 11 is then computed using Eq. (36). The table summarises the individual parameter to parameter influence scores among user requirements.

Table 10 The Normalised relation matrix (A) for User Requirements

URS	LE	LM	S	C	DM	AS	V	S	
LE	0.0000	0.0175	0.0175	0.0175	0.0263	0.0175	0.0175	0.0175	**0.1316**
LM	0.0175	0.0000	0.0088	0.0088	0.0088	0.0088	0.0088	0.0000	**0.0614**
SY	0.0000	0.0263	0.0000	0.0000	0.0175	0.0263	0.0000	0.0175	**0.0877**
C	0.0263	0.0263	0.0175	0.0000	0.0175	0.0175	0.0175	0.0175	**0.1404**
DM	0.0175	0.0088	0.0088	0.0000	0.0000	0.0175	0.0000	0.0088	**0.0614**
AS	0.0263	0.0263	0.0088	0.0000	0.0088	0.0000	0.0088	0.0175	**0.0965**
V	0.0263	0.0263	0.0175	0.0000	0.0175	0.0263	0.0000	0.0175	**0.1316**
S	0.0263	0.0263	0.0175	0.0000	0.0263	0.0263	0.0000	0.0000	**0.1228**

Table 11 The total Relation Matrix of The Social Housing User Requirements

	LE	LM	SY	C	DM	AS	V	S
LE	0.0028	0.0203	0.0191	0.0177	0.0282	0.0200	0.0182	0.0191
LM	0.0185	0.0014	0.0097	0.0091	0.0099	0.0100	0.0094	0.0011
SY	0.0020	0.0277	0.0010	0.0003	0.0185	0.0274	0.0005	0.0182
C	0.0287	0.0290	0.0193	0.0008	0.0199	0.0201	0.0184	0.0192
DM	0.0185	0.0102	0.0096	0.0004	0.0012	0.0185	0.0006	0.0096
AS	0.0278	0.0280	0.0101	0.0007	0.0106	0.0019	0.0096	0.0185
V	0.0284	0.0288	0.0190	0.0008	0.0196	0.0284	0.0010	0.0190
S	0.0281	0.0284	0.0188	0.0007	0.0279	0.0281	0.0010	0.0016

The graph in *Figure 6-17* summarises the $D_k + R_j$ vs $D_k - R_j$, i.e. the cause-effect relationships. The segregation of parameters indicates the sense that *'Low Energy, Low maintenance, Security and Ample Space'* have an '*effect'* relationship while *'Costs, Durable materials, Ventilation and Safety'* are causal agents in the relationship. The latter group appears to have a much profound impact on the former than the other way around because of its higher intensities.

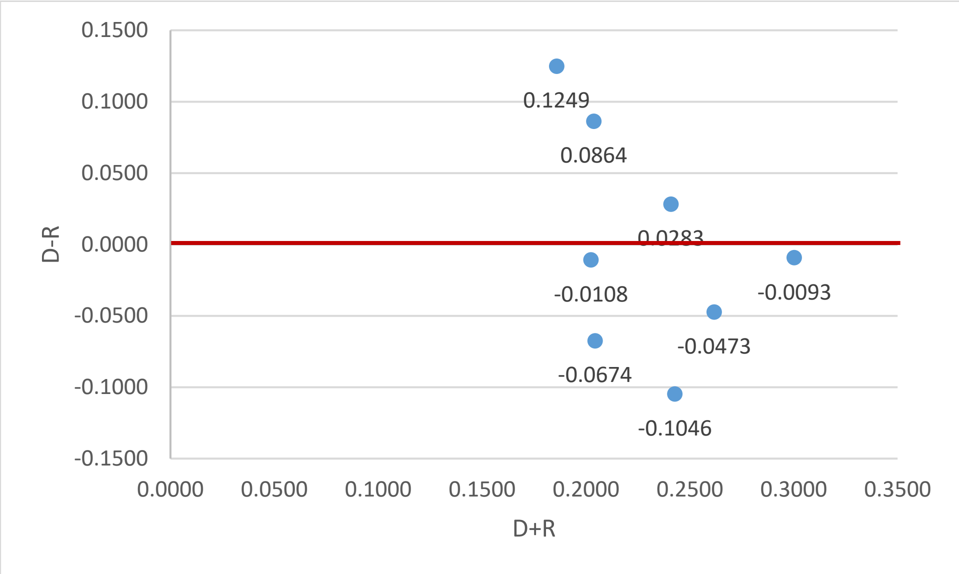

Figure 6-17 causal diagram of Social Housing User Requirements

The plot arises from the results of Table 12 capturing the influences of the various D and R vectors. Table 12 also captures the causal and effect results and well as weights for the user benefits/requirements represented as normalised $D_k + R_j$. The derived causal diagrams of both the user and design requirements are captured in *Figure 6-18* (a) and (b), respectively, perhaps to indicate the interconnectedness in the factors.

Table 12 Conversion of Vectors D and R Total and net effects for each User Requirement

URS	D_K	R_K	D_K+R_K	D_K-R_K	GROUP	WEIGHTS D_K+R_K
LE	0.1455	0.1548	0.3003	-0.0093	Effect	0.1630
LM	0.0691	0.1737	0.2428	-0.1046	Effect	0.1318
SY	0.0958	0.1066	0.2024	-0.0108	Effect	0.1099
C	0.1554	0.0305	0.1859	0.1249	Cause	0.1009
DM	0.0685	0.1359	0.2043	-0.0674	Cause	0.1109
AS	0.1072	0.1545	0.2617	-0.0473	Effect	0.1421
V	0.1451	0.0587	0.2038	0.0864	Cause	0.1106
S	0.1346	0.1063	0.2410	0.0283	Cause	0.1308

The process then proceeds to analyse the transformation of user and design requirements using expert input and elicitation an important step in the DQFD. This trade-offs process in decision making is the basis of the direct interpretation of the user requirements in a FED process perspective (Yan & Ma, 2015). The DQFD approach of defining the 'WHATs' from the 'HOW's' is thus as outlined previously in section 5.3.1 and the resultant matrix from the user and design requirements are summarised in Table 13. The rankings are elicited using open structured interviews from expert designers and academics. This in a utilitarian approach, allows the analyst to ensure the subjective views of the decision-maker are consistent over their utility function. *Table 13* is a representation of their interpretation of the interactions of the various user requirements/expected benefits in relation to design practice through the consequence space (previously illustrated in *Figure 3-3* and later conceptualised in a utilitarian application in *Figure 5-5*). The requirements are then weighted and normalised.

Table 13 QFD Model for Design of Social Housing

HOWS (URS)	**WHATS (CRITERIA)**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
	Co	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**Si**	**Weight**
LE				6		6	1	6	**0.163**
LM		1		1	3	6	1	1	**0.132**
SY		1	1	3	3	6		3	**0.110**
C				3	6	6	6	6	**0.101**
DM	3			6		6			**0.111**
AS	1		6		6	6	6	6	**0.142**
V	3	3	1	3	6	6	1	6	**0.116**
S		6		3	3	1		1	**0.131**
	0.807	1.358	1.073	3.132	3.239	5.346	1.863	3.692	
NORMALISED	0.039	0.066	0.052	0.153	0.158	0.261	0.091	0.180	

Simultaneously, pairwise comparisons of design requirements based on each design model, i.e. VL, L, ML, M, MH, H, VH are elicited. Table 14 and Table 15 show the pairwise comparison of each design model against each design requirements for the criterion constructability (Co) and Compliance (Cp), respectively.

Table 14 Pairwise comparison of Social Housing Models for Constructability criterion

	VL	**L**	**ML**	**M**	**MH**	**H**	**VH**	
VL	1	2	3	5	7	7	9	
L	0.5000	1	2	3	6	6	9	0.3161
ML	0.3333	0.5000	1	1	4	5	7	0.2557
M	0.2000	0.3333	1	1	1	30	6	0.1751
MH	0.1429	0.1667	0.2500	1	1	2	4	0.1165
H	0.1429	0.1667	0.2000	0.3333	0.500	1	1	0.0796
VH	0.1111	0.1111	0.1429	0.1667	0.250	1	1	0.0311

Table 15 Pairwise comparison of Social Housing Models for Compliance criterion

	VL	L	ML	M	MH	H	VH	
VL	1	3	2	3	4	8	9	0.2070
L	0.333	1	4	5	6	7	9	0.2231
ML	0.500	0.250	1	5	6	8	9	0.2053
M	0.333	0.200	0.200	1	6	8	9	0.1707
MH	0.250	0.167	0.167	0.167	1	6	9	0.1156
H	0.125	0.143	0.125	0.125	0.167	1	8	0.0668
VH	0.111	0.111	0.111	0.111	0.111	0.125	1	0.0116

Similar comparison matrices are developed for corresponding design requirements and summarised in the decision matrix in Table 16. The results are further analysed against the design models through normalisation and weighting, respectively. In order to establish a consistent scaling of the criteria, Table 16 is normalised in Table 17 with the COPRAS approach.

Table 16 Initial decision matrix for Social Housing Models

WEIGHTS	**0.0393**	**0.0662**	**0.0523**	**0.1527**	**0.1579**	**0.2606**	**0.0908**	**0.1800**
MODEL	**Co**	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**S**
VL	0.3161	0.2070	0.2697	0.0266	0.0865	0.0834	0.0772	0.0581
L	0.2557	0.2231	0.2277	0.0242	0.0995	0.0512	0.0843	0.0586
ML	0.1751	0.2053	0.1856	0.0725	0.1050	0.1156	0.1266	0.0978
M	0.1165	0.1707	0.1270	0.1091	0.1222	0.1991	0.1202	0.1702
MH	0.0796	0.1156	0.0815	0.1676	0.2207	0.2019	0.1852	0.1874
H	0.0311	0.0668	0.0876	0.2431	0.2187	0.1862	0.1991	0.1881
VH	0.0259	0.0116	0.0209	0.3569	0.1474	0.1627	0.2075	0.2398

The analysis process then proceeds to apply utility analysis on the basis of COPRAS (Table 17 and Table 18); and Pj, Rj values established to determine the positively contributing (benefits) and negatively contributing (dis-benefits) attributes in the COPRAS and MOORA approaches respectively. In the COPRAS analysis, Qj is then computed for relative significance for each design model to give a utility ranking Nj as a percentage ranking on the basis of the highest Qj model (Low Housing Model – 0.2466) seen in Table 18. The least Qj value, in this case, is determined to be the *'Very High'* Housing Model (VH) – 0.0817; giving a percentage utility of 33% compared to the best choice utility.

Table 17 Weighted normalised decision matrix for Social Housing Models

Models	Co	Cp	FS	MU	DF	C	SA	S
VL	0.0124	0.0137	0.0141	0.0041	0.0137	0.0217	0.0070	0.0105
L	0.0101	0.0148	0.0119	0.0037	0.0157	0.0133	0.0077	0.0105
ML	0.0069	0.0136	0.0097	0.0111	0.0166	0.0301	0.0115	0.0176
M	0.0046	0.0113	0.0066	0.0167	0.0193	0.0519	0.0109	0.0306
MH	0.0031	0.0077	0.0043	0.0256	0.0349	0.0526	0.0168	0.0337
H	0.0012	0.0044	0.0046	0.0371	0.0345	0.0485	0.0181	0.0339
VH	0.0010	0.0008	0.0011	0.0545	0.0233	0.0424	0.0189	0.0432

Table 18 PJ, RJ, QJ, NJ Values for the Design Models

MODEL	P_J	R_J	Q_J	N_J	RANK
VL	0.0609	0.0362	0.2028	82%	2
L	0.0601	0.0276	0.2466	100%	1
ML	0.0583	0.0588	0.1457	59%	3
M	0.0527	0.0992	0.1046	42%	5
MH	0.0667	0.1119	0.1127	46%	4
H	0.0629	0.1195	0.1059	43%	6
VH	0.0450	0.1401	0.0817	33%	7

The MOORA analysis is summarised in Table 19 and Table 20. Again in order to establish a consistent scaling of the criteria, Table 19 results are normalised using Eq (35) and Eq. (40) respectively.

Table 19 Normalised MOORA Analysis

Weights	**0.0393**	**0.0662**	**0.0523**	**0.1527**	**0.1579**	**0.2606**	**0.0908**	**0.1800**
Models	**Co**	**Cp**	**FS**	**MU**	**DF**	**C**	**SA**	**S**
VL	0.6778	0.4854	0.6189	0.0551	0.2151	0.2055	0.1926	0.1396
L	0.5482	0.5232	0.5224	0.0502	0.2474	0.1261	0.2104	0.1407
ML	0.3755	0.4814	0.4259	0.1502	0.2612	0.2850	0.3160	0.2350
M	0.2499	0.4002	0.2915	0.2261	0.3039	0.4908	0.2999	0.4089
MH	0.1706	0.2710	0.1870	0.3472	0.5490	0.4979	0.4623	0.4500
H	0.0666	0.1567	0.2010	0.5036	0.5441	0.4592	0.4968	0.4518
VH	0.0555	0.0272	0.0480	0.7393	0.3667	0.4013	0.5179	0.5760

In applying the MOORA analysis to the same problem, the highest Sj value is again for the (L – *'Low'* Housing Model – 0.0758) followed by the *'Very Low'* Housing (VL) Model– 0.0555 seen in Table 19. The utility ranking (see Table 20) for VL model is now 95% while the least desirable model *'Very High'* (VH) Model fares slightly lower at 24% on the basis of the best utility model L. The overall order ranking for the models is thus as $L > VL > ML > MH > M > H > VH$. *Figure 6-19* represents the graphical ranking orders for the models for both analyses influenced by the interdependences among the various user and design attributes forming part of the modelling (see *Figure 6-18*). The performance of *'Low'* Model design appears to be the model presenting the greatest opportunities in maximising the design form (including aesthetics) and delivering on compliance while also minimising materials use and overall costs and performing competitively on-site use and needs. This appears to relate strongly to the general stakeholder needs of low-cost housing i.e. easy to maintain, maximises site use, safe and secure for end-users while looking great something that correlates with the Hentschke et al. (2018) study of the same scheme. On the other hand, the *'Very High'* model performs worse in areas of site use, compliance, and constructability. It appears that beyond the need for a large site, the complexity of the design models might be an extra burden in implementing them, including requirements for higher percentages of service areas beyond the needed functional spaces. All this can mean a less rigid compliance regime. The design form, including aesthetics, however, appears to be less of a pressing issue with the VH model though, as expected, safety is a key issue which might increase the complexity of the design.

Table 20 Weighted and normalised Design Models and design requirements Matrix and ranking using MOORA

MODELS	CO	CP	FS	MU	DF	C	SA	S	S_j^+	S_j^-	S_j	RANK
VL	0.0267	0.0321	0.0324	0.0084	0.0340	0.0536	0.0175	0.0251	0.1427	0.0871	0.0555	95%
L	0.0216	0.0346	0.0273	0.0077	0.0391	0.0329	0.0191	0.0253	0.1417	0.0659	0.0758	100%
ML	0.0148	0.0319	0.0223	0.0229	0.0412	0.0743	0.0287	0.0423	0.1389	0.1395	-0.0006	80%
M	0.0098	0.0265	0.0152	0.0345	0.0480	0.1279	0.0272	0.0736	0.1268	0.2361	-0.1092	51%
MH	0.0067	0.0180	0.0098	0.0530	0.0867	0.1298	0.0420	0.0810	0.1631	0.2638	-0.1006	53%
H	0.0026	0.0104	0.0105	0.0769	0.0859	0.1197	0.0451	0.0813	0.1546	0.2779	-0.1233	47%
VH	0.0022	0.0018	0.0025	0.1129	0.0579	0.1046	0.0471	0.1037	0.1115	0.3212	-0.2097	24%

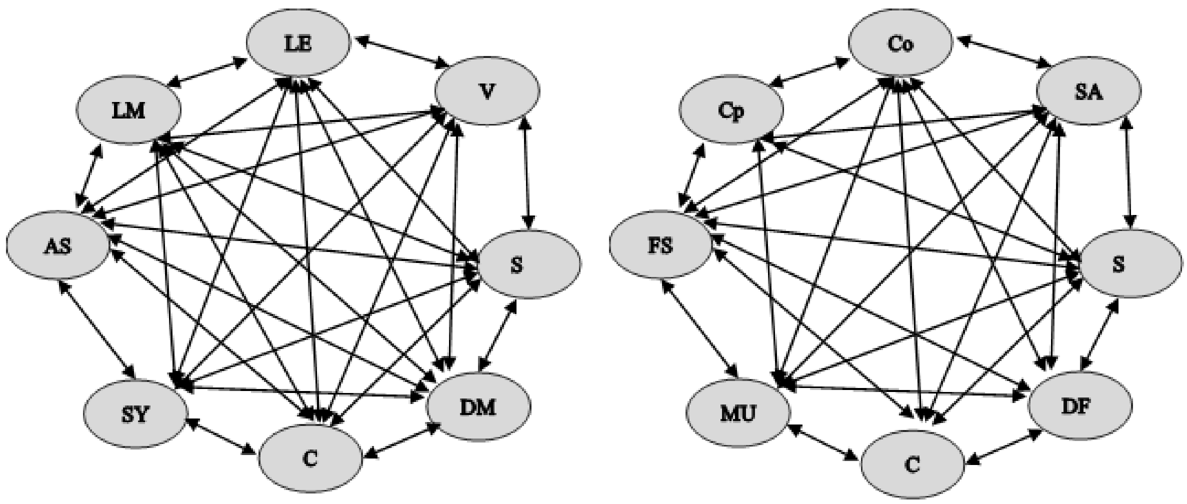

Figure 6-18 Interdependency between (a) URs and (b) DRs in Social Housing Design

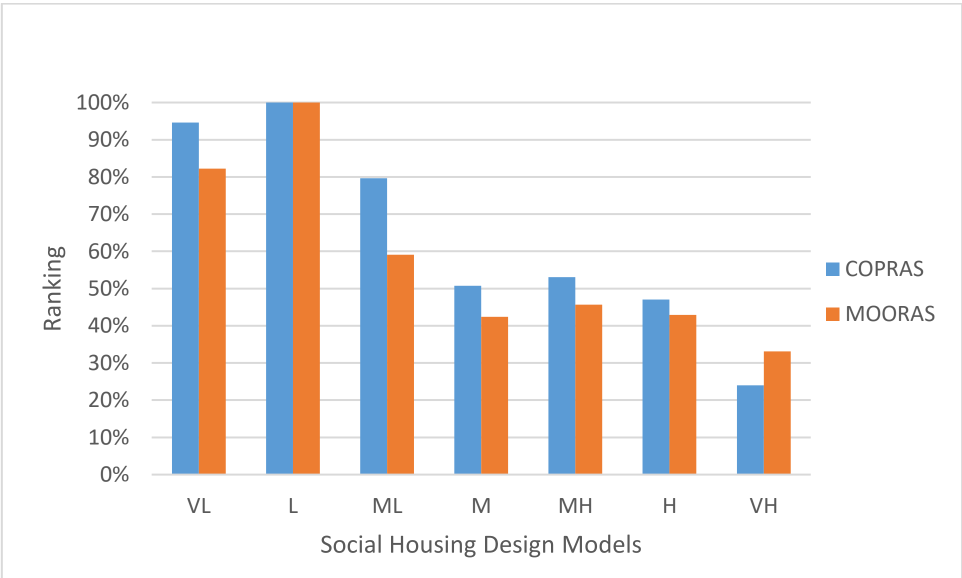

Figure 6-19 Comparative Ranking of Social Housing Design Models

6.2.6 Uncertainty Modelling

The decision analysis assesses the *bpa* for these focal elements accounting for incompleteness/completeness in the assessment of decision making. The corresponding user and design requirements were listed earlier in *Table 8*. The basic weighting for the user and design requirements are based on DQFD and ANP pairwise comparisons respectively, while the focal elements are identified as utilities based on utilitarian COPRAS analysis. Pairwise comparisons and ANP can account for interdependences of the various parameters through pairwise comparison matrices. The methods are also important in transforming qualitative attributes into forms for quantitative ones for analysis.

FED design processes are inherently complex, and collaboration between stakeholders means that the process is highly uncertain.

This step is essential for requirements forecasting while a concurrent and additional DS-T analysis determines uncertainty in the body of evidence. This data is, therefore, input through a DS-T/ ANP model to both underscore any interdependences within the attributes and uncertainty in the BoE. For drawing to the utility of decision making, DQFD is used to support a utility analysis using COPRAS and MOORA to refine and rank user and design requirements (Yazdani et al., 2017). The next step of the analysis involves production and analysis of preliminary results ready for any parameter adjustments where this may be needed against a set threshold. Combined evidence from the BoE is collected alongside their uncertainty calculations from the FoD to define Expected Benefits, deviations; as well as defining the probability of those parameters exceeding targets. This step is based on the results of the preceding DS/ANP analysis. A sensitivity analysis follows to assess how far the analysed parameters are from the threshold, to discern any causal factors impacting on the uncertainty.

It is thus possible that user and design requirements are not reflective of the full spectrum of that required to deliver intended benefits. The resultant DS-ANP analysis is based on expert weighting for the user and design requirements analysis in a reverse operation to evaluate the belief and plausibility structure of the housing models and the expert and end-user assessments. The DQFD for user requirements interdependences in the COPRAS analysis resulted in the normalised user and design requirements weightings shown in Table 21. The collected bpa information for the DS-ANP analysis is shown in Table 23 and

Table 25 for design and user requirements, respectively. A $7w_1$ weighting for the 'constructability' design requirement criterion indicates that it is extremely favoured for housing model A. On the other hand, a weighting $\boldsymbol{w_3}$ of the 'functional space' is moderately preferred for the housing model G. These ratings are drawn from a corresponding COPRAS weighting and ranking as illustrated in Table 23. The FOD is awarded a scaling 1 following on from Benyon (2001). After weighting of the various criteria against the alternatives, a DS-T analysis using definition 2 is carried out. The Dempster rule of combination in Equation (53) is used to fuse data progressively from one criterion to the next i.e. $[m_{j_1} \oplus m_{j_2}](E)$. First, the 'Constructability and Compliance' criteria are fused, and the results fused with the 'functional space' criterion and progressively through to the 'site' criterion. Table 26 and Table 28 are the initial matrices from the analysis, while Table 27 and
Table 29 are the normalised matrices for both the user and design requirements analyses, respectively. Table 22, on the other hand, is the adopted verbal preference in the DS-ANP analysis.

Table 21 Derived Weightings Using the QFD and COPRAS Analyses

DESIGN REQUIREMENTS							
CO	Cp	FS	MU	DF	C	AS	S
0.0393	0.0662	0.0523	0.1527	0.1579	0.2606	0.0908	0.1800
USER REQUIREMENTS							
LE	LM	SY	C	DM	AS	V	S
0.163	0.1318	0.1099	0.1009	0.1109	0.1421	0.1106	0.1308

Table 22 Adopted Preference Scales for DS-ANP

RATING	**1 ..**	**4 ..**	**7**
VERBAL STATEMENT	Moderately preferred	Strongly preferred	Extremely preferred

Table 23 Translated Total Weighted Relation Matrix of User Requirements

Co	**Cp**	**FS**	**MU**	**DF**	**C**	**AS**	**S**	
VL	100.00%	92.78%	100.00%	99.63%	39.18%	90.32%	37.19%	100.00%
L	80.88%	100.00%	84.41%	100.00%	45.06%	100.00%	40.62%	99.90%
ML	55.39%	92.01%	81.53%	92.35%	47.57%	80.62%	61.01%	92.02%
M	36.86%	76.49%	47.10%	86.54%	55.35%	55.52%	57.91%	77.46%
MH	25.18%	51.80%	30.22%	77.27%	100.00%	54.66%	89.26%	74.02%
H	9.83%	29.95%	32.47%	65.29%	99.11%	59.38%	95.93%	73.87%
VH	8.18%	5.20%	7.75%	47.25%	66.80%	66.44%	100.00%	63.47%

Table 24 Preference for design requirements focal elements decision alternatives

Co	**Cp**	**FS**	**MU**	**DF**	**C**	**AS**	**S**
A - ($7w_1$)	ABC - ($6w_2$)	A - ($7w_3$)	ABC - ($6w_4$)	FG-($5w_5$)	AB - ($7w_6$)	GH - ($6w_7$)	ABC - ($6w_8$)
B - ($4w_1$)	D - ($4w_2$)	BC - ($6w_3$)	D- ($5w_4$)	H - ($3w_5$)	C - ($5w_6$)	F - ($4w_7$)	DFG - ($4w_8$)
C - ($3w_1$)	F - ($3w_2$)	F - ($4w_3$)	F - ($4w_4$)	D - (w_5)	H - ($4w_6$)	C - ($3w_7$)	H - (w_8)
Θ - 1	Θ - 1	G - w_3	G - $4w_4$	Θ - 1	DFG - $3w_6$	D - w_7	Θ - 1
		Θ - 1	Θ - 1		Θ - 1	Θ - 1	

Table 25 Preference of URs focal elements decision alternatives

LE	**LM**	**SY**	**C**	**DM**	**AS**	**D**	**VS**
A - (7w)	ABC - (6w)	A - (7w)	ABC - (2w)	FG - (7w)	AB - (2w)	GH - (6w)	ABC - (3w)

B - (6w)	D - (3w)	BC - (6w)	D- (4w)	H - (5w)	C - (3w)	F - (5w)	DFG - (5w)
C - (3w)	F - (3w)	F - (3w)	F - (6w)	D - (4w)	H - (7w)	C - (3w)	H - (7w)
Θ - 1	Θ - 1	G - 2w	G - 7w	Θ - 1	DFG - 5w	D - 4w	Θ - 1
		Θ - 1	Θ - 1		Θ - 1	Θ – 1	

Table 26 Design Requirements Initial Fused Matrix

Weights							
0.0393	**0.0662**	**0.0523**	**0.1527**	**0.1579**	**0.2606**	**0.0908**	**0.1800**
Design Requirements							
Co	Cp	FS	MU	DF	C	AS	S
0.0393	0.0662	0.0523	0.1527	0.1579	0.2606	0.0908	0.1800
0.2753	0.3974	0.3662	1.0689	0.9475	1.8245	0.5451	1.0800
0.2360	0.1987	0.3139	0.6108	0.4738	1.0426	0.3634	0.7200
0.1180	0.1987	0.1046	0.3054	0.1579	0.2606	0.2725	0.1800
1.0000	1.0000	0.0523	0.1527	1.0000	0.7819	0.0908	1.0000
		1.0000	1.0000		1.0000	1.0000	

Table 27 Normalised Fused Matrix for Design Requirements

Co	**Cp**	**FS**	**MU**	**DF**	**C**	**AS**	**S**
0.1690	0.2214	0.1993	0.3407	0.3674	0.3716	0.2399	0.3624
0.1448	0.1107	0.1709	0.1947	0.1837	0.2124	0.1600	0.2416
0.0724	0.1107	0.0570	0.0973	0.0612	0.0531	0.1200	0.0604
0.6138	0.5572	0.0285	0.0487	0.3877	0.1593	0.0400	0.3356
1.0000		0.5444	0.3187		0.2037	0.4402	1.0000

Table 28 URs Initial Matrix

Weights							
0.1630	**0.1318**	**0.1099**	**0.1009**	**0.1109**	**0.1421**	**0.1106**	**0.1308**
User Requirements							
LE	**LM**	**SY**	**C**	**DM**	**AS**	**V**	**S**
1.1410	0.7907	0.7691	0.2018	0.7764	0.2841	0.6638	0.3924
0.9780	0.3954	0.6592	0.4037	0.5546	0.4262	0.5532	0.6540
0.4890	0.3954	0.3296	0.6055	0.4437	0.9944	0.3319	0.9156
1.0000	1.0000	0.2197	0.7065	1.0000	0.7103	0.4425	1.0000
		1.0000	1.0000		1.0000	1.0000	

Table 29 Normalised Matrix for URs

User Requirements							
LE	**LM**	**SY**	**C**	**DM**	**AS**	**D**	**VS**

0.3162	0.3063	0.2583	0.0692	0.2798	0.0832	0.2219	0.1325
0.2711	0.1532	0.2214	0.1384	0.1999	0.1248	0.1849	0.2208
0.1355	0.1532	0.1107	0.2075	0.1599	0.2912	0.1110	0.3091
0.2772	0.3874	0.0738	0.2421	0.3604	0.2080	0.1479	0.3376
		0.3358	0.3428		0.2928	0.3343	

Table 30 First Level Combination of Constructability and Compliance criteria

		A		B		C		Θ
ABC	A	0.0374	B	0.0321	C	0.0160	ABC	0.1359
D	{}	0.0187	{}	0.0160	{}	0.0080	D	0.0679
F	{}	0.0187	{}	0.0160	{}	0.0080	F	0.0679
Θ	A	0.0942	B	0.0807	C	0.0404	Θ	0.3420

Table 31 Second Level Combination of Compliance Functional Space criteria

		A		B		C		D		F		ABC		Θ
		0.1414		0.1212		0.0606		0.0730		0.0730		0.1460		0.3675
A	A	0.0282	{}	0.0242	{}	0.0121	{}	0.0146	{}	0.0146	A	0.0291	A	0.0733
BC	{}	0.0242	B	0.0207	C	0.0104	{}	0.0125	{}	0.0125	BC	0.0250	BC	0.0628
F	{}	0.0081	{}	0.0069	{}	0.0035	F	0.0042	{}	0.0042	{}	0.0083	F	0.0209
G	{}	0.0040	{}	0.0035	{}	0.0017	{}	0.0021	{}	0.0021	{}	0.0042	G	0.0105
Θ	A	0.0770	B	0.0660	C	0.0330	D	0.0398	F	0.0398	ABC	0.0795	Θ	0.2001

The priority values of each social housing model basing on each DR and Θ are as follows: $(\{A\} -\ 0.1592, \{B\} -\ 0.1100, \{C\} -\ 0.1830, \{D\} -\ 0.0557, \{F\} -\ 0.0793,\ \{G\} -\ 0.1110,\ \{H\} -\ 0.0259, \{AB\} -\ 0.1386, \{BC\} -\ 0.0238, \{GH\} -\ 0.0213, \{ABC\} -\ 0.0633, \{DFG\} -\ 0.0162, \{\Theta\} -\ 0.0126)$ while those for each UR and Θ are: $(\{A\} -\ 0.1365, \{B\} -\ 0.0866,\ \{C\} -\ 0.1098,\ \{D\} -\ 0.1108,\ \{F\} -\ 0.1221, \{G\} -\ 0.2167\ \{H\} -\ 0.1123,\ \{AB\} -\ 0.0108,\ \{BC\} -\ 0.0251,\ \{GH\} -\ 0.0169,\ \{ABC\} -\ 0.0254,\ \{DFG\} -\ 0.0142, \{\Theta\} -\ 0.0127)$

The sets of focal points sum to unity as earlier pointed out. A plot of URs and DRs for the analysed social housing models reveals a general agreement in the BoE. Definitions 3 and 4 are the basis for the belief intervals shown in Table 32 while Figure 6-20 captures the overall relationship graphically. The results indicate a mixed picture in the belief and plausibility $[Bel\ (\{b_i\}), Pls\ (\{b_i\})]$ preference structures. The results from the *'Medium'* (M/C) and *'Very Low'* (VL/A) housing model have the highest belief and plausibility performance ([0.1830, 0.2828], [0.1592, 0.3738]). While the previous utility assessment highlighted social housing model *'Low'* (L/A) to have the highest utility, accounting for incomplete information, designers have more belief in the *'Medium'* (M/C) Model followed by *'Very Low'* (VL/A) while plausibility is the other way round. In terms of end-user requirements, there is more belief and plausibility in the information sets of *'Very High'* (VH/G), ([0.2167, 0.2606]) followed by the *'Very Low'* (VL/A) ([0.1365, 0.1854]) model. When two models are considered, there is a stronger overall belief and plausibility in the combined *'Very Low'* and *'Low'*-income models ([0.4078, 0.5076], [0.2339, 0.2972]) respectively. In terms of a mixed three model housing choice, The *'Very Low, Low'* and *'Medium'* housing models have the best belief and plausibility sets ([0.6780, 0.6907]) from a design perspective while from a user perspective it is the *'Medium, High'* and *'Very High'* mixed models ([0.4638, 0.4935]).

Table 32 Ranking of Design Models Based on Belief and Plausibility

	DRS		URS	
FOCAL POINTS	**Belief**	**Plausibility**	**Belief**	**Plausibility**
A	0.1592	0.3738	0.1365	0.1854
B	0.1100	0.3484	0.0866	0.1607
C	0.1830	0.2828	0.1098	0.1731
D	0.0557	0.0845	0.1108	0.1378
F	0.0793	0.1081	0.1221	0.1490
G	0.1110	0.1611	0.2167	0.2606
H	0.0259	0.0598	0.1123	0.1419
AB	0.4078	0.5076	0.2339	0.2972
BC	0.3169	0.5314	0.2215	0.2705
GH	0.1581	0.1870	0.3459	0.3729
ABC	0.6780	0.6907	0.3942	0.4070
DFG	0.2621	0.2961	0.4638	0.4935

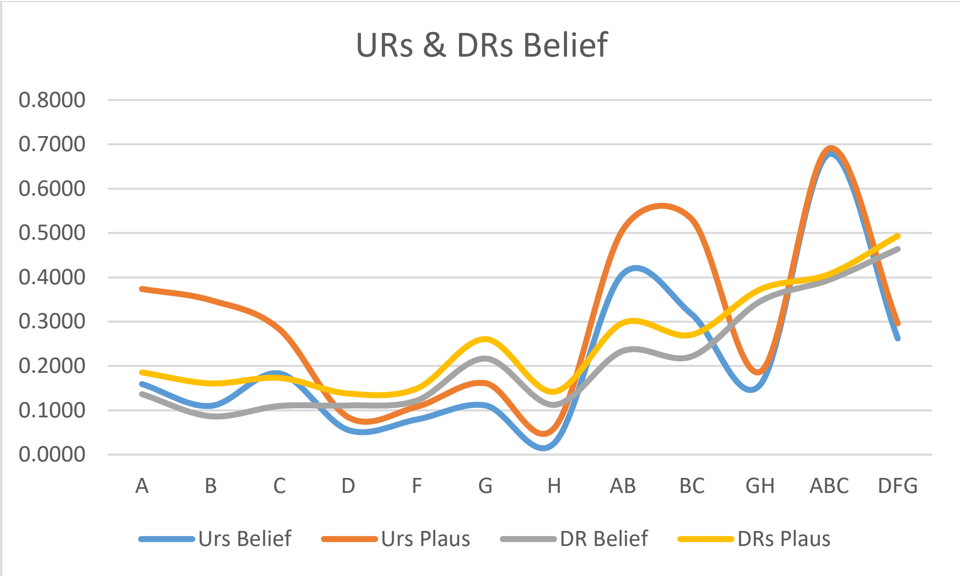

Figure 6-20 Plot of URs and DRs analysis of Social Housing Models

6.2.7 Requirements Forecasting

In modelling for requirements forecasting, the proposed model applies the analysis to high order factors as summarised in

Table 33. In this table, its aimed that the transition and emission probabilities are ranked using expert feedback and documentary evidence as to the likelihood of the factors changing between bad, average, and good reflecting the interdependences among them. In the ranking, it is aimed to establish, for example, how likely the economic environment that is good to transition to average and any chance of it transitioning to a bad situation. A similar analysis is established for a corresponding emission for each of the criteria.

Table 33 Expert and Documentary assigned transition and Emission Probabilities

		Transition (A)			Emission (B)		
		Bad	Average	Good	Bad	Average	Good
Economic	Good	0.3	0.2	0.5	0.1	0.2	0.7
	Average	0.3	0.6	0.1	0.2	0.6	0.2
	Bad	0.5	0.3	0.2	0.6	0.3	0.1
Social	Good	0.4	0	0.6	0.4	0.1	0.5
	Average	0.3	0.4	0.3	0.1	0.6	0.3
	Bad	0.4	0.4	0.2	0.6	0	0.4
Health and Safety	Good	0.2	0.2	0.6	0	0.1	0.9
	Average	0.4	0.4	0.2	0.1	0.5	0.4
	Bad	0.6	0.3	0.1	0.6	0.4	0
Technical	Good	0.1	0.2	0.7	0.3	0.1	0.6
	Average	0.1	0.7	0.2	0.1	0.5	0.4
	Bad	0.1	0.3	0.6	0.7	0.1	0.2
Maintainability	Good	0.1	0.4	0.5	0	0.2	0.8
	Average	0.3	0.4	0.3	0.2	0.6	0.2
	Bad	0	0.4	0.6	0.3	0.7	0
Occupancy	Good	0.5	0.4	0.1	0.2	0.1	0.7
	Average	0.3	0.6	0.1	0	0.7	0.3
	Bad	0	0.2	0.8	0.7	0.1	0.2
Geopolitical	Good	0.4	0.2	0.4	0	0.4	0.6
	Average	0.3	0.3	0.4	0.2	0.5	0.3
	Bad	0.4	0.4	0.2	0.6	0.4	0
Environment	Good	0.1	0.1	0.8	0.2	0.2	0.6
	Average	0	0.5	0.5	0.2	0.7	0.1
	Bad	0	0.2	0.8	0.3	0.7	0

Governance	Good	0	0.2	0.8	0.1	0.3	0.6
	Average	0.3	0.3	0.4	0.5	0.5	0
	Bad	0.7	0.3	0	0.7	0.2	0.1

The success of this prediction mechanism relies on accurate assessments and use of either publicly available data or indeed, assessment of actual physical events. This assessment process, therefore, should account for the level of credibility of the assessor(s). The assessed probabilities are first computed using equations (19) to (31) to help determine the changes in ratings from the HMM process. The results from this assessment are then fed into the HoQ for their impact on the 'HOWs' following interdependence analysis (see *Figure 6-21*).

For the *'Governance'* factor, the following matrices capture the computations:

The Transition Matrix

$$A = \begin{Bmatrix} 0 & 0.2 & 0.8 \\ 0.3 & 0.3 & 0.4 \\ 0.7 & 0.3 & 0 \end{Bmatrix}$$

The Emission Matrix

$$B = \begin{Bmatrix} 0.1 & 0.3 & 0.6 \\ 0.5 & 0.5 & 0 \\ 0.7 & 0.2 & 0.1 \end{Bmatrix}$$

States Matrix

$$T = \begin{Bmatrix} 5 \\ 3 \\ 1 \end{Bmatrix}$$

The following matrices capture the first step computation

The inverse of the Emission Matrix

$$B^{-1} = \begin{Bmatrix} -0.2331 & 0.1856 & 1.0475 \\ 0.9731 & 0.3544 & -0.3275 \\ 0.5856 & 0.2919 & 0.1225 \end{Bmatrix} \qquad B^{-1}A = \begin{Bmatrix} 1.1438 & 0.3313 & -0.475 \\ -0.5438 & 0.2688 & 1.275 \\ 0.0813 & 0.1438 & 0.775 \end{Bmatrix}$$

Then next

$$B^{-1}AB = \begin{Bmatrix} -0.0525 & 0.4138 & 0.6388 \\ 0.9725 & 0.2263 & -0.1988 \\ 0.6225 & 0.2513 & 0.1263 \end{Bmatrix} \qquad A_{1j}B^{-1}AB = \{0.6925 \quad 0.2463 \quad 0.0613\}$$

$$A_{1j}B^{-1}ABT = 4.2625$$

The first step when $n = 1$ is represented as $A^n = A$. The weight for the project governance requirement after step 1 is, therefore 4.2625. Proceeding steps raise the matrix A to corresponding value $1,2, \dots, n$. The second step computation computes for $A^2 = AxA$ and the results are as follows:

The inverse of the Emission Matrix

$$B^{-1}A^2 = \begin{Bmatrix} -0.2331 & 0.1856 & 1.0475 \\ 0.9731 & 0.3544 & -0.3275 \\ 0.5856 & 0.2919 & 0.1225 \end{Bmatrix} \qquad B^{-1}A^2B = \begin{Bmatrix} 0.8028 & 0.2324 & -0.0351 \\ 0.0453 & 0.4036 & 0.5511 \\ 0.2903 & 0.3461 & 0.3636 \end{Bmatrix}$$

Then next

$$A_{1j}B^{-1}A^2B = \{0.2413 \quad 0.3576 \quad 0.4011\} \qquad A_{1j}B^{-1}A^2BT = 2.6803$$

After the second step, the requirement for project governess is 2.6803. Further steps for the governance requirements are detailed below.

$$A_{1j}B^{-1}A^3BT = 3.9023 \qquad A_{1j}B^{-1}A^4BT = 2.9836$$

$A_{1j}B^{-1}A^5BT = 3.6756$ $A_{1j}B^{-1}A^6BT = 3.1544$

$A_{1j}B^{-1}A^7BT = 3.5469$ $A_{1j}B^{-1}A^8BT = 3.2513$

The detailed evaluations for all requirements are summarised in Table 34

Table 34 Summary of eight Step High Order Requirements Hidden Markov Model Analysis

	Economic	Social	Health and Safety	Technical	Maintainability	Family	Geopolitical	Environment	Governance
Initial	2.9547	3.3714	2.7800	3.3800	2.9200	3.4560	2.3867	3.3040	4.2625
Step 1	2.8355	2.9600	2.4180	3.1920	3.0520	3.2584	2.9493	3.4696	2.6803
Step 2	2.8519	2.9909	2.5614	3.1168	3.0652	3.1287	2.8808	3.4847	3.9023
Step 3	2.8440	2.9744	2.4967	3.0867	3.0665	3.0397	2.8989	3.4858	2.9836
Step 4	2.8446	2.9756	2.5247	3.0747	3.0667	2.9777	2.8957	3.4858	3.6756
Step 5	2.8440	2.9750	2.5124	3.0699	3.0667	2.9344	2.8964	3.4857	3.1544
Step 6	2.8440	2.9750	2.5178	3.0680	3.0667	2.9040	2.8963	3.4857	3.5469
Step 7	2.8439	2.9750	2.5154	3.0672	3.0667	2.8828	2.8963	3.4857	3.2513

When the emission matrix is raised to high power, all results tend to uniform. The results are computed in the HoQ matrix to yield a seven-step weighting using the DQFD analysis summarised in *Figure 6-21*. The Figure/Table also captures the maximum change in requirements for each category based on the range.

Cost of Construction	Costs (Rent/Mortgage)	Monetary Value	Comfort	Integrated Design	Views	Demographics	Safety	Acoustics	Flow of Spaces	Hygiene	Security	Constructability	Compliance	Design Form/Aesthetics	Functional Space	Specification	Accessibility	Site Planning	Maintenance Costs	Size	Income	Status/Aspiration	Political Leadership	Legislation/Compliance	Energy Use/Costs	Solar Gain/Loss	Materials Use	Adaptability	Project Governance
9	9	9	7	4	8	7	5	5	5	6	7	7	7	8	7	8	5	8	8	7	8	9	6	4	7	2	9	2	7
5	5	7	6	6	7	7	7	6	6	6	7	2	4	8	6	1	6	6	5	7	6	9	7	8	5	2	8	6	6
0	3	6	1	6	7	7	9	4	6	8	6	6	8	5	6	7	6	6	8	5	0	0	2	8	8	6	8	4	2
7	9	7	9	9	8	9	8	9	9	8	8	9	8	9	9	9	8	9	7	2	0	8	0	8	9	9	9	9	8
7	7	7	6	5	5	5	5	1	6	6	1	7	5	8	6	7	4	6	9	2	6	2	0	6	7	2	8	0	1
7	7	2	8	4	5	1	7	7	6	7	6	1	7	8	9	6	6	7	5	9	8	8	4	6	8	2	8	7	6
7	6	7	0	8	1	4	7	1	5	5	9	2	9	4	5	6	6	6	5	6	8	7	9	9	9	2	7	6	8
7	6	6	9	7	9	1	7	7	7	7	6	7	7	8	7	7	8	8	7	6	6	8	7	8	9	9	9	5	4
5	2	2	0	4	1	0	2	1	1	1	1	4	8	7	4	4	1	2	1	0	0	0	0	2	0	0	4	5	9
172.89	169.51	162.94	149.02	166.84	162.00	125.07	177.59	133.43	159.68	168.27	157.23	143.37	200.95	211.75	188.75	172.56	156.15	181.96	169.28	136.03	127.95	160.60	105.32	182.76	189.50	107.01	220.72	144.02	167.84
	0.1037				0.1238				0.1635					0.1883				0.1042			0.0872			0.0591			0.1358		0.0345
165.17	164.35	157.80	144.36	159.23	154.27	120.01	170.56	126.11	154.75	162.49	153.26	134.53	186.91	195.98	178.24	164.92	151.87	175.61	164.65	132.99	129.24	158.27	106.43	177.43	187.92	104.57	210.35	133.08	152.18
	0.1042				0.1235				0.1640					0.1840				0.1052			0.0899			0.0607			0.1360		0.0325
159.26	163.81	158.48	147.21	155.96	156.73	124.25	170.87	127.64	156.49	164.47	154.78	132.01	176.80	187.46	174.58	161.60	153.61	175.54	167.01	136.32	132.04	160.63	109.91	177.63	191.14	108.52	207.12	127.46	139.69
	0.1034				0.1254				0.1662					0.1787				0.1065			0.0921			0.0617			0.1361		0.0300
157.50	161.77	156.74	145.10	154.05	154.53	122.42	168.49	125.46	154.34	162.13	152.70	130.30	174.56	185.13	172.15	159.47	151.51	173.30	164.88	134.17	130.40	158.67	108.51	175.44	188.76	106.76	204.64	125.39	137.86
	0.1035				0.1253				0.1660					0.1787				0.1065			0.0921			0.0618			0.1361		0.0300
167.36	163.68	159.06	141.56	161.56	154.02	119.47	170.57	124.73	153.72	161.51	152.07	138.02	192.65	200.41	179.37	166.89	150.89	175.29	164.40	130.74	126.91	155.09	105.32	177.54	185.38	103.71	211.97	135.34	158.53
	0.1045				0.1230				0.1627					0.1872				0.1047			0.0880			0.0603			0.1358		0.0338
164.41	155.94	151.51	141.15	146.57	150.00	119.29	162.76	120.65	149.66	157.39	148.02	123.16	162.81	174.22	164.15	151.79	146.84	167.51	160.37	130.27	126.56	154.70	105.12	169.79	184.89	103.51	196.78	116.56	125.13
	0.1065				0.1257				0.1666					0.1751				0.1071			0.0929			0.0620			0.1358		0.0282
166.15	162.82	158.56	140.89	160.65	153.41	119.28	169.68	123.99	153.04	160.76	151.40	137.33	191.00	198.82	178.08	165.82	150.22	174.41	163.79	130.02	126.32	154.44	105.01	176.73	184.67	103.46	210.75	134.09	156.86
	0.1046				0.1232				0.1628					0.1868				0.1048			0.0881			0.0604			0.1358		0.0336
164.52	162.06	157.91	140.71	159.36	152.99	119.23	168.91	123.53	152.60	160.29	150.96	136.10	188.46	196.56	176.69	164.49	149.78	173.64	163.37	129.81	126.15	154.26	104.92	175.99	184.48	103.40	209.37	132.45	154.06
	0.1045				0.1234				0.1631					0.1860				0.1050			0.0885			0.0606			0.1358		0.0332

Figure 6-21 Computing for Design requirements in relation to User requirements in the HOQ Relationship Matrix

Table 35 Analysis of Changes in Design requirements as a Result of Changing User requirements

Analysis Step	Economic	Social	Health and Safety	Technical	Maintainability	Family	Geopolitical	Environment	Governance
Initial	0.1037	0.1238	0.1635	0.1883	0.1042	0.0872	0.0591	0.1358	0.0345
Time 1	0.1042	0.1235	0.1640	0.1840	0.1052	0.0899	0.0607	0.1360	0.0325
Time 2	0.1034	0.1254	0.1662	0.1787	0.1065	0.0921	0.0617	0.1361	0.0300
Time 3	0.1035	0.1253	0.1660	0.1787	0.1065	0.0921	0.0618	0.1361	0.0300
Time 4	0.1045	0.1230	0.1627	0.1872	0.1047	0.0880	0.0603	0.1358	0.0338
Time 5	0.1065	0.1257	0.1666	0.1751	0.1071	0.0929	0.0620	0.1358	0.0282
Time 6	0.1046	0.1232	0.1628	0.1868	0.1048	0.0881	0.0604	0.1358	0.0336
Time 7	0.1045	0.1234	0.1631	0.1860	0.1050	0.0885	0.0606	0.1358	0.0332
Max % change	**3.02%**	**2.19%**	**2.44%**	**7.53%**	**2.84%**	**6.54%**	**4.89%**	**0.28%**	**22.03%**

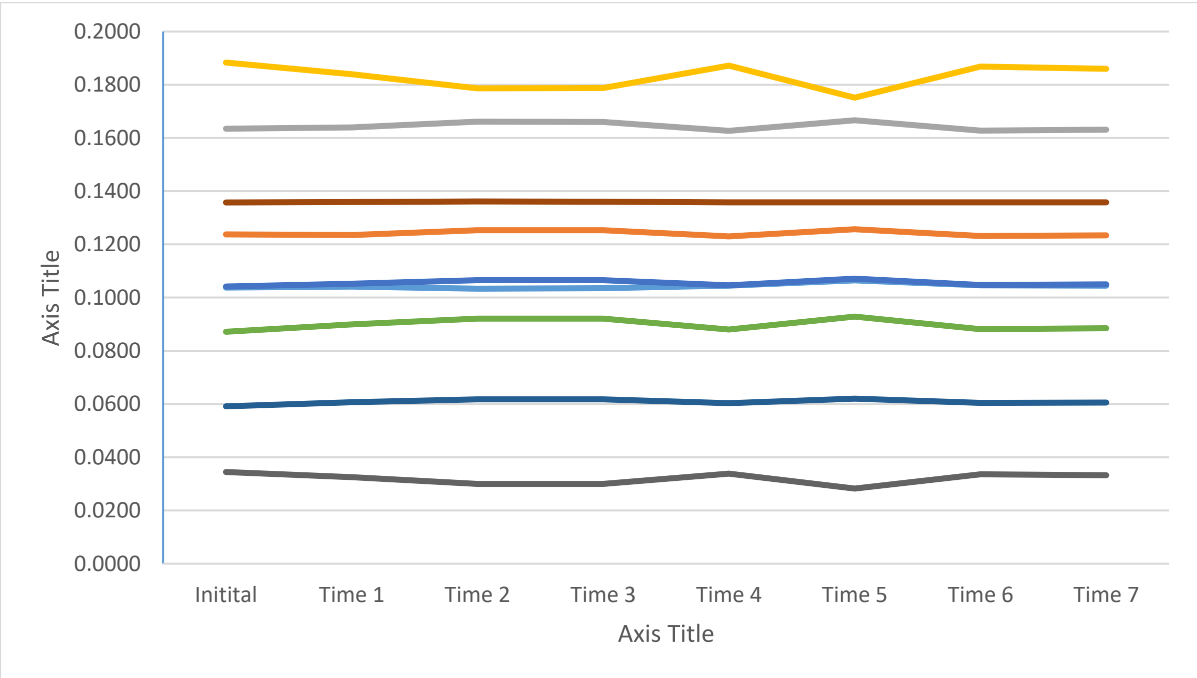

Figure 6-22 Time Step Analysis for MCMV - HMM

The first step is to compute for the high order requirements weighting using the HoQ matrix and progressively build on this through further time steps. The initial step for the *'economic'* performance requirement in the MCMV programme is 0.1037, at time step 1, 0.1042, time step 2 – 0.034, time step 3 – 0.135, time step 4 – 0.1045, time step 5 – 0.1065, time step 6 – 0.1046 and time step 7 – 0.1045 at which point the values stabilise through degeneracy. This process is repeated for all other high order requirements as summarised in Table 35 and illustrated in *Figure 6-22* depicts the trends in the requirements over seven time steps. *'Governance'* appears to change the most (22%) followed by *'Technical'*, *'Family'* and *'Geopolitical'* factors at 7.53%, 6.54% and 4.89% respectively. Decision making on this basis can monitor and revise design decisions dependent on how the values are represented. Moreover, when reality changes, the HoQ – matrix values can be changed alongside any changes in the transition matrices in

Table 33 to reflect new realities. This could be through new sources e.g. new customer surveys or updated expert and documentary evidence.

Critically, elements, patterns, interdependences, and boundary events that are important for a particular stage of the process can be identified to determine for example how far a particular stakeholder is allowed to be involved in a particular process in benefits delivery cycle.

6.3 Case Study Context TWO – U.K.

The case study context two aimed to validate the applicability of the full system in a real-world setting in a social housing project. Capturing the various dynamics of the context was valuable in establishing and refining the various parameters for interdependence analyses important for FED decision making, as well as applicability of the various model component to the overall modelling process. The U.K. case study context, therefore, aims to validate DESIDE to address the research objective four.

6.3.1 Key Factors Case Study Two

The case study context two is a retrofit of a former elderly residents accommodation first built in the 1960/70s and part of an extant social housing provision program by a major charity (SBC) in the West Midlands, U.K. for homeless young people aged 19-22. The social provision aims to provide accommodation facilities that give young people independence while providing them with readily available support at the point of need alongside a program of engagement to help them build the confidence and skills for their future careers. Therefore, design should reflect this support network in the accommodation provision. Regarding the property, there has been an evolving ownership over the years until its recent purchase by the new social landlord (under a social value rather than market value basis), SBC, a care support, and management social housing charity. The property is over two floors organised on three wings with a mix of some shared facilities and independent living accommodation. The property has been purchased through a mixture of funding mechanisms, including from local, central government and charitable funding sources. The planned retrofit by the contractor together with the property purchase is on a social value basis meaning the costs are below market values. The complex funding mechanisms place some conditions on the project e.g., in costs, target users and project lead times. Other project-specific performance requirements are energy performance and an immediate contribution to the community upon completion.

Key facts about the facility

- Comprised of 30 one-bedroom rented flats
- Mobility and wheelchair access
- Social Care services with management staff and Careline alarm service
- Shared facilities like Lift, Lounge, Dining room, Laundry, Garden
- Community access including to local transport routes, post office, social centre, and town centre
- Previously used as a residence for the elderly (over 60 years of age)
- Previously owned by the local council as a social housing facility

In this case study context, the overall aim is to apply, test and validate the full system in modelling the various facets of the decision support system including to utility assessments, uncertainty and high order requirements changes that impact on Benefits Realisation.

Ultimately this context is the basis of comparative evaluation and other validity testing of the decision support system.

Data from this case study again draws to specific parameters in user and design requirements that impact on desired benefits but within the specific constraints. The data is gathered through observations and direct interviews as well as questionnaires and documentary evidence to explore further or corroborate factors seen in section 3.2 and later analysis in and 7.3: Some of the factors are illustrated in the foregoing and summarised in *Table 36*.

Figure 6-23 The Main Access to the Facility (source: GOOGLE)

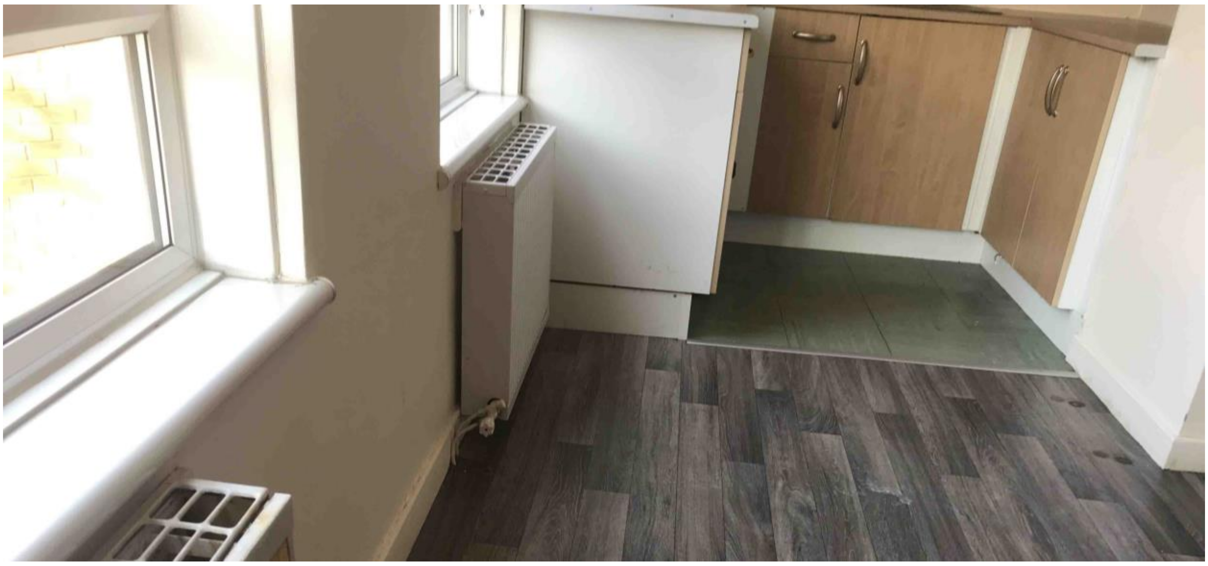

Figure 6-24 Kitchen-Diner Facility in a Typical Flat

Figure 6-25 Current Shared Electrical Installation

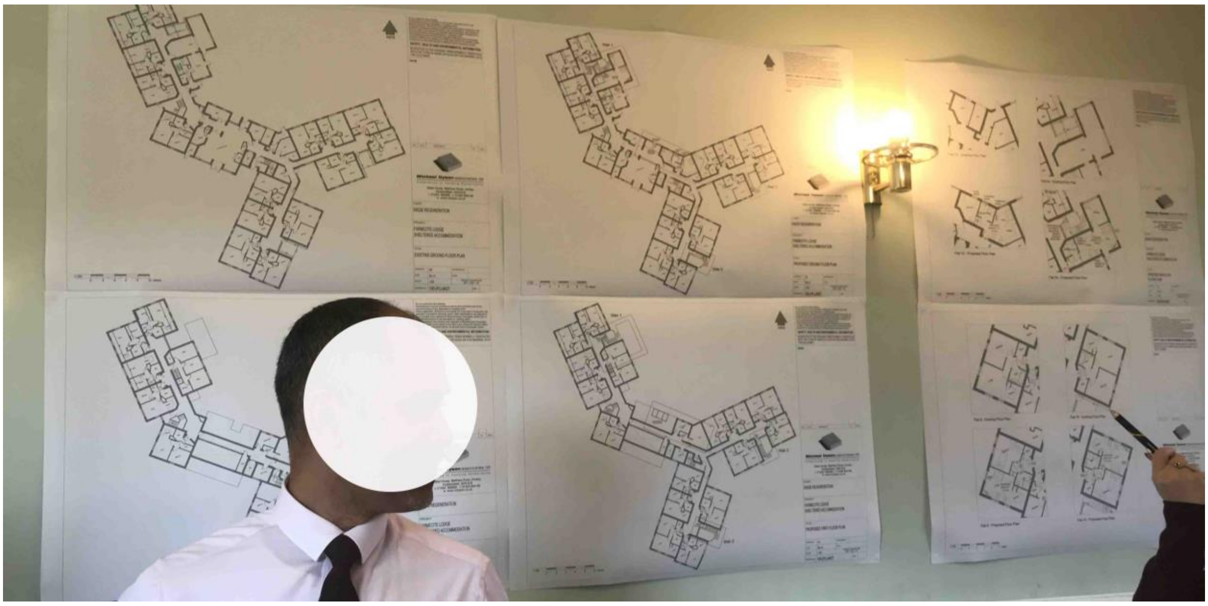

Figure 6-26 Project Meeting

Figure 6-27 Project Team Meeting

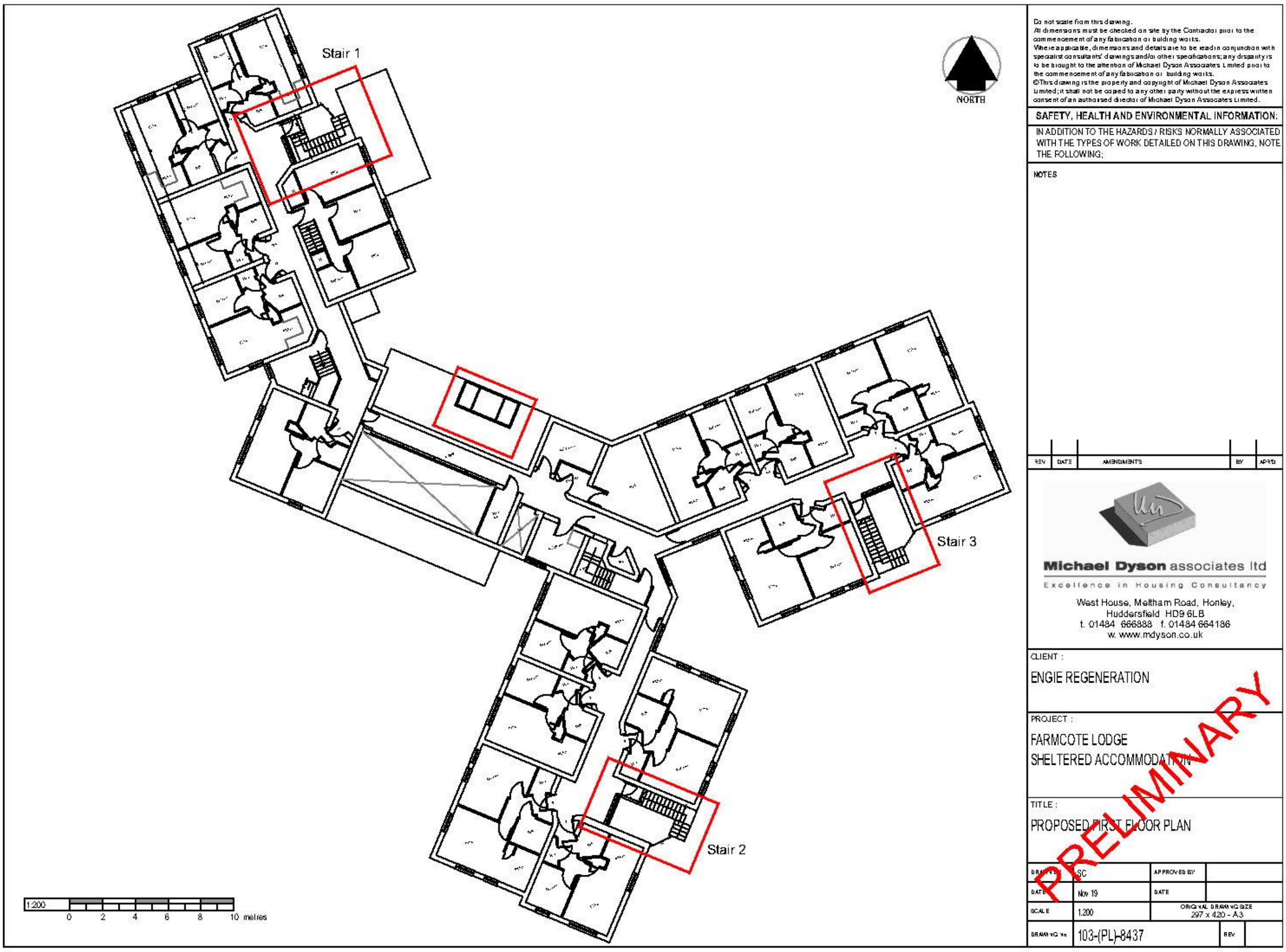

Figure 6-28 Floor Plan Showing Proposed Improvements

Table 36 Identification of Potential Modelling Parameters

Figure	Requirements Identified	Associated Potential Uncertainties
Figure 6-23	Technical, Environmental	The project presents some legacy constraints not least those relating to Space and functional performance. Uncertainties abound because of the constraints.
Figure 6-24	Technical, Environmental, Lifecycle Performance, Health and Safety	The accommodation provision should foster independent living requiring provision of functional space, adaptability to frequently changing use, energy performance and `flow that fosters these requirements
Figure 6-25	Technical, Lifecycle Performance,	Constructability is a key element for the proposed redevelopment in fulfilling the lead times constraints from major stakeholders. Alongside this, the design should ensure integration of spaces for training and care support as well as energy performance for both the individual accommodation units and the overall development.
Figure 6-26	Project Governance, Technical	Understanding the technical aspects of the design is important in ensuring the requirements as constructability, legal and compliance, functional design, and the optimal specification withing the constraints are integrated into design decision making collaboratively.
Figure 6-27	Technical, Project Governance	Stakeholder management is a key element in the delivery of the proposed changes including organising funding, design, construction, care support, training, and coordination of potential residents,
Figure 6-28	Technical, Health and Safety, Lifecycle Performance, Occupancy	The proposed redevelopment should conform to the project objectives of accommodation provision and occupancy that embodies the ideals of the sponsoring stakeholders and the needs of the end-users. Mobility, wellbeing, training, education safety and security, as well as accessibility, are among the key desired benefits that design decision making should foster.

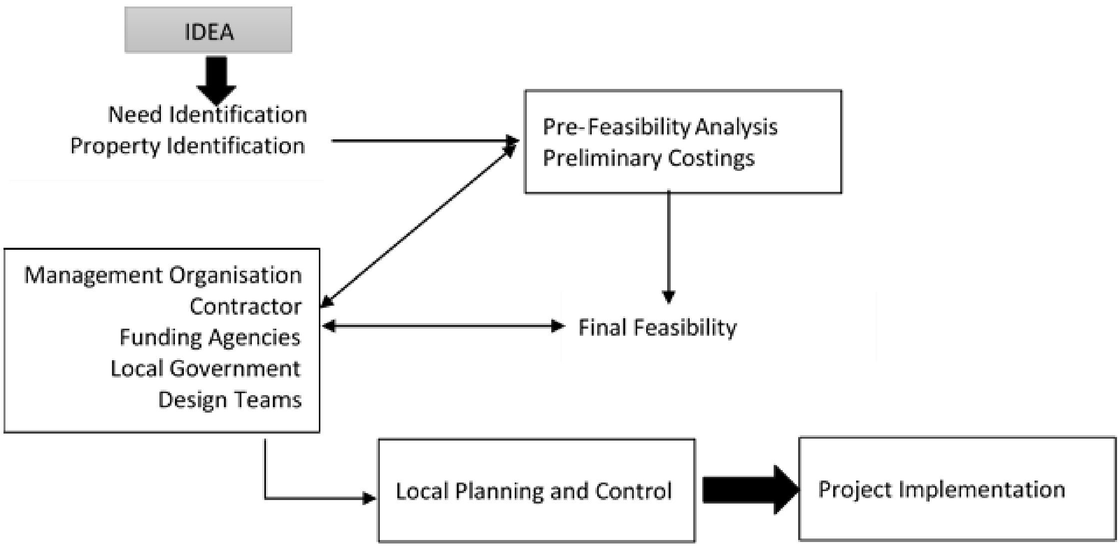

Figure 6-29 Process of Design Case study two

6.3.2 Requirements Forecasting

Using the steps adopted in section 6.2.7 transition and emission matrices for the case study are summarised in Table 37. The analysis aims to assess how the economic, sociocultural, health and safety, technical, Lifecycle performance, occupancy, geopolitics environment and governance factors could change over time to impact on the use of the proposed facility. The extant QFD analysis is shown in *Table 91* Appendix E.

Table 37 Expert and Documentary assigned transition and Emission Probabilities

		Transition (F)			Emission (V)		
		Bad	Average	Good	Bad	Average	Good
Economic	Good	0.4	0.2	0.4	0.3	0.2	0.5
	Average	0.4	0.5	0.1	0.4	0.5	0.1
	Bad	0.3	0.3	0.4	0.5	0.3	0.2
Sociocultural	Good	0.6	0	0.4	0.5	0.1	0.4
	Average	0.3	0.4	0.3	0.3	0.6	0.1
	Bad	0.3	0.4	0.3	0.1	0	0.9
Health and Safety	Good	0.7	0.2	0.1	0	0.1	0.9
	Average	0.4	0.4	0.2	0.3	0.5	0.2
	Bad	0.2	0.3	0.5	0.2	0.4	0.4
Technical	Good	0.7	0.2	0.1	0.3	0.1	0.6
	Average	0.5	0.4	0.1	0.4	0.5	0.1
	Bad	0.1	0.3	0.6	0.1	0.1	0.8
Lifecycle Performance	Good	0.4	0.4	0.2	0.4	0.2	0.4
	Average	0.5	0.4	0.1	0.5	0.4	0.1
	Bad	0.1	0.4	0.5	0.3	0.6	0.1
Occupancy	Good	0.7	0.3	0	0.3	0.1	0.6
	Average	0.4	0.6	0	0.4	0.5	0.1
	Bad	0.1	0.2	0.7	0.5	0.1	0.4
Geopolitical	Good	0.6	0.2	0.2	0.2	0.4	0.4
	Average	0.5	0.3	0.2	0.4	0.5	0.1
	Bad	0.1	0.4	0.5	0.6	0.4	0
Environment	Good	0.7	0.1	0.2	0.2	0.2	0.6
	Average	0.3	0.5	0.2	0.4	0.5	0.1
	Bad	0.1	0.2	0.7	0.1	0.7	0.2
Governance	Good	0.5	0.2	0.3	0.4	0.3	0.3
	Average	0.3	0.3	0.4	0.5	0.4	0.1
	Bad	0.4	0.3	0.3	0.7	0.2	0.1

The first step, as seen in 6.2.7, is to compute for the high order requirements weights using the HoQ matrix and progressively build on this through further time steps. Similarly, following the steps outlined in section 6.2.7, Table 38 summarises the initial high order requirements change analysis for the case study; while Table 39 is the normalised computation. Again using equations (19) to (31) the modelling process assesses the probabilities and computes them to determine the changes in ratings from HMM (see Table 37). Using the HoQ matrix, their impact on the 'HOWs' following interdependence analysis is derived.

Table 38 Summary of eight Steps User Requirements Hidden Markov Model Analysis

	Economic	Sociocultural	Health & Safety	Technical	Lifecycle Performance	Occupancy	Geopolitical	Environment	Governance
Initial	3.2600	2.3855	5.9667	3.1450	3.4267	3.7100	4.2800	2.9185	3.5700
Step 1	3.2460	2.5556	4.2900	2.8095	3.4160	3.3980	3.7040	2.6566	3.6670
Step 2	3.2340	2.6067	3.1603	2.6802	3.4128	3.2309	3.4592	2.6373	3.6784
Step 3	3.2308	2.6220	2.5999	2.6232	3.4118	3.1293	3.3786	2.6722	3.6805
Step 4	3.2302	2.6266	2.3427	2.5962	3.4116	3.0628	3.3536	2.7075	3.6808
Step 5	3.2301	2.6280	2.2276	2.5830	3.4115	3.0177	3.3461	2.7323	3.6809
Step 6	3.2301	2.6284	2.1766	2.5765	3.4114	2.9865	3.3438	2.7476	3.6809
Step 7	3.2301	2.6285	2.1540	2.5732	3.4114	2.9648	3.3431	2.7564	3.6809

Table 39 Normalised Changes in Design requirements as a Result of Changing User requirements

Analysis Step	C1	C2	C3	C4	C5	C6	C7	C8	C9
Initial	0.0782	0.1085	0.1445	0.2416	0.0880	0.0698	0.0495	0.1511	0.0687
Time 1	0.0802	0.1089	0.1407	0.2431	0.0866	0.0712	0.0489	0.1493	0.0710
Time 2	0.0801	0.1124	0.1437	0.2333	0.0876	0.0767	0.0509	0.1510	0.0644
Time 3	0.0809	0.1127	0.1422	0.2333	0.0871	0.0774	0.0509	0.1505	0.0650
Time 4	0.0829	0.1097	0.1356	0.2443	0.0848	0.0732	0.0485	0.1473	0.0737
Time 5	0.0849	0.1138	0.1431	0.2282	0.0873	0.0791	0.0515	0.1510	0.0611
Time 6	0.0833	0.1097	0.1351	0.2444	0.0847	0.0732	0.0486	0.1471	0.0740
Time 7	0.0833	0.1097	0.1350	0.2444	0.0846	0.0732	0.0486	0.1471	0.0741
Max % change	**8.49%**	**4.91%**	**7.06%**	**7.10%**	**3.91%**	**13.25%**	**6.05%**	**2.78%**	**21.20%**

In the initial step for the *'economic'* performance attribute, the weighting is 0.0992, then, 0.0924 at time step 1, 0.0858, at time step 2, 0.0835, at time step 3, 0.0841, at time step 4, 0.0856, at time step 5, 0.0836, at time step 6 and 0.0835 at time step 7. After this point, the values again stabilise through degeneracy. The derived values from the repeat process for other high order requirements are summarised in Table 39 and illustrated in Figure 6-30 for the trends in the requirements. The results in Table 39 indicate a significant potential change in the *'governance'* factor of the project (21.2%) while also indicating that changes in the *'occupancy'* factor (13.25%) are significant. Other factors like *'Lifecycle'* and *'environmental'* performance are relatively nuanced at 3.91% and 2.78% respectively. *'Economic'* (8.5%) and *'health and safety'* (7%) also present some notable changes over time.

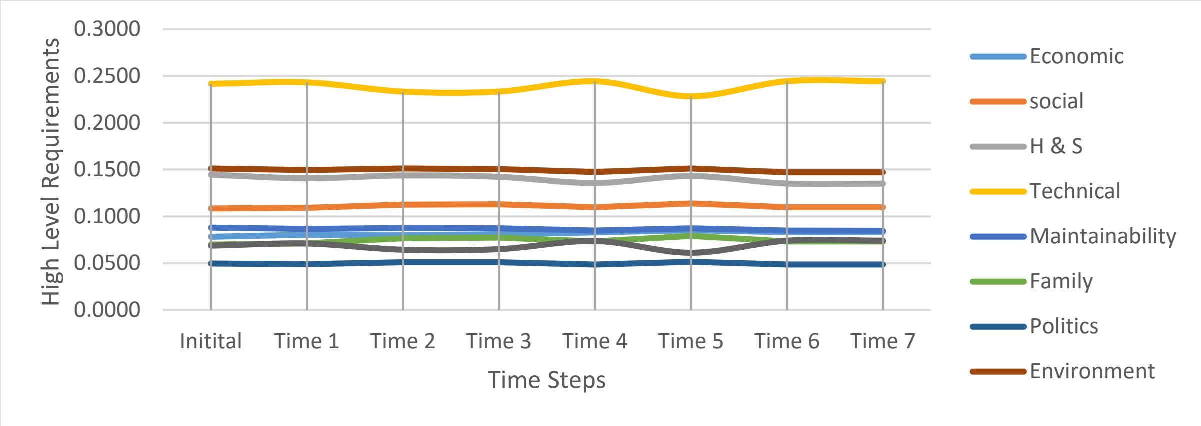

Figure 6-30 Graphical Illustration of changes in high order requirements in a U.K. social housing.

6.3.3 Utility Assessment of Requirements

The process for utility ranking and analysis follows the steps outlined in section 6.2.4 and the data analysis following the structure for section 6.2.5. The stakeholder requirements adopted for direct utility assessments and derived design requirements (see section 3.2 and 7.3) are summarised in Table 40. The User Requirements/benefits elicited can be summarised as Accommodation (AC), Cost (C), Comfort (Ct), Safety (S), Security (SY), Hygienic (Hy), Training and Education (TE) and Employment (E). Through a series of interviews with several key stakeholders, the corresponding eight key utilities/benefits derived include Mobility (MT), Accommodation (AC), Work (WK), Education (ED), Financial Stability (FS), Welfare (WF), Community (CO) and Wellbeing (WB).

Table 40 Elicited User and Design Requirements and Utility Assessments

Design Requirements	**User Requirements**		**Utility Assessments**		**Rating**
F1 (d), **F2** (d), **F3** (i), **F4** (i), **F5** (i), **F6** (i), **F7** (i), **F8** (i), **F9** (i), **F10** (i), **F11** (i), **F12** (i), **F13** (i), **F14** (i), **F15** (i), **F16** (i), **F17** (i), **F18** (i), **F19** (d), **F20** (i), **F21** (i), **F22** (i), **F23** (i), **F24** (i), **F25** (i), **F26** (i), **F27** (d), **F28** (d), **F29** (i), **F30** (d), **F31** (d), **F32** (d), **F33** (i), **F34** (i), **F35** (i), **F36** (i), **Key: d – decrease, i- increase**	Accommodation	AC	Mobility	MO	High
	Comfort	Ct	Accommodation	AC	High
	Costs	C	Work	WK	High
	Safety	S	Education and Training	ED	High
	Security	SY	Financial Stability	FS	High
	Hygienic	Hy	Welfare	WF	high
	Training & Edu	TE	Community	CO	Low
	Employment	E	Wellbeing	WB	High

The full requirement factors analysed in this research (see section 7.3.1), are adopted for analysis. Following the Yan and Ma (2015) and Kwong et al. (2011) normalisation approach using Eq. (34) the results in

Table 43 reveal a influences in the order: *'Mobility'* (0.1925), *'Financial Status'* (0.1666), *'Education'* (0.1575), *'Work'* (0.1486), *'Community'* (0.1354), *'Accommodation'* (0.1348), *'Welfare'* (0.1131) and lastly *'Wellbeing'* (0.0907) in terms of expected benefits.

Table 41 The initial direct-relation matrix (A) for User Requirements

	MT	AC	WK	ED	FS	WF	CO	WB	
MT	0	3	4	4	5	3	4	2	25
AC	7	0	5	5	7	5	8	5	42
WK	5	4	0	5	4	3	3	2	26
ED	6	4	4	0	5	3	4	3	29
FS	5	4	6	5	0	3	3	2	28
WF	7	4	5	5	6	0	4	2	33
CO	5	4	3	5	5	3	0	4	29
WB	8	7	6	6	5	5	4	0	41
	43	30	33	35	37	25	30	20	
	253	253	253	253	253	253	253	253	253

Table 42 Normalised direct-relation matrix (A) for User Requirements

URs	MT	AC	WK	ED	FS	WF	CO	WB	
MT	0.0000	0.0119	0.0158	0.0158	0.0198	0.0119	0.0158	0.0079	0.0988
AC	0.0277	0.0000	0.0198	0.0198	0.0277	0.0198	0.0316	0.0198	0.1660
WK	0.0198	0.0158	0.0000	0.0198	0.0158	0.0119	0.0119	0.0079	0.1028
ED	0.0237	0.0158	0.0158	0.0000	0.0198	0.0119	0.0158	0.0119	0.1146
FS	0.0198	0.0158	0.0237	0.0198	0.0000	0.0119	0.0119	0.0079	0.1107
WF	0.0277	0.0158	0.0198	0.0198	0.0237	0.0000	0.0158	0.0079	0.1304
CO	0.0198	0.0158	0.0119	0.0198	0.0198	0.0119	0.0000	0.0158	0.1146
WB	0.0316	0.0277	0.0237	0.0237	0.0198	0.0198	0.0158	0.0000	0.1621
	0.1700	0.1186	0.1304	0.1383	0.1462	0.0988	0.1186	0.0791	1.0000

Table 42 supports the computation for the $D_k + R_j$ vs $D_k - R_j$, i.e. the cause-effect relationships, is shown in

Table 43. The Total influence Matrix for User benefits computed using Eq. (36). The $D_k + R_j$ vs $D_k - R_j$, are summarised in Table 44 and graphically represented in Figure 6-31.

Table 43 The total Weighted Relation Matrix of User Requirements

	MT	AC	WK	ED	FS	WF	CO	WB
MT	0.0026	0.0136	0.0176	0.0177	0.0217	0.0133	0.0174	0.0091
AC	0.0314	0.0031	0.0228	0.0230	0.0308	0.0220	0.0339	0.0215
WK	0.0221	0.0174	0.0021	0.0216	0.0180	0.0133	0.0137	0.0092
ED	0.0262	0.0176	0.0179	0.0025	0.0221	0.0135	0.0177	0.0132
FS	0.0223	0.0175	0.0255	0.0218	0.0025	0.0135	0.0138	0.0092
WF	0.0304	0.0179	0.0221	0.0222	0.0262	0.0020	0.0179	0.0094
CO	0.0225	0.0177	0.0142	0.0219	0.0221	0.0136	0.0022	0.0170
WB	0.0351	0.0300	0.0265	0.0267	0.0232	0.0220	0.0187	0.0021
	0.1925	**0.1348**	**0.1486**	**0.1575**	**0.1666**	**0.1131**	**0.1354**	**0.0907**

Further analysis reveals AC, WF and WB as the causes for the driving the new designs while MT, WK, ED, FS and CO are the effects (see Table 44 and Figure 6-31).

Table 44 Cause-Effect Analysis for Housing User Requirements

	Dk	Rk	Dk+Rk	Dk-Rk		Weights (Dk+Rk)
MT	0.1129	0.1925	0.3053	-0.0796	Effect	0.1340
AC	0.1885	0.1348	0.3233	0.0537	Cause	0.1419
WK	0.1175	0.1486	0.2661	-0.0312	Effect	0.1168
ED	0.1307	0.1575	0.2883	-0.0268	Effect	0.1265
FS	0.1262	0.1666	0.2927	-0.0404	Effect	0.1285
WF	0.1480	0.1131	0.2611	0.0349	Cause	0.1146
CO	0.1312	0.1354	0.2665	-0.0042	Effect	0.1170
WB	0.1843	0.0907	0.2750	0.0936	Cause	0.1207

The process then proceeds to analyse the transformation of the user and design requirements using expert input and elicitation an important step in the DQFD across the full thirty-six design requirements spectrum representing the 'WHATs' against the user requirements the 'HOWs' (see *Table 92*, Appendix F). This is as outlined previously in section 5.3.1. Yan and Ma (2015) observe that any trade-offs in the decision making at this point form a basis of the direct interpretation of the user requirements preferences. The results in Appendix F, *Table 93* inform the preceding MOORA and COPRAS analyses for the utilitarian assessment of design requirements through normalisation and weighting.

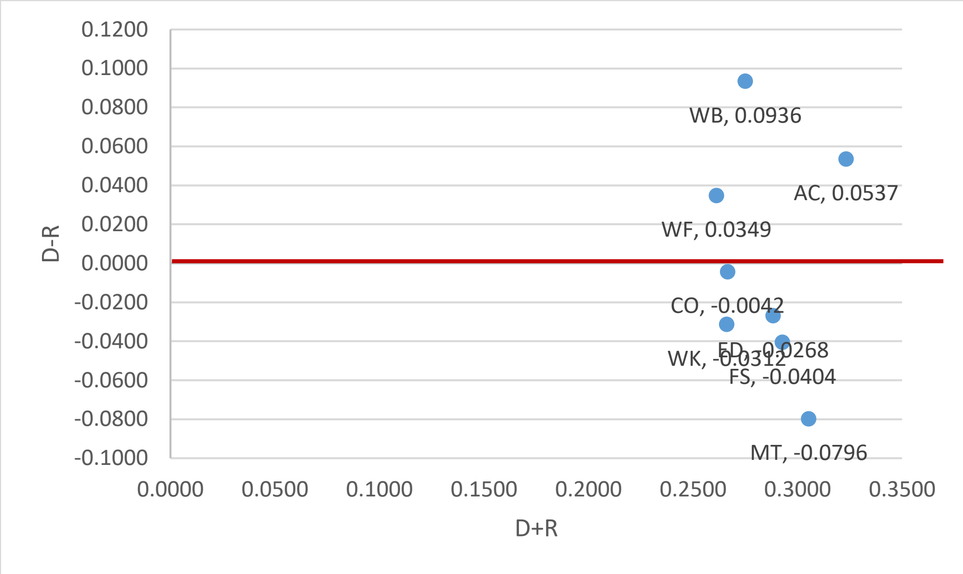

Figure 6-31 Illustration of the Cause-Effect Analysis

Table 94, *Table 95* and *Table 96* (Appendix F) represent the comparative modelling analysis for MOORA and COPRAS assessments, including a summary of the normalised and weighted normalised computations using equations in sections 5.4.2 and 5.4.3. Weighting is for both the user and design requirements categories to elucidate more understanding among the various interdependences. Influences by the benefits are summarised in Table 44 and Figure 6-31 for the $\boldsymbol{S_j^+}$ and $\boldsymbol{S_j^-}$ for the MOORA and thereafter for the corresponding COPRAS analysis (see *Figure 6-32* and *Figure 6-33*). The results reveal consistency in the dominating the role of F24 (*Occupancy level and patterns*) This pattern is followed by F33 (*Adaptability*) and F25 (*Financial Status*) with 96%/71% and 94%/62% for MOORA and COPRAS analyses respectively. This consistency is seen in most of the other factors like F4, F7, F18 and others. This consistency in both analyses keeps in step at the category/high order requirements level i.e. C4 – '*technical'* followed by C8 – '*Environmental'*, C6 – '*Occupancy'*, C3 – '*Health and Safety*', C2 – '*Sociocultural'*, C9 – '*Governance'*, C1 – '*Economics'* and finally C7- '*Geopolitics*'.

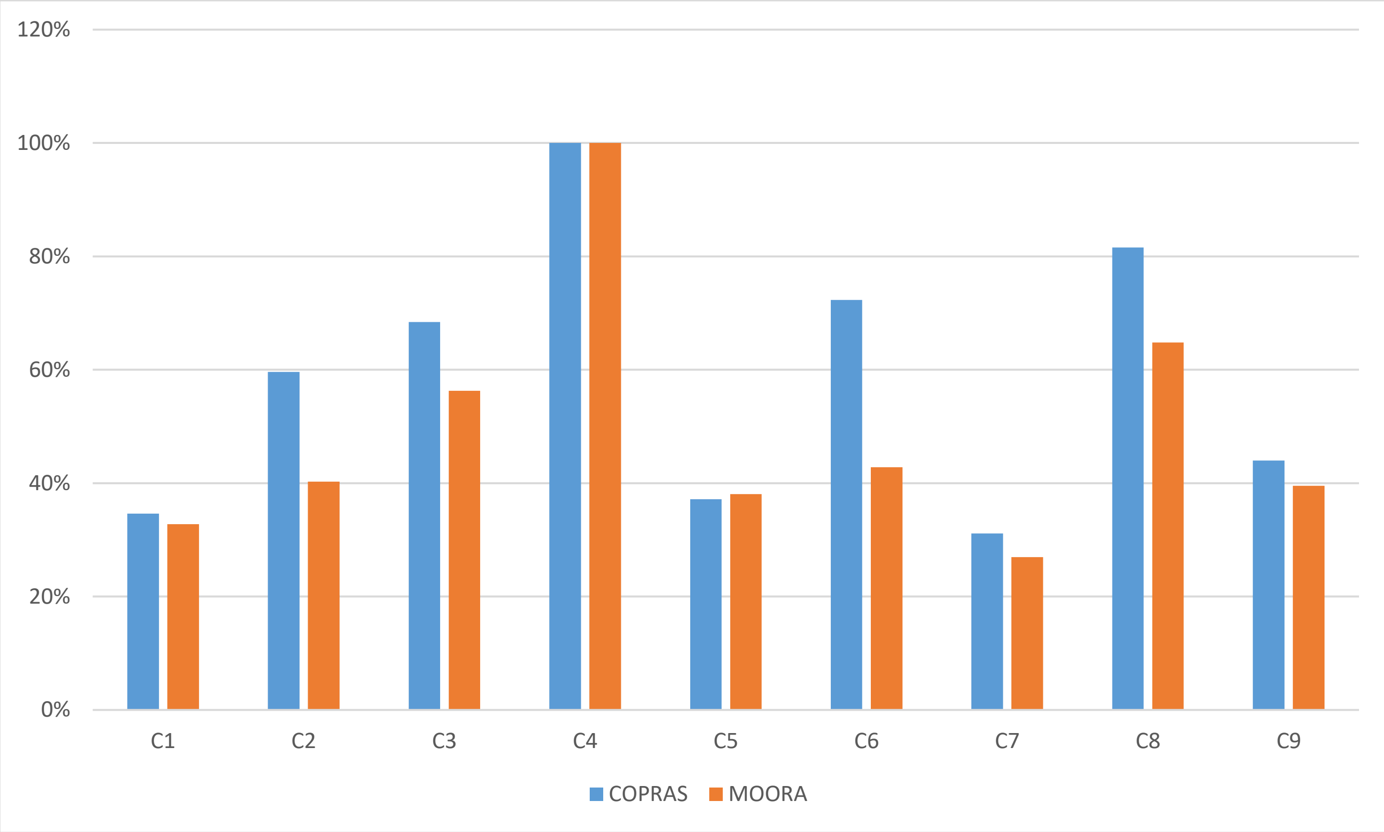

Figure 6-32 COPRAS and MOORA User Requirements Categorisations Comparative Modelling Results

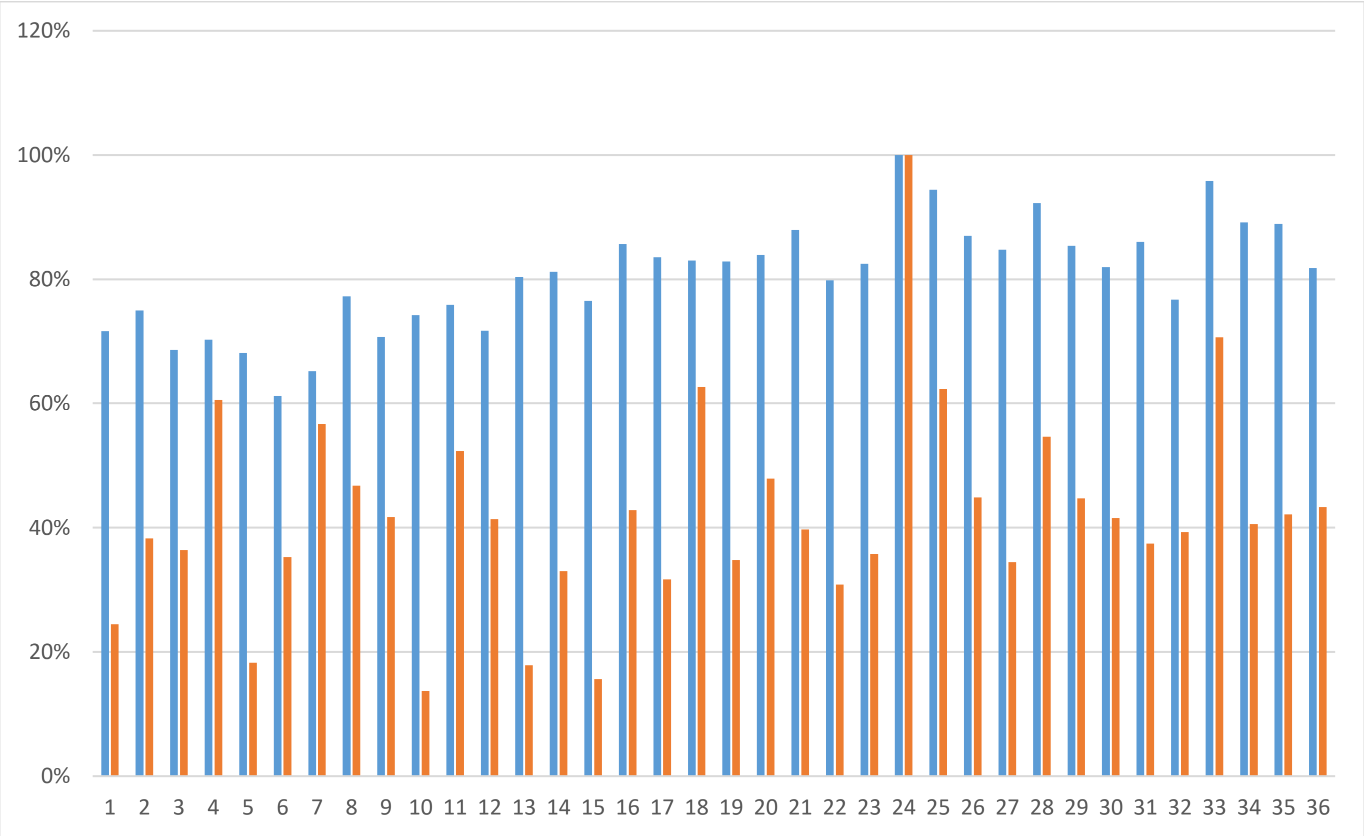

Figure 6-33 COPRAS and MOORA Design Requirements Comparative Modelling Results

While this pattern appears to hold for most of the design requirements, there appears to be some diversions in the MOORA and COPRAS analyses for some requirements like F2 - 69%/36%, F3 – 69%/36%, F5 – 68%/18%, F10 - 74%/18%, and F13 – 80%/18% among others for both analyses respectively.

6.3.4 Uncertainty Modelling

In modelling for uncertainty in Case study context two, decision making setting equations 49-58 seen in section 5.5 are employed. Similar to the process set out in section 6.2.5, the modelling process assesses the bpa of the focal elements set across the user and design requirements spaces summarised earlier in Table 40. Similarly, the results feeding onto this model component are from the MOORA and COPRAS utilitarian analysis in Table 41 and *Table 92*. The pairwise comparisons for the user and design requirements elicited as stated preferences from decision-makers help in the transformation of qualitative to quantitative data.

The belief and plausibility structure of the user benefits based on the expert and end-user assessments are based on a DQFD user requirements interdependences analysed using COPRAS in

Table 43 that summaries the normalised user requirements. The corresponding weighting for the requirements is summarised in

Table 45. This table again forms the basis for DS-ANP weightings as set out earlier in *Table 46* for the elicited bpa information for the DS-ANP analysis. Again a $7w$ weighting for the *'wellbeing'* user benefit/requirement criterion indicates that it is extremely favoured for the *'mobility'* benefit overall. Similarly, a weighting $3\boldsymbol{w}$ for the *'community'* benefit means that it is moderately preferred for the *'Work opportunity'* project benefit. The FOD awarded a scaling 1 following on from the Beynon et al. (2001) allows for the weighting of the various criteria against the alternatives, using DS-T definition 2. By applying the Dempster rule of combination in Equation (53), data is progressively fused from one criterion to the next i.e. $[m_{j_1} \oplus m_{j_2}](E)$. First, the '*Mobility'* and '*Accommodation'* criteria and the results fused with the '*Work'*, '*Education'*, '*Financial Status*', '*Welfare'*, '*Community'* and '*Wellbeing'* criteria, progressively. The initial and normalised fused matrices for the user requirements are

summarised in *Table 47* and *Table 48*, respectively. All proceeding levels of fusion for all the user requirements/benefits are summarised in *Table 48* and *Table 49* and subsequent stages in *Table 97* to *Table 101*

Table 45 Translated Total Weighted Relation Matrix of User Requirements

Annotation		MT	AC	WK	ED	FS	WF	CO	WB
A	MT	7%	45%	66%	66%	70%	60%	51%	42%
B	AC	89%	10%	86%	86%	100%	100%	100%	100%
C	WK	63%	58%	8%	81%	58%	61%	41%	43%
D	ED	75%	59%	68%	9%	72%	62%	52%	61%
E	FS	64%	58%	96%	82%	8%	61%	41%	43%
F	WF	87%	59%	83%	83%	85%	9%	53%	44%
G	CO	64%	59%	53%	82%	72%	62%	6%	79%
H	WB	100%	100%	100%	100%	75%	100%	55%	10%

Table 46 Preference for user requirements focal elements decision alternatives

MT	AC	WK	ED	FS	WF	CO	WB
H- 7w	H - 7w	EH- 7w	H 7w	B- 7w	B- 7w	B- - 7w	B- 7w
BF- 6w	CDEFG - 3w	BF- 6w	BCFG - 6w	F- 6w	ACDEG - 3w	ADFG - 3w	G- 5w
D- 5w	A - 2w	AD- 4w	A- 4w	ADGH- 5w	Θ - 1w	CE- 2w	D- 4 w
CEG-- 4w	Θ - 1w	G- 3w	Θ - 1w	B- 3w		Θ - 1w	ACEF- 2w
Θ - 1w		Θ - 1 w		Θ - 1w			Θ - 1w

Table 47 User Requirements Initial Fused Matrix

	MT		AC		WK		ED		FS		WF		CO		WB
	0.1340		**0.1419**		**0.1168**		**0.1265**		**0.1285**		**0.1146**		**0.1170**		**0.1207**
H	0.9381	H	0.9932	EH	0.8176	H	0.8856	B	0.8994	B	0.8023	B	0.8189	B	0.8448
BF	0.8041	CDEFG	0.4257	BF	0.7008	BCFG	0.7591	F	0.7709	ACDEG	0.3438	ADFH	0.3510	G	0.6034
D	0.6701	A	0.2838	AD	0.4672	A	0.5061	ADGH	0.6424	Θ	0.1146	CE	0.2340	D	0.4827
CEG	0.5361	Θ	0.1419	G	0.3504	Θ	0.1265	C	0.3855		0.0000	O	0.1170	ACEF	0.2414
Θ	0.1340			Θ	0.1168			Θ	0.1285					Θ	0.1207
	3.0825		1.8445		2.4529		2.2774		2.8267		1.2608		1.5208		2.2930

Table 48 User Requirements Normalised Fused Matrix

	MT		AC		WK		ED		FS		WF		CO		WB
	3.0825		**1.8445**		**2.4529**		**2.2774**		**2.8267**		**1.2608**		**1.5208**		**2.2930**
H	0.3043	H	0.5385	EH	0.3333	H	0.3889	B	0.3182	B	0.6364	B	0.5385	B	0.3684
BF	0.2609	CDEFG	0.2308	BF	0.2857	BCFG	0.3333	F	0.2727	ACDEG	0.2727	ADFH	0.2308	G	0.2632
D	0.2174	A	0.1538	AD	0.1905	A	0.2222	ADGH	0.2273	Θ	0.0909	CE	0.1538	D	0.2105

CEG	0.1739	O	0.0769	G	0.1429	Θ	0.0556	C	0.1364	0	Θ	0.0769	ACEF	0.1053
Θ	0.0435			Θ	0.0476			Θ	0.0455				Θ	0.0526

Table 49 First Level Combination for the Mobility and Accommodation Criteria

	H		BF		D		CEG		O		
H	H	0.163881	{}	0.1405	{}	0.1171	{}	0.0936	H	0.023411	
CDEFG	{}	0.0702	F	0.060201	D	0.050167	CEG	0.040134	CDEF	0.010033	{} =
A	{}	0.0468	{}	0.0401	{}	0.0334	{}	0.0268	A	0.006689	0.5686
Θ	H	0.023411	BF	0.020067	D	0.016722	CEG	0.013378	Θ	0.003344	

The priority values of each benefits on the basis of uncertainty modelling of design requirements and Θ are as follows: ($\{A\} - 0.3089, \{B\} - 0.6880, \{C\} - 0.0110, \{D\} - 0.0020$, while those for each user requirements and Θ are: ($\{A\} - 0.0947, \{B\} - 0.4651$, $\{C\} - 0.0068$, $\{D\} - 0.02990, \{E\} - 0.0043$, $\{F\} - 0.1025, \{G\} - 0.0279$ $\{H\} - 0.2658$, $\{AD\} - 0.0002$, $\{BF\} - 0.0009$, $\{CE\} - 0.0004$, $\{\mathrm{CG}\} - 0.0011$, $\{\mathrm{CE}G\} - 0.0002, \{\Theta\} - 0.0127$). Definitions 3 and 4 are again the basis of the computations in *Table 50* for the belief intervals and also represented graphically in *Figure 6-34*.

Table 50 Ranking of Benefits Based on Belief and Plausibility

	Design Requirements				User Requirements		
	Belief	Plausibility	Uncertainty		Belief	Plausibility	Uncertainty
A	0.3089	0.3089	0	A	0.0947	0.0948	0.0002
B	0.6880	0.6880	0	B	0.4651	0.4660	0.0009
C	0.0011	0.0011	0	C	0.0068	0.0085	0.0017
D	0.0020	0.0020	0	D	0.0299	0.0300	0.0002
E	0	0	0	E	0.0043	0.0049	0.0006
F	0	0	0	F	0.1025	0.1030	0.0004
G	0	0	0	G	0.0279	0.0292	0.0013
H		0	0	H	0.2658	0.2658	0
AB	0	0	0	AB	0	0	0
AD	0	0	0	AD	0.0002	0.0002	0
BF	0	0	0	BF	0.0009	0.0009	0
CD	0	0	0	CD	0	0	0
CE	0	0	0	CE	0.0004	0.0006	0.0002
CF	0	0	0	CF	0	0	0
CG	0	0	0	CG	0.0011	0.0013	0.0002
CF	0	0	0	CF	0	0	0
DE	0	0	0	DE	0	0	0
DF	0	0	0	DF	0	0	0
ABD	0	0	0	ABD	0	0	0
CEG	0	0	0	CEG	0.0002	0.0002	0
CDE	0	0	0	CDE	0	0	0
CDEF	0	0	0	CDEF	0	0	0
O	0	0	0	O	0	0	0

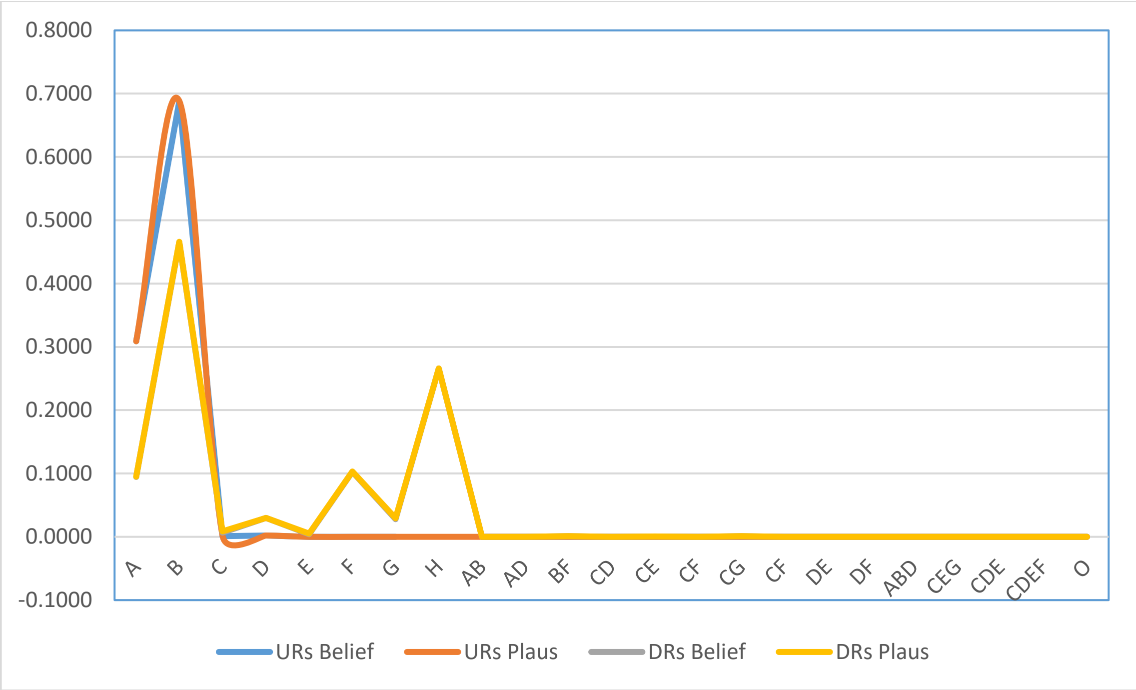

Figure 6-34 Plot of User and Design Requirements Belief Structure

6.4 Summary

This chapter presented an analysis of two case study contexts with DESIDE. The chapter specifically demonstrated the use of utilitarian analysis of for alternatives as well as forecasting using the HMM using two case study contexts. The two case study contexts form an important element in demonstrating the modelling capabilities of the proposed system. The understanding of the key modelling elements is an important step in the process as seen in sections 6.2.1 and 6.3.1. The initial DQFD construction and analysis using the HoQ relation matrix and others depends on the accuracy of understanding and capturing of the interdependent variables. Subsequently, the interdependent variables are vital in any utilitarian modelling including the cause-effect relationships of the various project benefits (see sections 6.2.5 and 6.3.3). Comparative MOORA and COPRAS utilitarian modelling provides a process of internal validation in the model's ability to assess similar attributes of the same project. Uncertainty modelling helped underscore the confidence in the knowledge base using the FoD. Case study context two was important in underscoring how the thirty-six requirements and their categorisation can be essential in guiding a structured Requirements Management process. The adapted DQFD was crucial in establishing interdependences in the requirements while HMM was applied at the requirements category level. The case study context two was essential to draw out any contextual dynamics when the decision system is applied. Differences are for example highlighted in the understanding of user and design requirements in both case contexts from the corresponding user and design perspective. This has contributed to the breakdown in transitivity in the results, particularly in case context two. In case study context one, transitivity is observed to breakdown at the lower end of the design models. At the same time, the analysis reveals higher belief and plausibility in the high-end models from designers as opposed to users. This suggests differences in clarity or effort in understanding and possibly a lack of collaborative effort at the lower end in engaging with this level of users. The change in high order requirements is also observed to respect the contextual dynamics in the respective cases. The cause/effect analysis of the benefits served as an important element in informing decision makers of those benefits that not only influence the most but may also be a causal or effect agent. The decision system is thus important in assessing resilience in designs from a FED perspective in as much as they deliver on the intended project benefits throughout the project's life cycle. The following chapter is the detailed discussion of the findings from both case study results.

7 FINDINGS AND DISCUSSIONS

7.1 Introduction

The previous chapter presented the case studies and subsequently the modelling of the various elements using DESIDE. This chapter presents the findings of the research and discusses them considering the evaluated decision support system to address gaps in current research as well as meet the objectives set out in chapter one. Various tools continue to be used in decision making in FED (see 3.4 and 7.4). However, rational, and visual aid decision making in design still dominates practice. Elsewhere in AEC, there is an increasing application of MCDM and hybrid tools to address project-specific complexities, but the practices have yet to be fully embraced in FED processes. The research findings thus prompt a discussion of how DESIDE placates the gaps in current FED decision-making practice comparable to tools. First, the influencing role of the project context is explored followed by a discussion of the results from the state of the art analysis previously seen in sections 3.2 and 3.3. The various influencing high and low-level attributes are discussed as a basis of informing the subsequent mathematical modelling. The chapter concludes with a comparative discussion of the results from both case study contexts first with the utilitarian assessments, requirements forecasting and finally the results from the uncertainty analysis of the contextual attributes. Parts of the data analysis informing this chapter are, therefore, derived from published works as part of the extant research in Serugga, et al. (2020a), Serugga, et al. (2020b), and Serugga, et al. (2020c).

7.2 FED Decision Making in Complex and Dynamic Contexts

FED has been described as and found to be inherently dynamic in this research. It has been demonstrated how emergent events impact on processes that in turn, impact on the realisation of benefits. Emergent events in case study context one include those relating to sociocultural, geopolitical, environmental, and economic shifts. Occupants' individual and collective aspirations, economic status and perception of events and benefits can be projected to change over the coming years. Change in local and federal political and policy environments place constraints on processes e.g. in planning and implementation level affecting high order requirements. Similarly, there are projected shifts identified in the socio-cultural configuration of the project context, just as there are emergent environmental shifts among other changing factors. All these factors can be complex as well as dynamic and impact on the *'structure and agency'* of FED decision making. Current decision-making practice is unable to model them sufficiently in an integrated manner to support Benefits Realisation. The proposed decision support tool helps model the complexities and subjective elements of FED contributing to Benefits Realisation in this vital stage of project implementation in a new approach.

7.3 Requirements Management

Laplante (2017) has highlighted how poor Requirements Management practices lead to disbenefits in projects. The research has found evidence of the lack of emphasis on Requirements Management in the case study contexts that is also backed by literature (see earlier 3.2). The limited application of requirement management practices has been attributed in some cases to disbenefits in projects. Requirements Management embeds practices of *'discovery, development, tracing, analysing, qualifying, and communicating'* requirements at various orders and levels necessary for project implementation. Employing such practices can mean design is able to cope with any emergent requirements as a result any evolution in stakeholder needs. DESIDE extends both the management of requirements and modelling of any emergent needs in an integrated manner. The use of HMM supports the identification of any patterns in emission and transition matrices relating to changing needs. It is, for example, important that a pattern of '*economic'* performance in a project context is discerned, so it better informs design decisions today. According to DESIDE modelling, '*Economic'* and '*Sociocultural'* shifts in case study one meant that consideration for only a low-cost design model as the only alternative rendered parts of the MCMV programme obsolete in many areas sooner rather than later. The decision support system allows the attributes to be modelled early in the project lifecycle, which helps the design process focus in detail on understanding the design problem than quickly rush to a solution.

Requirements analysis defines the essential elements of i) *derivation, i.e. why is a requirement being considered?* ii) impact – *what are the potential effects, including of any emergent changes?* and c) coverage – *ensuring all aspects of requirements, including any interdependencies, have been covered*. Tracing requirements, on the other hand, ensures that objectives, goals, aims aspirations, expectations and needs align with specific lower-order requirements and are owned. This is the process that supports confidence-building in the design process, brings accountability to the process alongside the ability to trace back any progress.

The decision support system embodies the elements and additionally supports decision making in cause-effect analyses during trade-offs and attribute weightings.

Modelling requirements supports communication during analysis in the process of decomposing the functional as well as performance requirements, among others. It focusses design decision making on the articulation of the purpose of the project into its lower level orders. The decision support system further supports the discernment of the utilities of this purpose in the course in the delivery of project benefits. The decision support system, therefore, supports the essential elements of Requirements Management of:

i. defining and discerning the design problem,
ii. scoping process to support the definition of project benefits,
iii. stakeholder collaboration in defining the problem and solution,
iv. development and assessment of alternatives that align any solutions to the problem.

The proposed system removes any predication to the solution and rather supports the building of shared knowledge of the problem through discernment, modelling and managing all requirements, including those seemingly non-functional. Emergent requirements based on seemingly non-functional requirements as occupancy and health and safety are seen in case study one to quickly gain importance and through interdependence with others impact negatively on end benefits. DESIDE treats requirements concurrently and explicitly for their potential influence during design and in the future.

7.3.1 Requirements Categorisations

Following a systematic detailed assessment of the state of the art in requirements management, it is found that overall, the most common requirement category in the literature examined is the '*technical'* requirement (26%) that looks at factors like Constructability of the design, legal and compliance, design form and aesthetics, collaboration among project stakeholders, project processes, how functional a design is, project lead time and specification requirements. At 23%, the economic performance of design follows with such factors as the cost of construction, project costs (Rent/Mortgage, management, contracts) and most importantly the strategic value that considers the residual economic performance of the design. Project governance, including project governance and knowledge governance, project context, and stakeholder management comes third at 18%. The environmental performance of a design is fourth at 14% and includes considerations for a design's energy performance (sound, solar gain/loss, energy costs), physical management and landscaping, life cycle costs, materials use, and how a design adapts to changing use. They are followed by geopolitical, sociocultural (5%), health and safety (4%), lifecycle performance (3%) and lastly occupancy (2%) factors. A similar narrative is seen for occupancy category where financial status dominates (56%) over Occupancy Level & Patterns (33%) and Social Status/Aspiration (11%) all summarised in *Figure 7-1*.

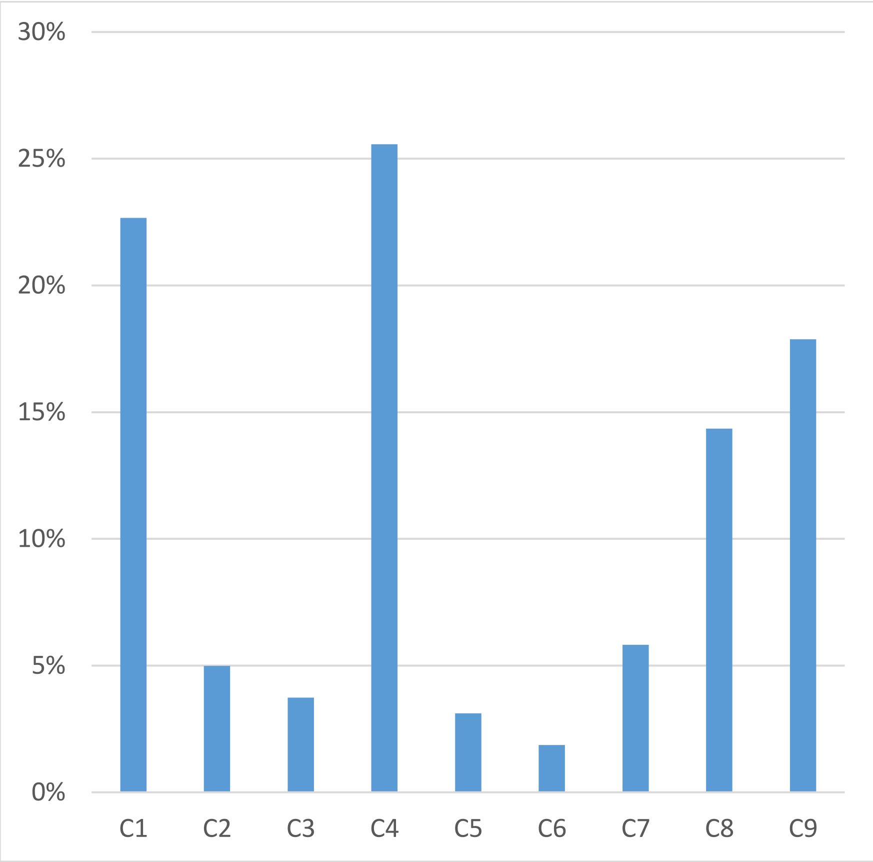

Figure 7-1 Factor Categorisations For Requirements Management in FED

C1-C9 are the high-level requirements categorisations as established in 3.2. It is notable that within the requirements categories, there appear some significant differences in consideration of factors (lower level requirements F1-F36 as established in 3.2) impacting in the broad research base (see *Figure 7-2*). For example, while nearly half of all research is around the technical and economic factors, in the former, majority research about 80% focusses on strategic value while in the latter, collaboration among stakeholders is seen in over 55% of research considered followed by project processes but within only 14% of research. In the technical requirements, there appears limited research for the requirements of specification of the design, legal and compliance issues, design form and aesthetics and project lead times all at 5%. This is perhaps due to current trends in AEC towards collaborative processes that appears to come at the expense of other requirements understanding within practice; that are similarly essential for the realisation of project benefits (Senescu et al., 2013). Similarly, while construction and project costs have been considered in recent years, much of current research emphasis appears on the strategic value of projects again at the expense of the other requirements essential for wider understanding of economic performance of a design from a Benefits Realisation perspective. Similarly, in the influence of geopolitics, a vast majority of research covers legislation and policy (61%) as a vital influencing factor in the success of project benefits delivery while research is thin on political leadership that can be critical for many project contexts.

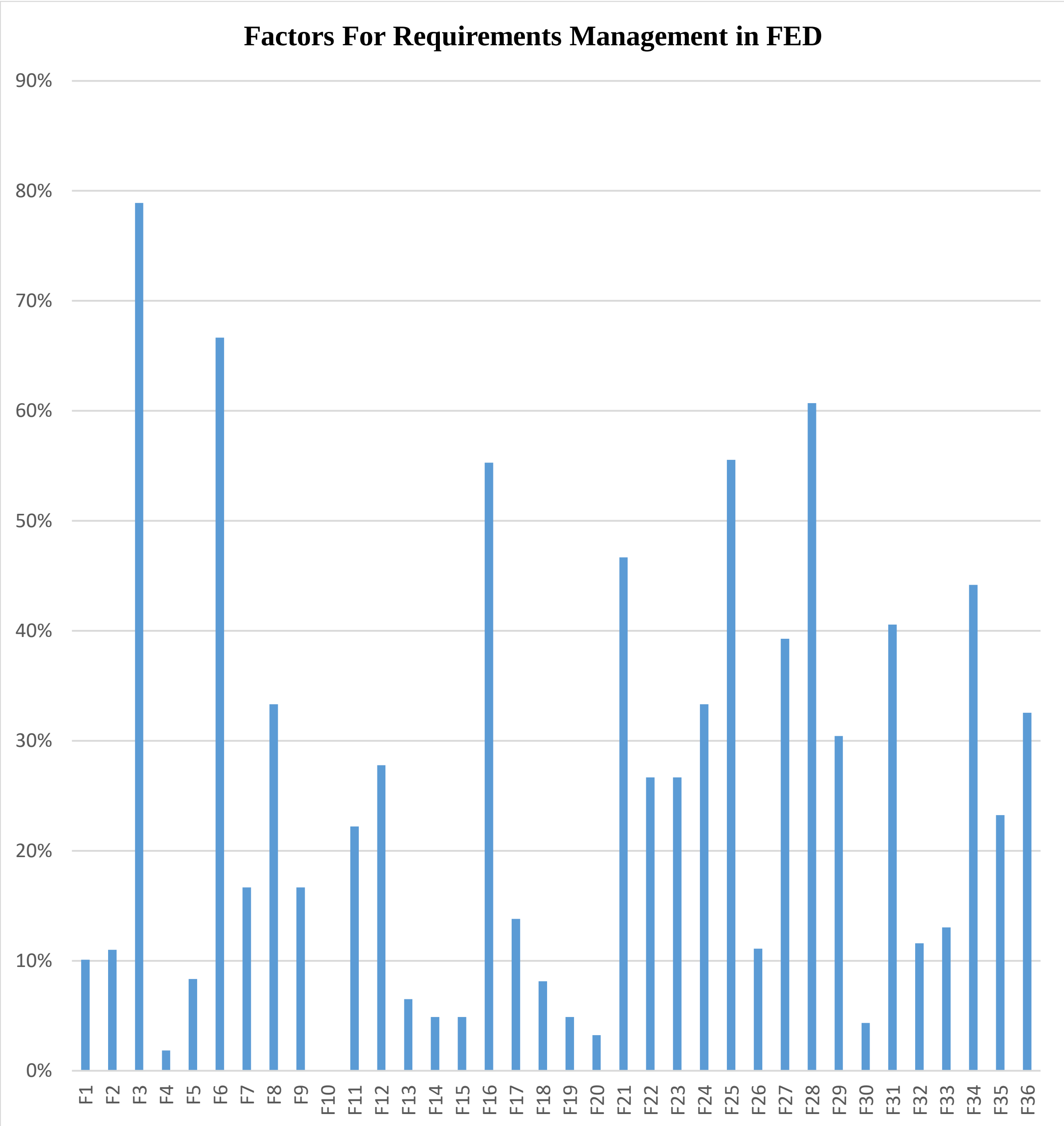

Figure 7-2 Factors For Requirements Management in FED

The sociocultural implications on design performance and Benefits Realisation are highlighted by authors like Mok et al. (2017), Locatelli et al. (2017) and Jay and Bowen (2011) among others. However, while considerations for culture and community dominate current research (67%), only 2% of research explores the influencing role of mobility as a factor important in design processes. Demographics accounts for only 17% while integrated design is 8%. This appears to suggest that research lacks a broader look particularly from a Benefits Realisation perspective of the essential aspects that impact on benefits perceptions while it might acknowledge some of the essential requirements factors that often draw on the contextual nature of project delivery. This also suggests that design decision may unduly place emphasis on factors while neglecting others that may be much more influential in a given setting.

Literature highlights nine influential categorisations important for consideration in design processes and modelling particularly for high level HMM. In answering the research objectives, this section discusses the requirements category findings.

7.3.1.1 Economics

Considerations for economic performance are important in most design decision making. Leśniak and Zima (2018) highlight that the cost of construction may be impacted on by factors that relate indirectly to the environmental performance requirement, comfort, and space quality as a design benefit to the end-user. Others include those relating the lifecycle performance of a design impacting on influencing elements as the cost of the choice of materials to be used. Lin et al. (2011), on the other hand, highlight the costs of those essential resources in production elements in construction, for instance the price of land and labour. It is notable, however, that economic performance extends to stakeholders' economic influences that ultimately link to their derived benefit of the design as well as impacts from the *'structure and agency'* influences of the project context. Requirements relating to the cost of construction, which will play an essential role in the sale or rental price among others, are economic decisions. How well stakeholders perceive them moreover can depend on the general health of the economy (Jay & Bowen, 2011). During economic downturns, for example, different perceptions might be drawn than from economic boom times.

7.3.1.2 Sociocultural

The effect of culture and community as essential requirements in the realisation of project benefits has been explored widely in research (Moodley et al., 2008; Vernet & Coste, 2017; Thew & Sutcliffe, 2018). Sousa-Zomer and Cauchick-Miguel (2017) however explore issues of PSS (Product Service Systems) in facilitating sociocultural integration in as far as facilitating other benefits e.g. mobility. Whereas the authors refer to '*mobility'* in their study lending to movement in the shareable bicycle project, their concepts of economic empowerment do lend to mobility as understood in the social sciences in communities. Surlan et al. (2016) in their study, highlight the importance of mobility in value in how it relates to local contexts. While the authors attempt to explore mobility as an important requirement in project Benefits Realisation, research is limited in this area in terms of its impact and relationship with other requirements, and similarly to the requirement of demographics. Value perception is a social construct as pointed in research (Thomson et al., 2013).

Social influences on intended and perceived benefits can, therefore, in turn, be influenced by societal and cultural changes. Stakeholder requirements relating to the energy performance of a home, or how integrated the design is with its wider surroundings or any connections between internal and external spaces can be influenced by social perceptions. Social perceptions, according to Thew and Sutcliffe (2018) can at the basic level in turn be influenced by individual emotions, society values and collective people's feelings about a given design's benefits among others. Similarly, societies view demographical changes differently. Differences in stakeholder interests sometimes mean that there is differing perceptions about which requirements are important and therefore of precedence. Understanding the intricate details in design decision making and modelling can be crucial in facilitating better delivery of project benefits.

7.3.1.3 Health and Safety

From site security and safety to hygienic design considerations in healthcare facilities all through to acoustic compliance in individual built facilities, there is growing universal acceptance of health and safety as a requirement for compliance and therefore modelling. Designing for hygiene can be a strict requirement for healthcare facilities (Elf et al., 2012) which places an important weight in modelling. Security is essential for times when sites as well as other facilities may or may not be in use (Hsueh et al., 2013). Meanwhile, Malekitabar et al. (2016) report that design processes have a role to play in combating site safety risks., There, however, appears to be contextual differences dependent on sociocultural, geopolitical, technological and economic factors or otherwise in the perception of health and safety requirement factors. What stakeholders perceive as a safety benefit may differ from another group. For instance, acoustic expectations as a requirement will not only differ depending on location or surroundings but may also be perceived differently as to how much they contribute to one's derived benefit while critical for some designs. The flow or interconnection of spaces within the design may have a bearing on the hygienic requirement of a space or indeed how secure it is from physical or nonphysical security threats which may require an influencing weighting during modelling. This again is something that will likely not only differ in context but also perceived differently between and among different end-users.

7.3.1.4 Technical

Technical considerations often weight on design decision making more than other issues as demonstrated in both case contexts in the previous chapters. They are however interdependent with other attributes. Issues of constructability, design form, functional performance, collaboration and project processes are identified throughout this research as essential requirements for Benefits Realisation and ultimately modelling from a technical perspective (Thomson et al., 2013; Cavka et al., 2017). Constructability for example that lends to the efficiency of processes in using up resources is interdependent with other technical requirements as project lead times, design form and functional performance or legal and compliance among others (Chen et al., 2010b). This research finds consistency in the position that traditional AEC practice and therefore, Requirements Management has been biased towards technical requirements in the definition and perception of benefits with over a quarter of articles focussed on this attribute. Despite this bias, the technical requirements of design still influence much of what contributes to end-user perceived and derived benefits owing to the user-design requirement transformation process; although this appears to be at the expense of other requirements something that may obscure full understanding of the various complex interdependencies essential for full Benefits Realisation.

Similarly, although technical requirements have been dominant, collaboration has been the main emphasis of recent research in this requirements category with over half of the reviewed articles focussed on it. There needs therefore to be a broadening of understanding of the other technical factors as symbolism (design form) or functional design performance among others as may be needed in specific contexts. The dominance of research on collaborative processes might also indicate biases in the too often top-down AEC design practices meaning that technical teams have a propensity towards a prescriptive approach to design particularly when it comes to Requirements Management and how they are transformed into design requirements. Technical teams appear in practice to have control over how constructible a design is; defining design decisions on form, materials, and other specifications they adopt for design. Technology in construction is also increasingly influencing not only the course but the nature of project processes and ultimately design decision making as to the benefits delivery process; but also remains technically exclusive. Similarly, how the design performs on compliance or aesthetics will influence benefit perceptions from end-users, but again the requirements are in the main controlled by technical stakeholders. Although demonstrably important in practice for its importance in the modelling processes (Pignataro et al., 2014); there are limited studies on the specification as a technical requirement for its interdependency with other requirements with only 3% of literature in this category devoted to it. As demonstrated by Pignataro et al. (2014), specifications can be a vital driver in exploring wider benefits in projects and may therefore for some project contexts weight higher than in others.

7.3.1.5 Lifecycle Performance

During the Benefits Realisation cycle, stakeholders often find need where their spaces have to be serviced or maintained to improve the designs lifecycle performance. This research identifies increasing interest in lifecycle performance through processes as serviceability, accessibility (Almeida et al., 2015; Sousa-Zomer & Miguel, 2017) and maintainability (Romani et al., 2010). In particular, there are opportunities in integrated processes and standardisation (Almeida et al., 2015), Sustainable and continuing performance optimisations e.g. in PSS (Sousa-Zomer & Miguel, 2017), and data security in the IT (Müller et al., 2017) among others; all issues making lifecycle performance an important requirement category during design decision making and modelling.

Ease of maintenance of a space is increasingly a factor in derived and perceived benefits. Implications relate to issues of accessibility to the space or part of it to be maintained and how site planning facilitates this. Such factors will ultimately translate into costs, be it for replacement or new changes highlighting interdependence among attributes. Design modelling relating to the use of technologies, materials, and systems, among others, can play a significant role in highlighting influencing attributes in specific decision settings and ultimately benefits relating lifecycle performance. Although lifecycle performance in the case study contexts is widely accepted and acknowledged, there is a lack of clarity in wider research as to exactly how this impacts on perceived benefits. Moreover, there is a growing acceptance that this understanding of lifecycle performance now needs to extend to the benefits of knowledge generation and sharing in information interoperability, and usability across the project lifecycle (Cavka et al., 2017) that may be important in specific modelling situations.

7.3.1.6 Occupancy

Rodrigues and Freire (2017) report on how low occupancy is considered when planning retrofits for lifecycle performance. However, this research finds that research into occupancy influences in design decision making is limited – the least among all nine high order attributes at only 2%. Chiu et al. (2014), however report on opportunities for innovation and knowledge when occupancy is considered carefully as an essential requirement in design. Williams et al. (2013), on the other hand, explore the opportunities in terms of collaborative processes that link many stakeholders in a manner that fosters understanding of occupancy influences and its challenges.

Meanwhile, the Hsueh et al. (2013) study highlights the dangers of disused public buildings as a result of insufficient occupancy planning and therefore modelling, particularly in design leading to insecurity. Changing consumer trends into experiential consumerism are now filtering through into AEC. It is now, therefore, just as much crucial that spaces meet the changing needs of occupants as has been understood in many other sectors of industry for some time now. Occupants' needs change over time include a change in levels or patterns – which may mean new additions or family members or staff moving in/out of a home or company premises respectively; income and status changes be it through new or lost opportunities and social status/aspiration to match them and other changing circumstances as environmental concerns. Factors of this nature influence how stakeholders perceive and derive benefits concerning how a given space continually evolves to continue to meet changing family circumstances. The proliferation of garden cities is an example when occupancy factors were a significant consideration for design and benefits management processes. Modelling has to take all these elements into account and accord them their due weighting during analysis.

7.3.1.7 Geopolitics

The influence of geopolitics in terms of political leadership has been highlighted by recent research in how it influences decision making to impact on project value (Smyth et al., 2018), contexts (Thew & Sutcliffe, 2018), its impact on contractual relationships in AEC processes (Osei–Kyei & Chan, 2016); and how it can negatively impact on wider benefits (Chakraborty, 2011) among others. Weaknesses in policy and legislation on the other are cited by Locatelli et al. (2017) as a basis for proliferating corrupt project contexts. As a result, a lot of construction policy is now at the forefront of many local authorities and national political debates be it in Europe or South America. Growing populations and changing family lifestyles are creating acute contextual needs, for affordable social housing for instance or major infrastructure needs (Osei–Kyei & Chan, 2016). Geopolitical factors are, therefore, increasingly influencing benefit perceptions and benefits management processes and should be modelled as such; be it through prescriptive legislation and compliance regimes or merely changing policy from one position to another. Weightings for geopolitics may be influencing in some projects than others.

7.3.1.8 Environment

The increasing focus on the environmental performance of designs now extends widely to the vital aspects as design for adaptability (Adeyeye et al., 2010; Wang et al., 2018). Some designs often now require refurbishment at some point in the design's lifecycle, including bringing any upgrades to say the aesthetic and functional performance of the fabric or envelop (Adeyeye et al., 2010). The designs may also come under the need for rehabilitation or some modernisation sometimes with some extension work or indeed full retrofits; to include new materials for enhanced or new performance (Garcia-Ceballos et al., 2018). Lifecycle costs (Himpe et al., 2013; Russell-Smith & Lepech, 2015); as well as issues relating to physical management of the immediate building's environment as well its wider one (Chakraborty, 2011) similarly play an increasing role in design decision making.

Such requirements are being driven by the increasing awareness of the world and its finite resources that now demand AEC practices move towards environmentally friendly designs. Environmentally friendly designs are now and in the future likely to influence benefits perceptions and delivery and therefore integral to any decision modelling. Design decision making, thus needs to increasingly focus on areas like energy performance, physical management, materials use, lifecycle costs and adaptability of design and their interdependences with other attributes. This also extends to considerations for design specifications as to the appropriate glazing design for instance, that addresses seasonal solar gain/loss, environmentally friendly materials, and adaptability of designs in the face of increasing need for environmental performance as part of any design decision analysis.

7.3.1.9 Governance

Locatelli et al. (2017) and Wolter and Meinel (2010) are among a growing number of authors to explore the essential dynamics of project governance, stakeholder management and project contexts. Of particular notice is the limited research coverage of project context among them that can, however, be a vital requirement for the delivery of contextual project benefits and influence any modelling results. Carrizo et al. (2017) observe that the effectiveness of the requirements elicitation process is dependent on the context – basically the structure of the project context. Chakraborty (2011) draws on the utilitarian biases among Japanese policymakers in the continuing proliferation of dam projects despite their impact on the environment; again, reflecting the contextual nature of design decision making. On the other hand, however, van de Kar and Den Hengst (2009) draw on the importance of participatory and collaborative processes in drawing out any essential contextual nuances that may be critical to benefits perceptions and bear on any modelling to support decision making.

Additionally and while acknowledging challenges that may come with wider stakeholder involvement, Knauss et al. (2018) point to opportunities for innovation and stakeholder association and ownership of any benefits. Shared stakeholder understanding that is important in helping meet today's diverse project stakeholder expectations is what has been referred to as value co-creation (Kruger et al., 2018); and is typically less reflected in modelling approaches in design.

From a Benefits Realisation perspective, project governance is central to the delivery of project benefits through advocacy for organisational change as a critical element in the successful delivery of projects. Increasingly literature is adding to the knowledge that project governance does impact on the success of projects. As a result, how projects are governed, and knowledge shared and governed play an essential role for stakeholders in the perception of benefits be it through collaborative and integrated design practice or otherwise. Research and practice need to extend, however, to the exploration of the intricacies of governance requirements and draw out their clear implications on projects' benefits during decision making and modelling.

The key project requirements are summarised in *Figure 7-3*, including essential categories of economics, socio-culture, health and safety, technical considerations, project lifecycle performance, occupancy factors, geopolitics, environmental considerations and governance.

The categorisations are based on studies' representation of requirements across many disciplines in AEC. Some studies have used related or similar meanings that this table collates to support the categorisations. For example project governance (Locatelli et al., 2014; Pemsel et al., 2014; Samset & Volden, 2016; ul Musawir et al., 2017), project context (Fellows & Liu, 2016; Smyth et al., 2018; Mota et al., 2019) and stakeholder management (Moodley et al., 2008; Aragonés-Beltrán et al., 2017; Mok et al., 2017; Drevland & Tillmann, 2018) are all requirements relating to governance and are grouped together.

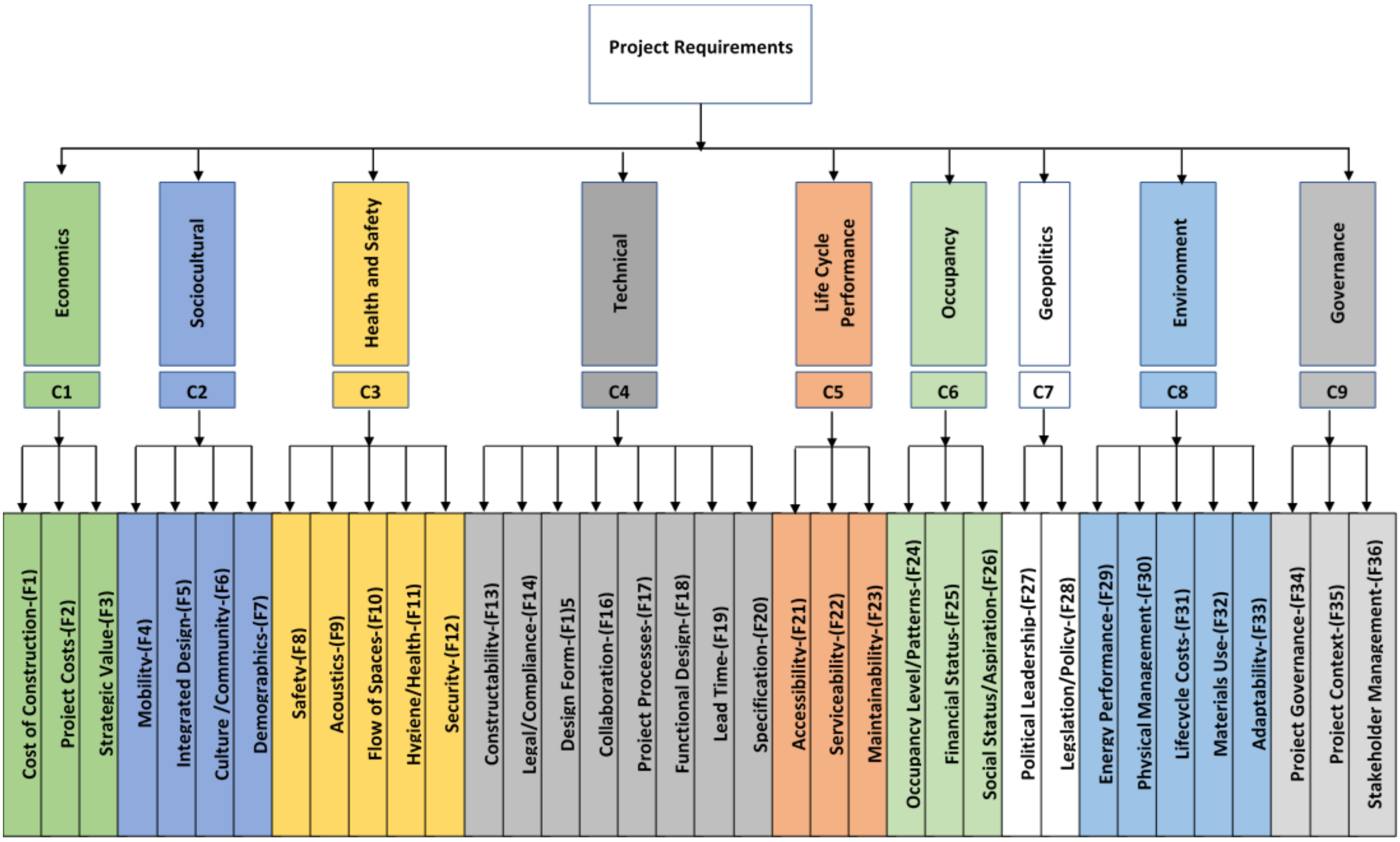

Figure 7-3 Summary of categories and factors of design requirements

Similarly, the economic categorisation groups requirements relating to cost of construction, project costs, i.e. the project implementation costs not directly relating to construction (Becker et al., 2014; Leśniak & Zima, 2018; Tezel et al., 2018); and strategic value (ul Musawir et al., 2017; Callegari et al., 2018; Garcia-Ceballos et al., 2018) of the projects all of which impact and directly translate into the economic viability requirement of a project. On the other hand, life cycle costs, energy performance, materials use and adaptability of a design over its life or the management of physical setting of design all impact on the environment and are grouped together. This is supported by author considerations in studies as Vezzoli et al. (2015); Cavka et al. (2017); Sousa-Zomer and Cauchick-Miguel (2017) and Jay and Bowen (2011) among others. The rest of the categorisations, including sociocultural, health and safety, technical, lifecycle performance, occupancy, and geopolitics, have been developed and grouped on a similar basis. The categorisations in *Figure 7-3* are supported by the summary in Table 51 of some of the studies that discuss, represent and inform this research's taxonomical approach to the major requirements. All the requirements categories are considered among the thirteen selected studies ranging from construction, IT, Product-Service Systems and Engineering design (see *Table 51*). This highlights the importance of widening scope to other sectors in drawing to the understanding of the essential dynamics in FED modelling as influenced by the different contexts and applications.

Table 51 Selected Literature on the Requirements Categorisations

Author	Category	Research Questions/Goals
Cavka et al. (2017)	Technical, Economics, Governance, Environment, Health and Safety, Life Cycle Performance	A study to understand and facilitate processes of developing and formulating BIM requirements to support the lifecycle of their assets through an iterative approach to the identification and characterisation of owner requirements
Sousa-Zomer and Miguel (2017)	Governance, Environmental, Technical, Health and Safety, Life Cycle Performance	The study investigates PSS applied to sustainable design during conceptual design
Locatelli et al. (2017)	Economics, Technical, Geopolitics, Governance, Sociocultural	A study into new ways to select, plan and deliver infrastructure in corrupt project contexts
Mok et al. (2017)	Governance, Economics, Technical, Sociocultural	An investigation of stakeholder complexity and understanding how major pitfalls in cultural building projects from a stakeholder perspective are crucial to the successful management of these projects
Osei–Kyei and Chan (2016)	Economics, Governance, Geopolitics, Technical, Occupancy	A study into the success and failure factors of Public-Private Partnership Transport Infrastructure in Sub-Saharan Africa
Palm and Reindl (2016)	Environment, Economics, Geopolitics, Life Cycle Performance	A study into renovation processes for reduced energy consumption in front end design
Vezzoli et al. (2015)	Environment, Economics, Geopolitics, Sociocultural, Technical, Governance, Health and Safety, Occupancy	State of the art into user satisfaction and acceptance of Sustainable Product-Service Systems solutions and how industrial partnerships and stakeholder interactions can be designed for environmental and socio-ethical benefits, socio-technical change and transition management
Buyle et al. (2015)	Environment, Economics, Geopolitics, Governance	An investigation into scenarios to improve the environmental profile of new buildings in the Flemish/Belgian context
Shackleton et al. (2014)	Occupancy, Economics, Technical, Environment, Geopolitics, Life Cycle Costs	A Study into how policy can foster urban forestry and greening through a regime of maintenance, use and appreciation of trees on private homesteads of residents of new and older low-income suburbs as well as informal housing areas
Thomson et al. (2013)	Technical, Economic, Environmental, Lifecycle Performance, Governance	Examining the construction practitioners' collective cognition of value to determine how their facilitation may bias this intent.
Jay and Bowen (2011)	Technical, Economics, Environment, Health and Safety, Sociocultural, Occupancy	A study of social housing value perceptions in South Africa
Moodley et al. (2008)	Sociocultural, Health and Safety, Economics, Governance	A Study into ethics of construction practices including exploration of social contracts and corporate responsibility

Current research provides a general basis of practice in AEC e.g., in how value concepts and propositions in design processes relate to the '*structure and agency'* influences on design (Thomson et al., 2013). Thomson et al. (2013) explore the various factors that are important in drawing out project requirements like the technical implications of collaborative processes, how lead times affect projects, as well as functional and form issues in design. The authors in their evaluative study also explore issues of environment, strategic value and economics of projects value, Economics alongside factors influencing lifecycle performance, among others. The research is interesting in its particular focus on how much the elements contribute to understanding of value from a practitioner's perspective. Similarly, the study by Cavka et al. (2017) through highlighting BIM capabilities looks at requirements categorisations and characterisations in as much as they support processes that adequately manage owner needs in design processes. The study by Cavka et al. (2017) also explores the iterative nature of design from an asset and facilities management perspective. In addition to the categorisations explored by Thomson et al. (2013), the Cavka et al. (2017) study looked to Health and Safety including the security and safety requirements that design processes had to take into account in consideration of owner requirements.

The evaluative study by Vezzoli et al. (2015) into sustainable PSS was important in highlighting design requirements relating to geopolitics in areas of policy and legislation. While geopolitics as an influence on design requirements and design practice, in general, is acknowledged throughout AEC practice (Chakraborty, 2011; Shackleton et al., 2014; Callegari et al., 2018); the influence for policy/legislation e.g. on the nature of the building fabric and envelope potentially as sustainable PSS as is argued is an essential highlight in design decision making. This is not only because of the potential influences on the other factors as economic performance and sociocultural impacts of buildings among others; but also, how geopolitics impacts the overall lifecycle performance of these buildings as they continue to adapt to changing user needs.

The study by Osei–Kyei and Chan (2016) drew on the requirements of occupancy alongside geopolitics, sociocultural and governance factors in Public-Private Partnership projects. The study highlights, the contextual nature of Requirements Management drawing on the peculiarities of the sub-Saharan project context. The strong influence of governance in the projects and geopolitics in such types of projects comes to the fore while the authors argue for actionable policy/legislation as guides, as well as the requirement for use and occupancy as communities, evolve both in their aspirations and status. This is not something identified in many research studies, particularly those in developed world project contexts where other contextual factors may be significant at play. This narrative is also highlighted by other studies like Locatelli et al. (2017), Mok et al. (2017) and others. The research in the foregoing serves to highlight, first the absence of coherence in requirements management but more importantly the need for a unifying basis for modelling of the various design requirements as is set in the preceding discussion.

7.4 Decision Making Methods and Techniques

This section presents the findings and analysis of decision support techniques and tools in present AEC practice. The application of explanatory/rational decision-making methods dominates in construction more than in any other sectors as part of a systematic literature review (See Appendix G) by about 33%. The rational techniques include DQI (Design Quality Indicator) applied in social housing design (Chohan et al., 2015) and in design of walkability and accessibility (Cook et al., 2013). Others include the use of Target Value Design (TVD) in the design of health facilities using the Last Planner System (Rybkowski et al., 2012); and use rational model-based techniques e.g., in urban planning and regeneration design (Della Spina et al., 2017).

One of the most dominant applications of explanatory/rational decision making in both construction and New Product Development (NPD) is seen in Set-based Design (SBD) either on its own or in complementary hybrid applications (Avigad & Moshaiov, 2009; Lee et al., 2012; Al-Ashaab et al., 2013; Yannou et al., 2013b; Unal et al., 2017; Rempling et al., 2019). SBD is, for example, used by Rempling et al. (2019) in enabling collaborative environments during structural design. Meanwhile, Unal et al. (2017) apply SBD with boundary modelling for the design of seismic resistant structure frames the authors arguing that the technique allows design decision making the wider freedom to support refining and selection of alternatives. Finally is the use of SBD by Lee et al. (2012) in conjunction with BIM and AHP in design of high rise buildings. Hybrid decision-making methods account for 10% of AEC design decision making. Besides SBD based hybrid methods, MCDM based hybrid systems in AEC include studies like Malak Jr et al. (2009) in applying SBD and MAUT to extend the former's ability to cope with imprecision and uncertainties in design decision making.

At a sub sector level, in Engineering design, unlike in construction and NPD, no visual methods are identified. Half of decision-making is by MCDM while hybrid methods and explanatory/rational each account for a quarter of decision making. The most commonly applied MCDM is QFD highlighted in studies of quantification of engineering characteristics by Jia et al. (2016), applications in product design for effective integration of design and specification processes by Jiang et al. (2015), and in the identification of product characteristics for remanufacturing by Zhang et al. (2019b) among others. Explanatory/rational decision making is seen in applications including reducing reworks in systems engineering design processes (Kennedy et al., 2014) among others.

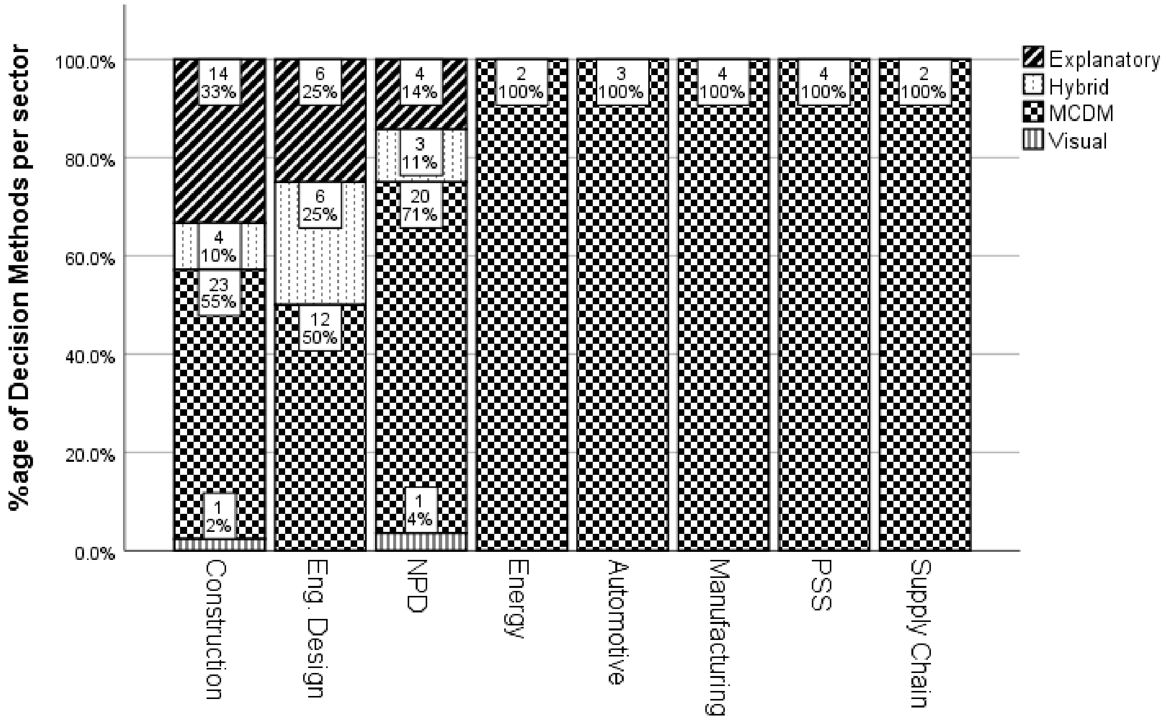

Figure 7-4 Summary of Analysis of Sector Distribution of Decision Methods

In other sectors, MCDM is the only dominant decision-making method identified including in Energy (Lanjewar et al., 2016; D'Agostino et al., 2019), Automotive (Tian et al., 2016; Mastura et al., 2017), Manufacturing (Talebanpour & Javadi, 2015; Eleftheriadis & Hamdy, 2018), PSS (Li & Song, 2016; Chen et al., 2019b), and Supply Chain (Ding et al., 2016). In all the latter sectors, it perhaps suggests that the emergent appreciation of the complex dynamics and the need for tools that cope with it are the drivers towards this trend. In construction and NPD, it is noticeable that a mixture of multiple stakeholders, traditional practices and a trend towards newer production processes and philosophies can account for the varied methods in FED decision making practices.

As is typical, in construction, complexity means complex decisions are never easy to make (Brownley, 2013). There has been a range of tools and methods over the years employed to support design decision making, including explanatory/rational methods, MCDM, hybrid and visual aids. MCDM techniques, generally, use an attribute system to analogise and quantify complex decision making for better analysis using weighting and evaluation.

The fundamental criticism cited in defence of some alternative explanatory/rational and visual techniques mainly is that in MCDM techniques, one gets different results from different methods of the same decision problem (Arroyo et al., 2012). However, some authors have argued whether, in practice, the same decision analysis setting can be replicated for different methods in the same manner, conditions and setting for accurate comparison. In defence of MCDM methods, however, it can be argued that while such differences do exist, it could suggest instead a case of inconsistency in or poor application of MCDM rather than MCDM techniques themselves. For example, while the AHP that is a basis for much criticism only allows for hierarchical analysis of the attributes that are essentially linear (Saaty, 2005; Arroyo et al., 2014), the ANP that is within the same domain allows for analysis of interdependences among attributes (Cheng et al., 2005; Dağdeviren & Yüksel, 2010; Ignatius et al., 2016); something that is essential for the multi-attribute nature of FED and may account for differences in results. Such approaches have been successful in supporting the selection of alternatives as applied in aircraft design processes in Bae et al. (2017).

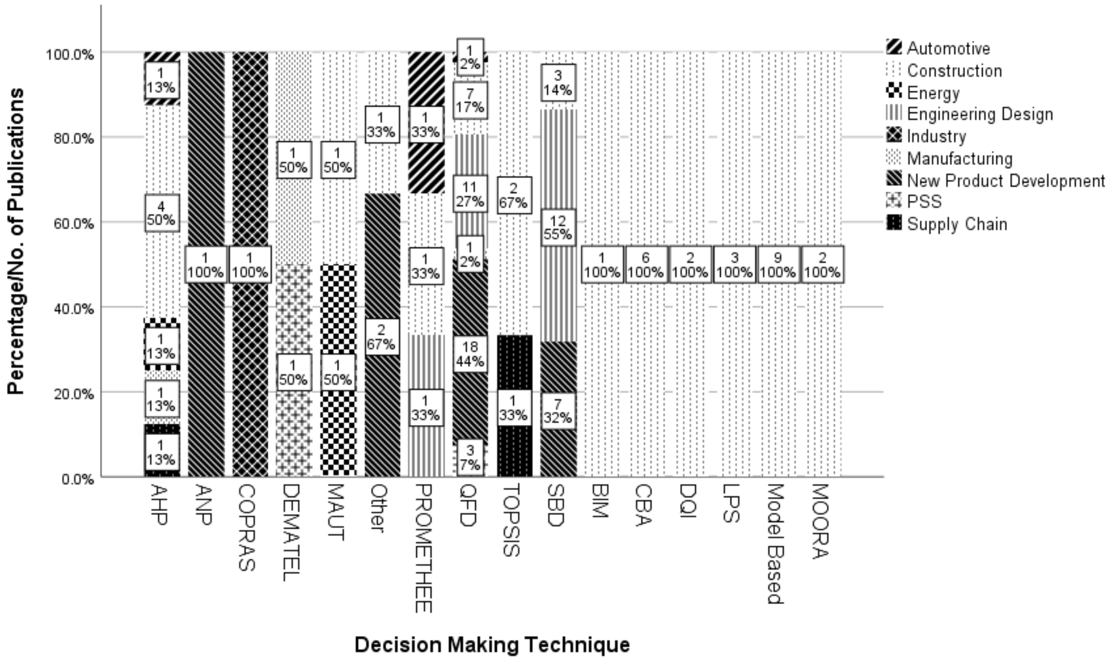

Figure 7-5 Summary of Reviewed Decision-Making Techniques in Design

7.4.1 Decision-Making techniques

Important to highlight is the complementarity in many MCDM approaches e.g., in QFD-ANP; (Zaim et al., 2014; Ignatius et al., 2016), AHP-MOORA (Akkaya et al., 2015), AHP-PROMETHEE (Macharis et al., 2004) QFD-TOPSIS (Akbaş & Bilgen, 2017) AHP-MAUT (Alshamrani et al., 2018) and many others. This allows for the extension of the methodical arguments and weaknesses in one by allowing for subjectivity analysis that may not be possible in one technique but in another. This section, therefore, presents the evaluation of the basic principles of some selected MCDM, Explanatory/Rational, and Hybrid decision-making techniques alongside some key features important for consideration in FED to assess any strengths and support the choices adopted in DESIDE.

7.5 Utilitarian Assessments

Case study context one establishes an evaluation mechanism for selection of design social housing models in the MCMV program. This is based on QFD and MAUT and its derivatives to support design decisions and processes hinged on multiple user requirements to inform multiple design requirements.

It is essential to highlight that in a utilitarian perspective, the utility function is multiplicative meaning that while the low-cost housing is preferred as the best option for end-users, the decision isn't monotonically increasing in the sense that the next option is actually the lowest cost (95%/82%) and medium-low housing (80%/59%). This is consistent with both the MOORA and COPRAS approach. Additionally, while the Very High-end design models are the least appealing to end-users (24%/33%), the Medium-High (53%/46%) and High End (47%/43%) design models are more preferred than the medium model (51%/42%) overall respectively. This is reflective of a Brazilian context. Uncertainty is accounted for through probability density functions in the utility function mapping expected consequences to certainty equivalents. Requirements forecasting based on utilitarian certainty equivalent principles can be explored, establishing indifference points along the decision-making process between the future and current design process—both can aid decision-making. The results from this modelling are unsurprising as the multidimensional utility of the user and design Requirementss means yields an uncertain expected utility.

In case study context 2, the results from MOORA and COPRAS analysis confirm the context-specific emphasis of design and delivery of social housing, particularly in this sector, with a focus on the end-user. The Performance of factors like Occupancy, adaptability and financial status that dominate the model results reflect a strong emphasis on the understanding among project stakeholders. This further suggests that perhaps design decision making should continually meet the benefits relating to provision of accommodation, mobility, Financial status and wellbeing (see Figure 6-31 and Table 44). The performance of *'welfare'* below *'work'* and *'community'* as project benefits is another observation that reinforces the project-specific dynamics in terms of the funding mechanisms and the requirements stipulated on it by stakeholders. Similarly, the emphasis on and background of the project ownership/management teams rooted in a charity provision is notable. This compares with the results from case study one where the model indicates that Low Energy, Space provision, Low maintenance and Safety dominated as the desired user benefits during design decision making. Security performs lowest as a desired benefit in case context one which is perhaps surprising considering the wider security concerns in and around condominiums in many townships and cities in the country. This perhaps could owe to the user understanding that security provision comes as default in many of the new condominium developments anyway and therefore not considered with the same pertinency as safety or energy performance.

On the other hand, *Figure 6-19* represents the graphical ranking orders for the models for both MOORA and COPRAS analyses for case study context one influenced by the interdependences among the various user and design attributes forming part of the modelling (see *Figure 6-18*). In case study one, the performance of *'Low-End Model'* design appears to be in the model presenting the greatest opportunities in maximising the design form (including aesthetics) and delivering on compliance whilst minimising materials use and overall costs and performing competitively on-site use and needs. This appears to relate strongly to the general stakeholder needs and expectations of low-cost housing that is easy to maintain, maximises site use, safe and secure for end-users while looking great something that correlates with the Hentschke et al. (2018) study of the same scheme. On the other hand, the '*Very high'* model performs worse in areas of site use, compliance and constructability. It suggests that beyond the need for a large site, the complexity of the design models at this level might demand more in implementing them, including requirements for higher percentages of service areas beyond the basic functional spaces needed. All this could mean a less rigid compliance regime in pursuit of symbolism. The design form, including aesthetics, however, appears to be less of a pressing issue with the VH model though, as expected, safety is a key issue which ultimately increases the complexity of the design.

The results from the two case studies serve to underscore this gap between understanding of user requirements and design requirements; both from a utilitarian assessment (sections 6.2.5 and 6.3.3) and uncertainty modelling perspective (see sections 6.2.6 and 6.3.4). Figure 6-20, in case study one highlights an almost transitive understanding of design requirements by designers from low to very high-end designs. It appears that the higher the user demands in terms of expected benefits, the better the understanding of the benefits the user requires from a design process perspective. Similarly, the lower the demands, the less the understanding of the user requirements. This position is supported in large parts in case study two (see Figure 6-34) where transitive understanding and preference bears on the need for accommodation provision. In this case, however, this breaks down in the main for design requirements understanding in supporting benefits understanding. Case study one, therefore, suggests or perhaps confirms a prescriptive approach in current design practice where low to medium-income end users are *'designed for'* while higher-income models are *'designed with'* because of perhaps the latter's intricate understanding of their needs in this context. Ultimately, scrutiny should be brought to bear on the work of designers through modelling in the value cycle if inconsistencies in benefits delivery are to be addressed.

7.6 Requirements Management and Forecasting

The systematic literature review demonstrated (i) gaps in understanding, practice and process support for the management of project requirements in a FED perspective and (ii) a lack of basis for wholesome understanding the key essential requirements and any categorisations vital for decision making processes during FED.

A key factor in Benefits Realisation is how successful processes are in not only defining and managing the delivery of benefits to the end-user but also assess how they are likely to cope with change to meet any emergent needs (see section 3.2). This has, however, remained a complex undertaking so far in the benefits and value research and discussion; yet a lot of effort is expended in understanding user requirements. This research has adopted high level categorisations defined by contextual housing need to support the modelling and analysis, and in supporting the subsequent evaluation of DESIDE. The results reveal that overall, emergent needs resulting in changes in requirements and ultimately, how decision making should undertake FED; can be significant. The requirement for project governance is deliberately analysed independently for both case studies in part to draw to the need for sensitivity analysis during modelling. On its own, a significant change of over 22% and 21% for case study one and two respectively between the maximum and minimum influence of this category area on the design process is observed. The other areas are comparably lower for their aggregated analysis. This, however, still reveals that design technicalities do influence changes up to 7.5% and 7.1% for case one and two respectively over time. This appears to suggest that in social housing, user benefits depend on how, for example, constructible the housing is and to what extent the specifications continuously deliver benefit to the end-user. Compliance issues also have a role in the user benefit perceptions while the design form and aesthetics and how functional the design is to the needs of the end-user are also important.

Similarly, a 4.9% and 6.5% gap in observed changes can be attributed to Geopolitical and family factors respectively for case context study one respectively. While comparable to 6% for the former, there is a significant difference in change over time for the latter at 13.3% for case study context two. In the former case, this appears to relate closely to the relatively stable wider political contexts. While this may not arguably be true from general observation, as the MCMV program is a largely political endeavour; this is suggested from the results to be the case at least from the perception of stakeholders. Significant changes in *'occupancy and family'* are noted for both contexts as the most susceptible to change. This is even higher (twice as much as context one) for case study two. The suggestion here is the influencing role is in the nature of use and the target users for both contexts. While in context one use the accommodation is targeted towards ownership and therefore relatively stable occupancies would be expected, and despite the fundamental inherent uncertainty within the use patterns; analogous issues are exacerbated for case study two where use is targeted towards significantly shorter tenancies as compared to case study one. Users hold tenancies for between 1-3 years and ought to have gained stability in their lives to help them move into more stable accommodation elsewhere. Therefore, design decision making must reflect that continual and random change in occupancy levels and patterns will fluctuate more significantly over time as a result for case study two. Modelling with DESIDE can be important in highlighting such pertinent issues for the design process.

Political Leadership and Legislation/Compliance regimes appear to have a significant constraint on benefits delivery for both case study contexts. According to Chesbrough et al. (2018) sometimes, these constraints give rise to *'conceptual ambiguity'* impacting on the *'structure and agency'* (see in section 2.2.4) based design decision making and ultimately affecting benefits delivery. Regarding geopolitical influence, the occupancy and provision of accommodation are key drivers in decision making from among the other benefits in the two contexts. From the results for both contexts modelling, therefore, it appears that the family circumstances/ occupancy is important in determining benefits from the schemes. This includes but not limited to the size of the family and how this changes over time – e.g., when members move in/out of the family home or when young adults come of childbearing age; as much as the influence of changing family status/aspiration. The emergent influences are what design decision making should have to account for and model during FED.

Notable differences between case study one and two appear in economic – 3.02%/8.49%, sociocultural – 2.19%/4.91%, health and safety – 2.44%/7.06%, Family/occupancy patterns – 6.54%/13.25%, and Environment - 0.28%/2.78% factors.

When it comes to environmental issues, the results show only a 0.28% influencing change over the same time for case study one while for case study two, it is 2.78%. This is surprisingly the least significant change for all high order factors over the time steps. This could perhaps owe to the fact that environmental policies influencing decision making are clear for all stakeholders or that they are not considered with the same rigour as other factors. Another explanation that could be adduced from this is that in social housing and estates/condominiums, generally environmental issues perhaps do not weigh that much in deriving user benefits at this level of use; the overriding factors being occupancy and accommodation provision to meet the acute social and political pressures. The other reason could be that perhaps factors for instance energy performance and its costs are already controlled by the nature of the housing projects which is in the main *'functional'* as opposed to the grandeur in high-end use design models. This could also explains why issues like solar gain/loss are not in the main as influencing. The reasons would, however, be limited when environmental issues relating to materials use and adaptability are considered. It, therefore, appears to be an issue of use perception rather than importance of the issue. A sensitivity analysis developed as part of a subsequent uncertainty analysis highlights confidence areas of the analyses. It is important to highlight that forecasting level sensitivity analysis has been employed in other studies to highlight specific parameters and therefore something to consider as part of the future model development.

7.7 Uncertainty Modelling

The concepts of Benefits Realisation have been seen to date back to the 1980s (Bradley, 2016); and since Koskela (1992) remarks on the need for new production theory in construction processes with a focus on value creation, there has been an increasing flurry of conceptualisations on the basis of the TFV model targeted at various levels of the construction value cycle. User expectations have evolved in part due to their changing sociocultural, geopolitical, and environmental trends, among others. Their expectations have, however, come up against a still predominantly fragmented construction industry focussed on short-termism (Tezel et al., 2018).

This research has also established the gap in practice as a result of a lack of coherency in continuously resourcing the decision-making process, particularly in FED emanating from inadequacies in the wider stakeholder participation (Kpamma et al., 2017) and collective decision making in co-creation (Liu et al., 2018). This has resulted in uncertainty in design decision (see 5.5.1).

Thus sections 6.2.6 and 6.3.4 explored the decision support system's ability to model uncertainty in design decision in the realisation of project benefits. In case study one, project benefits centred on the delivery of affordable housing through the MCMV programme. In Case study two, on the other hand, user benefits were specific to the delivery of outcomes as accommodation for the young people as well as related benefits of work, mobility, and education, among others. Both contexts demonstrate the system's ability to utilise the belief structures in decision making so that the results can demonstrate transitivity and ultimately a focus on the utility of decision making. The Models *'Very Low'*, *'Low'* and *'Medium Low'* reflect the best belief structure in a very dynamic project context while a focus on accommodation provision almost entirely espouses the project's belief structure for both case study one and two, respectively. There are, however, notable gaps in the model results for both design and requirements modelling in both contexts.

The results from the systematic literature review serve to underscore this gap between understanding of user and design requirements and are supported by the utilitarian and forecasting modelling results in the previous sections of this chapter and sections 6.2.5, 6.2.6, 6.2.7, 6.3.2, 6.3.3 and 6.3.4 of chapter six. Figure 6-20 in case study one for instance highlights an almost transitive understanding of design requirements by designers from *'low'* to *'very high-end'* design models. It appears that the higher the demands, the better the knowledge of the benefits the user requires from a design process perspective. Conversely, the lower the user needs, the better the understanding of the Design Requirements. This appears to confirm a prescriptive approach in current design practice in which low to medium-income end users are *'designed for'* while higher-income models are *'designed with'*. This position is in part supported by Case study two modelling (see *Figure 6-34*) for accommodation provision being the main outcome of the project, particularly for user requirements modelling. This transitivity breaks down, however, for design requirements modelling in part perhaps lending to the wide range of stakeholders and design requirements, and their understanding of the user requirements. This could also lend to the nature of the case study in context two that reflects a controlled and less dynamic setting required to support the complex modelling DESIDE seeks to achieve. Ultimately, it is concluded that scrutiny ought to be brought to bear on the work of designers in the value cycle if these inconsistencies in benefits delivery are to be addressed.

7.8 Role of Users and Stakeholders in Participatory Design

Visual aids and rational thinking in today's design practise does little to engage users and other non-technical stakeholders in clarifying project benefits from their perspective. In case study one, two-bedroom apartments usually in large condominiums, over several floors have been adopted as a solution to the housing crisis in that context. In case study two, one-bed flats are suggested as a solution. End users are the target mortgage buyers of the MCMV housing, just like young potentially residents are in case study two. These stakeholders are largely nonparticipating in the process illustrated by the drastic differences between design and user requirements understanding in *Figure 6-34* for instance.

Many of the decisions that impact on their derived benefits are carried out by the mandated stakeholders who act on their behalf and as best as possible in their interests. For example, as part of the wider requirements, implementing stakeholders are required to deliver minimum space requirements, shared recreation and social facilities, minimum set levels of landscaping and environmental management practices during implementation and health and safety, among others. Requirements emerge from various levels of stakeholder regimes including from local and city level planning authorities, funding agencies, responsible political authorities, and environmental stakeholders, among others, placing specific constraints on design decision making. There still, however, needs to be a place to discern the constraints and assess performance requirements against intended benefits with the involvement of the end-users to enrich the decision-making process. The overriding requirement in case study one appears to be driven by economic and geopolitical factors. In case study two, there appears to be a broader approach from a geopolitical, sociocultural as well as economic performance perspective but all constraining the process in many ways. Requirements from an end-user perspective can thus in turn be constrained by the preconceived possibly predicated constraints. Integrating end-users into a participatory decision-making process has been reported elsewhere to bring benefits to projects. However, the tools used, including the rationalistic and visual-based aids, seem inadequate to discern the inherent complexities of projects. Modelling with DESIDE thus finds that housing alternatives based on economic and geopolitical performance as the overriding constraints needed to look beyond the choices adopted by decision-makers. The resilience of current choices against emergent and changing needs is suggested by the tool to be inadequate. The confidence level in the choices is also arguably below a threshold in a rigorous sensitivity analysis. Modelling refinement, in this case, appears to be around considerations of mixed-use alternatives to address emergent needs like geopolitical, economic, socio-cultural and health and safety shifts, among others. Unrelated research from case study one has shown many users to quickly embark on changes to their new homes, while security and affordability issues have also been reported in soon commissioned condominiums. These requirements are emergent from understanding user needs to the extent that evidence has shown some of the developments to underperform on their intended benefits quickly. The decision support system results from the analysis suggest a wider integrated design approach for mixed-use designs developed through participatory decision making. A similar narrative can be drawn for case context two.

7.9 Summary

This chapter has sought to discern some of the main strengths of DESIDE in addressing the limitations of current decision support techniques and methods. This included analysing the results from the case studies to find intrinsic conceptions that contribute to FED Benefits Realisation when the tool is applied to model and support decision making. A key observation is that in the main techniques and tools currently in practice are inadequate for the increasing complexity of FED processes in the delivery of project benefits and were evidently short in the two studies. They fail to model and manage requirements, assess interdependencies among them and forecast any emergent impacts from them onto Benefits Realisation. The uncertainty in processes because of dynamism in both processes and contexts is almost ignored in current tools, yet appears an invaluable part of the process. Thus, the author presents the proposed system as a step-change in bringing rigour, structure, and modelling capabilities to FED decision making. Throughout the discussion, the strengths of the proposed system are highlighted not least its ability to facilitate collaborative and participatory FED decision making in both defining the design problems and development of alternatives by managing and modelling of the project requirements. This overcomes many of the current limitations in decision support tools while introducing to FED a new technique for decision making that goes beyond the predominantly rational and visual-based techniques in present practice.

8 VALIDATION AND EVALUATION

8.1 Introduction

Chapter one set out the research aim and the objectives of this research to be addressed that included the development of a decision support system for FED Benefits Realisation. Part of the requirement of a rigorous decision support system was the ability for it to account for uncertainty within the body of evidence that informs design decision at this stage. Another important element was the ability for requirements forecasting alongside a utilitarian assessment using the ranking of attributes, in an integrated system. It is therefore important that rigour is enhanced through an evaluation and validation process; also highlighted as an essential aspect not just for any research more generally but for any proposed system (see 4.8). Validation and evaluation add credibility by ensuring systems as is proposed in this research can stand scrutiny and be assessed for their robustness. The consistency of the proposed system and how its component parts work in tandem to support the various facets it models is, therefore, an important part of this research. The validation and evaluation process are two-part; first from a component level through a rigorous peer-reviewed journal and secondly in a project setting of case study B for the full model through multiple of expert feedback – using a questionnaire survey (see Appendix H).

8.2 Consistency of decision support system

There are no widely accepted norms for consistency validation or evaluation methods for systems as is proposed in this research (Gass 1983). Gass (1983) essentially suggests that any consistency adopted in research is merely reflective of the specific requirements and goals of the research. Montibeller (2005) demonstrated the use of constructivism as part of a validation/evaluation process, arguing that participants in this approach contributed to the structuring of the process. The constructivist approach, therefore, aims to have, as part of the validation/evaluation process, views, judgements and opinions of a process or artefact through processes as of individual expert feedback/evaluation. The constructivist approach contrasts with the realist approach that would merely adopt the proposed system as is. The constructivist's approach adopted in this research, therefore not only assesses the methodological and theoretical but also the operational validity. In this research, the constructivist approach beyond these validation points to encompass to include validations of the component elements (see section 5.3.4). This latter validation process was also used for theory validation. Consistency validation as part of case study B explored practical implications of the proposed system from the perspective of expert stakeholders and end-users including design, contractor and maintenance teams, facility, and company management.

Table 52 is a summary of some of the validity techniques in research. Simulation and animation are graphical, while Comparative Modelling allows results to be compared to another validated model. This stage is applied in this research at points when e.g., a MOORA and COPRAS analysis for Utilitarian assessments of attributes/benefits is carried out. This is part of a multistage validation strategy that the research adopts i) first by developing the theoretical positions required to justify the components of the decision system, ii) validating these components through case study A empirically and iii) carrying out a second case study B for an overall comparison of modelling results and validation.

Degenerate tests, on the other hand, allow for testing of degeneracy through adjusting for input values. Event validity assesses operational models as to the occurrence of specific events while Extreme condition tests test the validity at extremes of the model. Face validity that is applied in this research allows the validation process to examine the behaviour of the model and underlying logic through a constructivist approach. A related validity method is a Turing test which employs expert input in differentiating a model from its outputs. In Traces validity, which is employed for the first part of the model validation (in case study A), parts of a system are tested to support overall verification of the full model (Poplawska, 2014).

Other validation techniques, like Historical data validation and historical methods can be applied for various areas of research e.g., in building and testing of models and rational, empirical, and positive economics model tests, respectively. For stochastic variability in a model, internal validity can be applied while multi-stage validity can involve various levels of model development and input-output data comparison. In operational validity, the model's correctness is checked against its performance while predictive validation forecasts a model's performance. Sensitivity analysis also contributes to model validity in the sense that internal parameter values can be adjusted to assess a model's behaviour.

Table 52 Summary of Validity Techniques in Research

Technique	Description
Simulation/Animation	This method compares to actual system behaviour any developed graphical animations or simulations as a way of establishing its operational performance.
Comparative Modelling	Results from a valid model inform a basis for comparison in this evaluation technique.
Degenerate Tests	This technique tests the degeneracy of a model by varying input and internal test parameters.
Event Validity	This is a similarity comparison of events between observed events from an operational and those from an actual model/system
Extreme Condition Tests	This technique tests the limits of the Structure and outputs of a model against extreme data sets and combinations.
Face Validity	This technique uses expert knowledge to assess behaviour and operational logic of a model/system.
Historical Data Validation	Parts of the historical data sets are used to build and test a model/system while the other parts are used for comparative testing of the new system/model.
Historical Methods	The three historical validations in this technique include Rationalism, empiricism and positive economics that are the basis for validity testing.
Internal Validity	In this technique, consistency and internal variability of a mode/system are tested as a way of establishing any internal stochasticity validity.
Multistage Validation	This technique applies the historical methods i.e. rationalism, empiricism, and positive economics in a) developing any theoretical assumptions behind a model/system and the theory behind it, b) apply empirical validation to the model/system, c) compare the results from the model/system against those of an actual one.
Operational Graphics	This technique assesses the operational consistency of a model/system as it is continually tested and assessed during performance overtime against a set of indicators.
Parameter Variability-Sensitivity Analysis	This technique involves the generation of results from a model through varying input and internal parameters to assess any operational variations that can be compared to an actual system.
Predictive Validation	This technique forecasts the validity of an actual system using test and operational assessment results from a model/system's data or behaviour against those of the actual system.
Traces	In this technique, the accuracy of a model/system is determined by assessing/testing and verification of its various constituent parts.
Turing Tests	System/model experts are used to set and define a model/system from its results in this technique.

In case study A, face validity ran from June to September of 2019. Participants were educated of the importance of the system components that built their understanding of the expected performance and results. Validity in the second part run comparative tests of the results from the various sets of data analysis. A degeneracy validity is important in an HMM analysis of high order attributes so that analysis is halted once the results become even (see Table 34 and Table 38). Face validity in this stage assessed the overall performance of the system using interviews with individual experts using questionnaire (Appendix H); in establishing the practical application of DESIDE in a real-world setting.

Individual expert feedback served the best alternative for this part of validation. The interview process opened with a 25 minutes presentation of the key concepts in FED and Benefits Realisation**,** so participants were oriented to not only the terminology but also the basic workings of the system (Dekkers et al., 2020). The orienteering is vital so that the individual experts stay in step with the themes, terminologies, and guides to understanding the results. A rating system based on Saaty (1986)'s rating was adopted as throughout the model development for consistency; to help guide participants in gauging the key aspects. Alongside this assessment, attention was drawn to the participant of the nature of input data that underlies the consistency of the proposed system, and how this translated into outputs to draw out any narratives. Input data in all system components of the decision system is in the form of real values that represent the assessed attributes. Together with a sensitivity analysis, input data would, at this point, be assessed as reliable data.

8.3 Validation/Evaluation Questionnaire and discussion

A questionnaire was adopted for the evaluation/validation process to elicit knowledge and judgements from the stakeholder panel (see Appendix H). The guiding principle for the questionnaire was to assess the accuracy, transparency, and completeness of DESIDE together with the degree of its comprehensiveness. The consistency assessment also attempts to rate the system on its cost-benefit modelling capability. Notably, the successful cross stakeholder evaluation process represents a significant level of transferability of the decision support system across different decision settings in a project's lifecycle. The questionnaire comes with a cover note drawing participants to their rights in participating in the evaluation process as part of the wider ethical approach for this research, and this was also relayed verbally to the participants. The questionnaire is also explicit in the quest for a consistency validation of the system – explaining what was required of the participants and drawing their attention to the graphical model underlying the decision system design. The evaluation of the team and the results are summarised in *Table 54*.

Table 53 Summary of Participants for Evaluation

Participant		Role and Expertise	Years in Role
Chief Executive	CEO	Managing Charity	12
Compliance Manager	CPM	Managing Charity	4
Facilities Manager	FM	Managing Charity	3
Contracts Manager	COM	Project Contractor	4
Housing Officer	HOF	Charity Sector	5
Finance Director	FD	Charity Sector	6
Project Manager	PM	Managing Charity	20
Care manager	CAM1	Managing Charity	3
Designer/Architect	ACH4	Project Architect	6
Care Manager	CAM2	Managing Charity	3
Funding Manager	FM	Project Funder	5
Site Manager	SM	Project Contractor	10
Housing Manager	HOM	Local Government	2
Academic	ACA1	Urban Planning	12
Academic	ACA2	Construction	15

Table 54 Participant Responses During Evaluation

Evaluation Question	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Importance of Uncertainty and accounting for Requirements changes in FED	8	7	8	8	9	8	7	7	8	9	8	8	7	7	9
the importance of Cause Effect Analysis	8	8	8	9	6	7	7	8	8	6	7	8	9	8	8
Importance of and Capability of decision support system to assess utilities	7	6	5	8	8	8	7	9	8	8	8	7	6	7	8
Suitability of the nine major categorisations in representing the thirty-six lower order requirements	7	8	8	6	6	6	5	6	5	7	8	8	8	5	8
Capability of Utilitarian Ranking of Benefits in FED	7	7	8	8	8	8	6	7	6	7	6	7	6	7	7
Capability of Assessment of Cause Effect Analysis in FED	8	7	7	8	8	8	8	7	9	8	8	8	7	8	7
Ability of Decision Support System to integrate the multiple Stakeholders and their requirements	7	7	8	8	8	9	9	9	7	7	8	8	7	8	9
Comprehensiveness of DESIDE	8	8	8	7	7	8	9	9	8	7	7	7	8	8	9
Suitability of DESIDE for dynamic contexts as opposed to alternatives	7	7	6	6	7	6	7	6	7	6	7	7	7	7	7
Adequacy of methods/ tools applied to address the problem	8	8	7	8	7	7	7	7	6	6	8	8	8	7	7
Acceptability of the decision support system in meeting in Supporting the project objectives	8	7	7	7	7	9	9	9	9	8	8	7	7	9	8
Assessment of overall decision support modelling structure	7	8	8	9	9	9	7	7	7	8	8	8	7	9	8

8.3.1 Assessing the Importance of Uncertainty and accounting for Requirements changes In FED Decision Making

Uncertainty in design can be a major influencing factor in the eventual decisions taken in projects in meeting the project benefits. Similarly, emergent requirements sometimes mean some project decision making is inadequate if emergent contextual events are not integrated into a project. Participants assessed the importance of uncertainty and emergent requirements in FED. All respondents agreed the two elements were crucial to design discourse. Participants agreed more generally that the decision support system's ability to discern contextual uncertainty and requirements changes in both case studies was demonstrable. The spirit was summed up as *"The idea is very good to bring to the industry an integrated analysis of uncertainty in benefit realisation in projects and the logic seems clear though might need further development"* (CEO).

8.3.2 Assessing the importance of Cause-Effect Analysis in Benefits Realisation

This research finds that the effective understanding of the cause-effect relationship among project benefits is an important layer in decision analysis. Participants assessed the capability of the proposed system in computationally modelling analysing and graphically presenting these relationships. All respondents agreed the system was comprehensive enough in this analysis and that the results contribute to a better understanding of the intricacies of decision making, based on cause-effect relationships in project benefits.

8.3.3 Importance of and Capability of the decision support system to assess utilities/ Rank attributes

Utilitarian decision making with a focus on the utility of outcomes is a classical decision-making approach that has been adopted in DESIDE's modelling. Participants were asked about the relevance of a decision-making approach for FED as is proposed. Only five of the participants felt this was particularly important in a FED setting. The other participants suggested that research around this concept required more exploration to integrate its relevance in design practice among other observations. Participants, on the other hand, assessed the ability of the decision system in ranking design attributes in a manner that was methodical and guided decision-makers. Ten participants rated the modelling processes extremely adequate in dealing with utility ranking. Regarding the capturing of user requirements for both the HMM and Utilitarian assessments *" …there needs to be a strong methodical link when you integrate the room setting of the benefit realisation model with a design case to support the evidence* *aggregation to support the dynamics of URs*". Part of this can be solved through automation of the capture process that integrates the fANP process for further subjective analysis. The process for this was explored in section 3.4.2 and can be part of further process improvements.

8.3.4 The comprehensiveness of DESIDE

The basis for the development of DESIDE was to address gaps in current tools e.g. the inability to model complex interdependencies in attributes that could impact on Benefits Realisation, inadequacies in accounting for emergent needs and requirements; and the lack of accountability for uncertainty in design decision making particularly for complex and dynamics decision settings in FED. The comprehensiveness of the decision support tool in meeting all these requirements is, therefore, an essential element for this research. Participants were invited to assess how comprehensive the DESIDE is in meeting comprehensively the goals set out. There was unanimous agreement in the system's ability to meet this requirement ranging from *'extremely meeting'* to *'very well meeting'* this requirement.

8.3.5 Suitability of DESIDE for dynamic contexts as opposed to alternatives

The methodological imperatives of developing this DESIDE were first set out in section 4.2 and validity considerations regarding this research in chapter 8 (see 8.2 above). Both positions meant that the validity of the proposed system is dependent in part on participants' assessment of the decision support system's applicability as opposed to alternatives to design decision making in dynamic contexts. Observations were made, for instance in exploring how the computational method could complement existing decision support methods like model-based or visual aids. It was suggested that this way, the tool would be able to find practical applications quickly in current design environments. `

8.3.6 The ability of the Decision Support System to integrate the multiple Stakeholders and their requirements

The reliability of the results from the decision support system much depends on the level of expertise and knowledge of participating stakeholders. This meant that collaboration is an essential element in any system modelling proposed. Participants were therefore asked for their views on how much the system supported collaboration essential in FED. Participants agreed that the categorisations of requirements supported collaborative design across all levels of project stakeholders that in turn, supported the generation of quality input data for modelling.

8.3.7 Acceptability of the decision support system in meeting in Supporting the project objectives

The main purpose of DESIDE is to address complexity with design processes at FED. A major part of the appropriateness of the system is, therefore, in as much as it meets the goals and objectives of the research set around process complexity in FED. Participants were therefore invited to evaluate this appropriateness, and all agreed extremely or to an appropriate level that the system represented the aims of the research. The cumbersomeness of the modelling process and the sources of input data were raised as areas that would need further consideration to increase the system's practical use perhaps through measures as use of programming.

8.3.8 Suitability of the nine major categorisations in representing the thirty-six lower-order requirements

Regarding requirements, the evaluation sought from participants their perceptions as to the thirty-six requirements. This was to establish whether they reasonably represented the key elements in FED. All participants rated them between extremely reasonable and reasonable, highlighting the important breadth of requirements consideration. Other suggestions included *'due diligence'*. The importance of any categorisations depended on the background of the participant. For instance, while some considered project governance as important – owing to their project management background, others considered aspects related to cost for those with a construction management background.

8.3.9 Assessment of overall decision support modelling structure

The relevance and coherence of DESIDE was another subject of evaluation. Participant perceptions were sought as to its ability to represent the research goals and objectives and its representation of relevant components guiding its modelling capabilities on the other. There was agreement as to the relevance of the decision system among participants. However, some participants wondered whether the concepts could be applied more widely and more generally across many decision-making settings. This latter position presents some interesting future opportunities for exploration of the limits of the decision system of applicability.

8.3.10 Suggestions for alternative integrations or tools

The development of DESIDE looked at the wider applications of decision making in FED across AEC. While the literature review attempted an extensive assessment and analysis of the appropriate components and techniques, respondents' views would also be vital to strengthen the validity of the proposed system further. Alternative components or methods were elicited from participants as part of the validation/evaluation process. The extensive modelling processes were an interesting area that some participants thought could be replaced by alternative methodologies. But in the absence of similar and complementary methods and tools of the same capabilities as those adopted for the system, two of those participants with extensive knowledge of the application of probability theory in prediction and uncertainty modelling felt that system was current in its tools and methods. Areas identified for further improvement, however, were identified as sensitivity and consistency analysis (see *Figure 8-1*).

8.3.11 General suggestions for Other integrations or tools

Participants views on any suggestions for future development or improvement of the model/system were also important in building its validity. All participants agreed on the appropriateness of the methods and techniques employed in building the decision system. A key element identified in support of the decision system is its consistency and elaborate adoption of tools that can model complexity and integrate subjectivity in a much more simplified manner than other tools can support. Together with the validity techniques employed, all participants felt the appropriateness of the system was demonstrable.

8.4 Findings from Evaluation

The importance and process of evaluation were first set out in section 4.2 to represent both the knowledge requirements of the research and research problem through assessing the effect of the decision system when tested in a real-world problem. It was established that alongside the workings of the system (effect questions), any process trade-offs had to be established. The proposed system is designed to be comprehensive and able to cope with dynamic and complex design environments, in FED that requires many trade-offs, particularly when considering attribute interdependences. Following the observation from respondents from the evaluation process, further scope of modelling in DESIDE (see *Figure 8-1*). Sensitivity and consistency of the system was seen to be an important element in contributing to the validity of the system and its further credibility during evaluation. This in a revised approach would affect the QFD, utility and ANP analyses stages in the utilitarian and uncertainty modelling cycles. This would therefore influence the nature and quality of information from experts, documentary reviews and user feedback, among others. The process would further enhance the quality of results though it would likely impact on the processing and modelling time.

Finally, and in overarching and anchoring all the considered elements, it was established that the importance of the validation and evaluation process was to ensure that both the stakeholders and research goals were met by any proposed system. The validation process was through the various validation approaches including comparative modelling, (in part supported by degenerate testing and peer review journals) and face validity (supported by of individual expert feedback/evaluation) among others to ensure that the system ranked utilities, accounted for uncertainty and subjectivity, as well as predicting high order emergent requirements. All the approaches have supported the position that the proposed decision system does meet all these requirements, including, of operational validity, comprehensiveness, transparency, sensitivity, accuracy, and meeting the first the aim and then the objectives of this research. It is, therefore, a useful tool in design decision making, particularly for dynamic and complex FED environments.

8.5 Summary

This chapter has drawn the critical link between the process of development of a design decision support system for FED and establishing its validity and practicability in two contexts. The chapter first set out why and how this process was important, including exploring the various ways this validation and evaluation process could be achieved. Observations as to the various elements of the system that rendered it valid were presented in the context of individual expert feedback. A computational cause-effect analysis was important in highlighting the intricacies and relationships among various project benefits for decision making; and providing a link between benefits realisation and uncertainty within its processes in FED.

The general perception of the model can be summed up by the position from one participant that *"The use of predictive analytics to inform FED is interesting and the research does a good job of motivating its use in the context of public housing projects. (ACA1)".* However, there are elements of DESIDE that understandably need further development (see *Figure 8-1*). One such concern is raised by ACA2 to the effect that:

"My primary concern with the results is that they do not adequately communicate the model results. It is unclear for instance whether the tool can be applied retrospectively or not.". (ACA2).

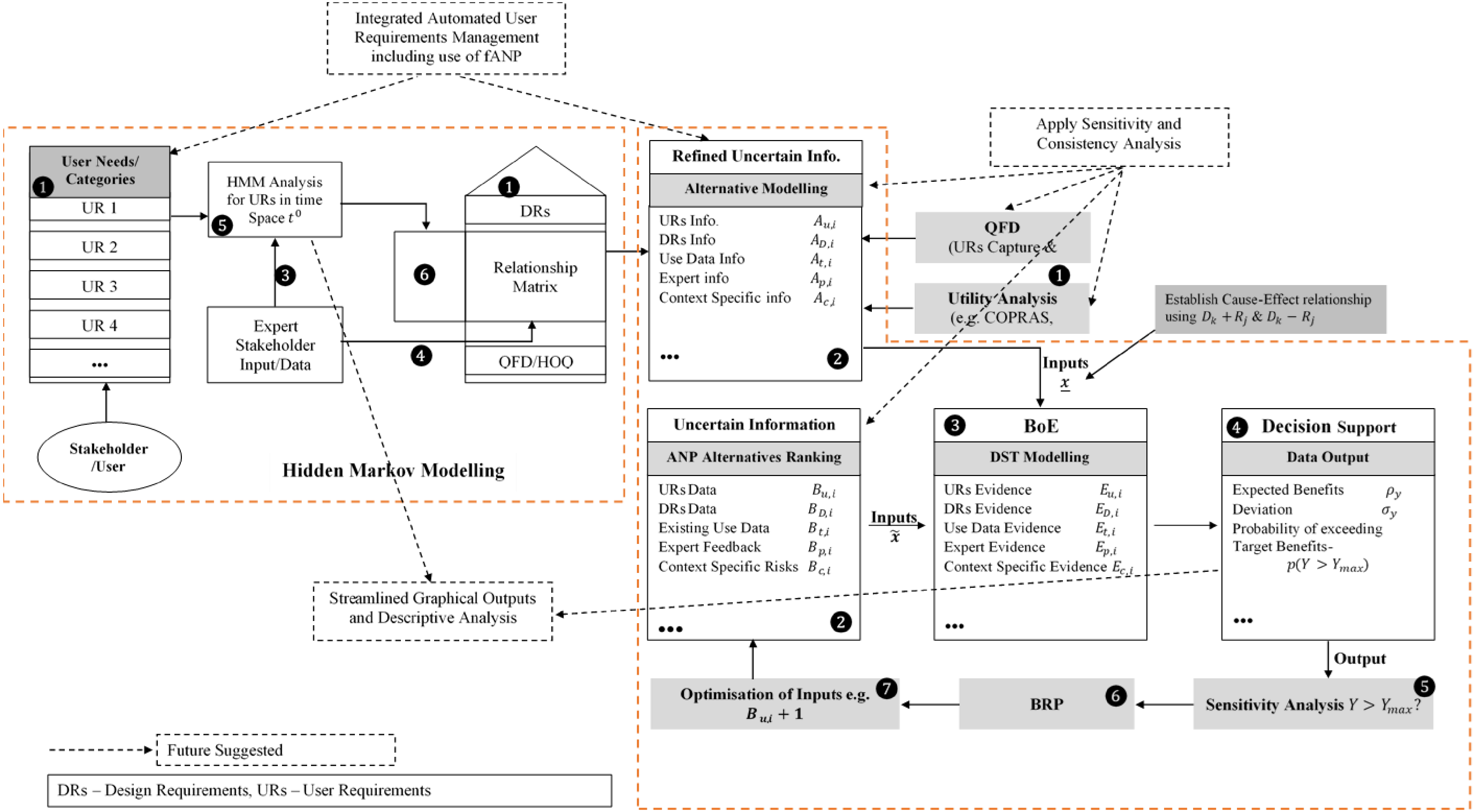

Figure 8-1 Final DESIDE Model

Observations like the above relating to clarity and rigour are illustrated in the revised model in *Figure 8-1* including areas relating to sensitivity and consistency analysis as well as visual/graphical results with descriptive analysis.

The application of DESIDE clearly needs to be strengthened in this area perhaps through improved visual/graphical analysis. Also, an area of further interest is exploring ways where the results pages can have improved descriptive analysis alongside any graphical representations or presented as part of a detailed generated report. The ACA1 and ACA2 observations are seen in the same light as (PM)…. *"As a side note, the complexity in connection with the procedure and representation may be impediment to the communication and decision process".*

This is true to the level that DESIDE can best complement complex and dynamic decision processes that are often seen in relatively large and complex projects that might need the support anyway. However, further research can help remove barriers to adoption for much less projects in size and complexity but may still be dynamic. Finally, there is an element of a need for general further study to understand the bounding limits of DESIDE's capabilities in other sectors or AEC as highlighted by ACA1.

"Finally, I suggest that the value of this work in the construction domain in general be enhanced. It might seem to me that this strategy is better suited for projects of a public nature -- perhaps the domain of urban planning would be a good home for this work. (ACA1)".

This view is quite legitimate as well as interesting in suggesting new strengths for DESIDE. It also suggests that there is a need for further studies to reinforce the modelling capabilities in alternative construction sectors e.g., in infrastructure, health or oil and gas design planning. Further capabilities need also to be explored in the realms of urban planning perhaps by extension to policy planning and development.

The following chapter presents the conclusions of this research together with future opportunities for and limitations faced by the research.

9 CONCLUSIONS AND FURTHER RESEARCH

9.1 Introduction

This chapter summarises the key research findings in how they met the requirements for the study aim and objectives. The key practical and theoretical contributions of this research are discussed considering the results from the modelling process of DESIDE. The chapter also presents the key limitations of the research as well as exploring future areas of research to improve the decision system. Parts of this chapter drawn from the varying observations in the related published works as part of the extant research.

9.1.1 Meeting the Research Aim

The research seeks to develop a decision-support System for Benefits Realisation in Dynamic Contexts in FED (see Chapter five). The proposed system described in Chapter five uses probabilistic DS-T and HMM and QFD and utilitarian MOORA and COPRAS computations is able to model interdependences among design attributes, forecast their changes, weight alternatives and model uncertainty in one integrated system. The proposed system, therefore, meets the aim set out for this research.

This has been demonstrated through progressive application and modelling of the DESIDE's components in case study context one and the detailed case study context two. HMM is applied to high order requirements to assess how they change over time. Both case contexts show that contextual factors are important in influencing the nature and scope of changes in these requirements. In the utilitarian analysis, requirements are ranked together with a cause effect analysis of the project benefits. Again, context specific influences are observed and demonstrable in the results. Finally, in the DS-T analysis, uncertainty in the understanding of both user and design requirements is seen to align with what clearly demonstrates the influences of *'structure and agency'* seen in section 2.2.4. Overall, the results from the evaluation indicate applicability of the system more generally to FED though further studies and improvements are suggested in the final DESIDE model (see *Figure 8-1*). The evaluation process (see Chapter eight) identifies DESIDE as a robust, structured, and empirically capable tool in modelling requirements interdependences and drawing our uncertainties in the BoE during decision making.

9.1.2 Meeting the Research Objectives

9.1.2.1 Research Objective one

As a starting point, the first objective of this research was to establish the state of the art in the key concepts of Requirements Management and Benefits Realisation in their contribution to project lifecycle performance. In meeting this objective, the research sought to answer the research objectives through firstly, carrying out a systematic literature review. In the second phase, further knowledge of the intricacies and dynamics of Requirements Management is built through interviews, questionnaires to research participants and other data gathering techniques alongside documentary reviews all of which are covered in chapters 2, 5 and 6 of this thesis.

The state of the art in Benefits Realisation and Requirements Management

This research aspect is answered in section 3.2 and subsequent analysis in section 7.3 where it is established that while Requirements Management is covered by a wide body of research, this is not the case for Benefits Realisation. It is also more importantly found that there is a lack of convergence in the two concepts, although they appear to be complementary and collectively vital in the success of projects. The two practices of Requirements Management and Benefits Realisation are also found to be key in influencing generation the early information and knowledge flow and exchanges in projects.

Potential factors in FED influence requirements changes

The research identifies a gap in understanding and practice of Requirements Management in FED. As a result of this and the disjointed body of research regarding the influencing role of Benefits Realisation and FED, there are notable biases in consideration and modelling of requirements. A systematic literature review develops a taxonomy in which thirty-six requirements in nine groups are identified (see section 7.3 and *Figure 7-3*). Among them, strategic value, collaboration, and project governance are widely applied as important project success requirements. In the categorisations, economic, technical, governance and environmental performance dominate the group of nine (see *Figure 7-2*). Knowledge of all project requirements is important in underscoring any mitigations should they change and any knock-on effect because of the interdependencies among them. Without full knowledge of the potential requirements sets, it is possible that modelling them can be a futile process, and alongside the limited research, any changes in requirements are impossible to model fully in the circumstance. Results from the case studies reveal that requirements categorisations and understanding also act as potential sources of requirements changes.

"*….we decided that in the next project in one of our highest standards of MCMV, we would put a waterproof slab, as we believe it would be easier and would solve various construction problems… however CAIXA does not allow it in the MCMV….. it is different for Band 1.. which is a demand from the (central) government, CAIXA (funding agency), city (local authority)*" RA1

RA1 infers influences from various stakeholders on various requirements, e.g., on those related to costs, materials, governance as a direct result of the interdependency with the geopolitics and governance.

How factors impact on Benefits Realisation

FED is explored as an intermediate Benefits Realisation process essential in the delivery of the higher project and organisational benefits. The research finds that ultimately, the dynamics of Requirements Management in FED do impact on the process of realisation of benefits. What RA1 essentially suggests above is that any influences ultimately mean changes to designs that will, in turn, impact on the benefits delivered for the project, e.g. through influencing costs.

9.1.2.2 Research Objective two

Similarly, in meeting the requirements of objective two, three focus areas support the identification, understanding and description of the current decision support tools for FED; and their limitations in accounting for dynamic and contextual factors that impact on Requirements Management. These include i), understanding the current state of the art in decision making ii) identifying the techniques and methods applied in FED, and iii) The objective contributed to highlighting gaps in understanding, research and application of decision making in FED. Building on this foundation in conceptual understanding required a separate systematic literature review to address the following:

Current state in design decision making

The answer to this research focus area is covered in sections 3.3 and 7.4 in which it was found that decision making is varied across AEC. It is mainly categorised as rational, hybrid, Visual or MCDM. The analysis found little research on visual aids comparably in the broader AEC FED process as a decision support method. The analysis at the same time revealed that on the current body of evidence; visual aids are limited in coping with complex design phenomena during FED. Visual aids as a major part of rational decision making are, however, noted for their particular dominance in construction design at 33% as compared to other decision methods in the sector (see Figure 7-4). This means that there is currently in research and practice, a bias towards model-based and visual aids decision support tools that may not be sufficient in modelling the intricate dynamics and in forecasting changes in user needs in dynamic contexts.

Techniques and methods for FED

Decision techniques and methods are essential elements in FED in supporting projects benefits delivery. The research found fifteen commonly applied decision-making techniques for FED decision making, grouped in four broad categories as explanatory/rational, MCDM, Hybrid and Visual methods (Serugga et al. 2020b). The research found that the most common of the MCDM is QFD, while among the rational/explanatory techniques is SBD. Similarly, the research found limited evidence of wide application of hybrid techniques although they present some unique opportunities to FED e.g. through complementarity. Hybrid methods had wide appeal in Engineering Design (25%) and only 10% in construction. While MCDM techniques appear to be taking a strong hold in their application recently in all areas of AEC, these are mainly variants of QFD in the main. While there is limited application of MAUT in decision making, this research finds that the robust consistency and structured approach better captures the intricate dynamics of FED, including modelling of the subjectivity, interdependences, and uncertainty in design discourse.

How the techniques and methods facilitate utility of decision making in FED

The MOORA and COPRAS assessment results confirm the need for a collaborative design process from a user perspective (see sections 5.4.2, 5.4.3, 6.2.5 and 6.3.3). As well as the robustness of the adopted approach, the system supports an open and structured FED decision making where evidence is the key driver for process. The decision support system proposed presents a computationally consistent and easily adaptable approach to supporting decision making in FED based on utility theory. The robust approach is also able to simultaneously accommodate any number of even conflicting quantitative and qualitative attributes using QFD and ANP relationship matrices, whilst supporting an objective and logical value generation in design decision making in the process.

The concepts of Benefits Realisation date back to the 1980s (Bradley, 2016). However, it is only the last 27 years since Koskela (1992) remarked on the need for new production theory in

AEC processes (i.e. with a focus on value creation, that there has been an increasing flurry of conceptualisations based on the TFV model); that have focussed minds at the intricate process in the benefits realisation cycle. FED is an intermediate process within the benefits realisation of project but plays a key role in setting the basis for further successes in projects and programs As a process that is influenced by 'structure and agency' FED is inherently uncertain while at the same time, the requirements management processes that form a key part of it alongside any stakeholder, knowledge and information sharing and management; make it a vital process in the realisation cycle. User expectations have changed markedly in the time of this new process understanding in AEC in part due to their changing sociocultural, geopolitical, technological, and environmental trends. Their expectations have, however, come up against a still predominantly fragmented construction industry focussed on short-termism (Tezel et al., 2018). Tezel et al. (2018) highlights a lack of coherency in continuously resourcing the decision-making process, particularly in FED as a result of processes that limit wider participation (Kpamma et al., 2017) and collective decision making during value co-creation (Liu et al., 2018).

The understanding of decision making in FED including the methods and techniques was, therefore, important in the process of recasting decision making focussed on the utility of outcomes. The research has found that while some techniques can facilitate utility of decision making, MAUT's complementarity, versatility and robust structure meant that it was the best place for utilitarian assessments. The proposed decision model adopts a utilitarian approach to analysis but within the complementarity of tools like QFD to model inter attribute interdependencies, DS-T for uncertainty modelling and HMM for requirements forecasting.

9.1.2.3 Research Objective three

This research objective sought to propose and describe an integrated mathematical based FED decision support system for Requirements Management and forecasting, and uncertainty modelling based on utility theory for FED. Chapter four addresses this objective as follows:

> *Complementary tools used in modelling requirements interdependencies, uncertainty and predict any changes in one integrated utilitarian decision system*

The decision support system is built around a core integrated DQFD-UT-DS-T/HMM model (see section 5.3.1 and illustration in *Figure 5-4*) for FED, able to cope with dynamic requirements. QFD has been described as a strong application in management of project requirements by modelling of interdependencies among them using the HoQ matrix. It is a basis for trade-offs during requirements transformation to evaluate the strengths of both sets of requirements and criteria through pairwise comparisons. The weighting of attributes and criteria coalesces end-users and designers in generating value for the project while focussing on project benefits.

Consistency checks using the Saaty (2004) ANP approach ensures that user and experts' feedback can be synthesised in a manner that supports prioritisation and ranking of criteria. Further consistency by exploring the nature of the decision maker's utility function serves to reinforce the analysis processes in the same light. The complementary nature of DQFD and utility theory in their conceptualisations supports weighting, relative importance analysis and assessment of correlation between various criteria. Above all, however, A MAUT-DQFD model is an essential building block for probabilistic DS-T (uncertainty modelling) and HMM (requirements forecasting) to further reinforce the versatility of DESIDE. The decision system's component parts and steps are developed due to their complementarity and concepts gathered through applications in the literature in wider AEC, and refinement following analysis of empirical studies so as to address FED process-specific requirements like dynamics in information flow and exchanges.

The system is able to support analysis of multiple interdependencies of complex FED settings including contextual issues pertaining to design the research case study contexts like Constructability, Compliance, Functional Space, Materials Use, Design Form, Costs, and environmental factors among others. The weighting of the interrelationships is an important step in capturing the dynamics. The tools utilise subjective expert opinion in the form stakeholder feedback as well as raw concrete data for aspects as emission and transition probabilities. The methodical approach of DESIDE comprises of formal steps of data acquisition and entry by use of expert, user and other stakeholder input which ensures a participatory and collaborative analysis process during design.

DESIDE supports utilitarian assessments incorporating mathematical cause-effect analysis of interdependent attributes and integrating subjectivity od decision making building on the prior QFD attributes modelling. Using MOORA and COPRAS analysis, alternatives can be weighted with the full contribution of each attribute to the overall weighting. Using modelling with DESIDE, this research was able to first to draw to the key influencing contextual attributes in the MCMV program in assessing how the design models and decision making contributed to benefits realisation. The computations suggest that a mixed model approach best serves the realisation of project benefits in MCMV. Similarly in case context two, the modelling suggests that the key influencing attributes are fast moving and therefore brings into focus the nature of design decision making in contributing to the benefits of emergency accommodation provision as well as related benefits of work, training, education, and mobility among others. Both case contexts demonstrate a break down in transitivity of decision making. The nature of the transitivity suggests that collaboration is not as is suggested and that user engagement needed to be enhanced in understanding benefits from their perspective.

9.1.2.4 Research Objective four

This objective sought to evaluate the performance of the proposed decision system in dynamic FED settings in case studies with a view of assessing how it impacted on benefits delivery. Chapters 5 and 6 addressed this objective by answering the following:

How DESIDE improves FED decision making for Benefits Realisation

Chapter 5 addressed two case study contexts that the decision system was evaluated in. In the case study context one, the study aimed to evaluate some of the important components of the decision support system, particularly the MAUT-DQFD. This involved eliciting data for the pairwise comparisons to ascertain the influence of the various design attributes on another. This model was supplemented by additional but separate evaluation of the forecasting component and the uncertainty modelling component by DS-T probabilistic approach. Participants with a wide range of expertise and stakeholder role in the development in both housing projects were elicited in this stage for the purpose of understanding the important dynamics and inform the configurations of the various components of the proposed system. It is the data that informed the subsequent evaluations that are now part of published research in journals. A key emphasis of the proposed system was:

i) can cope with unlimited numbers of attributes,

ii) integrate subjectivity of decision making as a way of reflecting the ‘agency and structure’ nature of design, and

iii) model uncertainty while having forecasting abilities to cope with changing requirements, in a single integrated and structured system.

While improving decision making by considering the breadth of alternatives, the detailed case study and subsequent analysis revealed the potential complementarity of the proposed system to existing decision making approaches, particularly rational and visual techniques. This adds the options available for decision-makers, particularly in complex decision problems. The decision system helped designers consider options more objectively. The versatility of the system also meant decision-makers had the ability to revisit their decisions to evaluate them and make changes where they thought transitivity was not forthcoming.

The evaluation process also revealed some outstanding weaknesses in the system, for instance in the cumbersomeness of the decision process. Up to this point, applying the decision support system requires some level of expertise and time-consuming process of data capture. Several recommendations were thus suggested, and areas of future improvement identified to develop the decision system further (see sections 8.4 and 8.5). Despite this, the tool was able to fulfil the requirements of the focus areas as it gave decision-makers new confidence from its results.

9.2 Research Contributions

This research makes both a practical and theoretical contribution to knowledge. In terms of theory, the contributions relate to how the findings address the gap identified in chapter two using DESIDE model. This is so the research can contribute to the advancement of the body of knowledge in decision making looking first, at the state of the art and secondly, how it relates to the delivery of project benefits. This is seen in the perspective of FED where contextual dynamics and uncertainties can weigh down on processes. The practical contribution, on the other hand, relates to how the proposed decision system can be applied to various settings to improve decision making in early project processes methodically as applied in the case studies.

9.2.1 Contributions to Theory

The complex interdependences among design attributes can now be modelled based on the user and design requirements as understood in dynamic and uncertain contexts, using the Dempster-Shafer theoretic and QFD. This capability in DESIDE has been built in this research's progressive understanding of FED state of the art. First it is established that because of the central role of FED in the benefits realisation cycle, it is increasingly coming into focus in the wider AEC processes. It has also been established in Chapter two, however, that this understanding is currently limited. Systematic literature review was, therefore important in establishing new knowledge areas in terms of the important dynamics of Requirements Management and decision making in the context of utility theory (see sections 3.2, 3.3, 7.3 and 7.4). The systematic review revealed in the conceptual gap in current bodies of research in linking FED as an important and critical process in the Benefits Realisation cycle (see sections 7.3 and 7.4). The review also revealed how decision techniques and methods played an essential role in supporting projects benefits delivery. Particular focus was drawn to decision techniques that are based on the utility of decision making (see section 3.4.3). The focus respected and reinforced the *'agency and structure'* nature of design (see section 2.2.4). The subjectivity of decision-makers was harnessed in decision making while the structure that the utilitarian decision process fostered ensured opportunities for consistency in design decision making. Glaring Biases in consideration or project requirements were also identified in the review that could potentially account for disbenefits in projects delivery (see section 7.3). Current approaches to capturing the important dynamics in FED are identified as rational in the main. Although hybrid and MCDM techniques have been applied elsewhere in AEC design, these have been limited at best and certainly not for FED processes.

DESIDE is thus vital in placating the gaps relating to uncertainty modelling and forecasting of requirements changes in user needs as well as bringing fresh understanding of project benefits in a utilitarian perspective; in current theory (see Chapter 5). It integrates the important interdependences among the various requirements and attributes in design using QFD's HoQ (see sections 5.3, 5.4 and 6.3.3).

DESIDE finally integrates HMM approach to support requirements forecasting. This probabilistic approach supports decision making basing on changing user needs. Thus, together with the predictive HMM (see sections 5.2, 6.2.7 and 6.3.2), DESIDE ensures that design processes stay in step and update continually as the changes in attributes. Alongside the capabilities to assess the future changes in attributes, the modelling up to this point keeps FED processes structured and relevant to the decision analysis. Probabilistic DS theoretic is essential in underscoring the uncertainties in the BoE, so decision-makers are aware of the level of confidence in their decisions (see sections 5.5, 6.2.6 and 6.3.4). This is quite an important departure from current rationalistic, hybrid and MCDM techniques as it adds rigour to decision making. The dynamic and complex demands on FED and projects, in general, mean that the decision system, in theory, can be a basis for robust assessments of an unlimited number of attributes in the same analysis (see section **Error! Reference source not found.**) and therefore able to cope with 1) complexity, 2) uncertainty, 3) interdependence. A consistency check process in the system creates a counterbalance adding to the rigour of decision making.

DESIDE can bring new understanding to FED of the nature of uncertainty and modelling capabilities. DESIDE also brings new understanding of influences changing high order requirements can have on benefits. The cause-effect relationships in project benefits can be important for design in focusing decision making on the key positive and negative influences.

DESIDE brings this understanding to design in an empirical manner. The contributions are not limited to the two case studies alone but present opportunities for wider context and project settings. Application of the decision system can gain wider usefulness with improving data sets, e.g., in the transition and emission probabilities in various project contexts.

9.2.2 Practical Contributions

An important potential application of this decision system is in the practical design decision making in FED, as evidenced in the evaluation process (see Chapter 8). The case studies analyse a total of thirty-six essential attributes (see section 7.3.1). Design decision making may be unaware of the attributes as dynamics in *geopolitics*, or *occupancy* that can be important in Benefits Realisation. The decision system in case study one, having taken all the attributes into account assessed that design discourse missed essential attributes for instance those relating to its prescriptive nature in the MCMV program (see section 7.4.1). This analysis suggested a mixture of design models for different income groups in developments as opposed to the approach adopted in the MCMV program. The emphasis on any attributes as *security, costs or materials use* in rational decision making could have been at the expense of attributes as mobility or occupancy patterns in the new designs. From a practical standpoint, therefore, DESIDE can elucidate model alternatives and related benefits through ranking both the utilities and computing for uncertainties in BoE something that can help designers evaluate what their decisions mean in practice.

9.2.2.1 Requirements Management

DESIDE (see chapter 4) presents some practical benefits to decision making in FED. First, the system supports a focus of decisions making on the utility of project benefits as a way of supporting Benefits Realisation in FED (see sections 6.2.5 and 6.3.3) by ranking utilities, highlighting cause-effect relationships in project benefits and computing for uncertainties in the design decision making as well as changes in high order requirements empirically. The high order requirements defined in section 3.2 and analysed in 7.3, including economic, sociocultural, geopolitical or environmental performance, among others, can be essential in focussing on the desired outcome of design performance because they form an important basis for the subsequent modelling. Lower order requirements seen in those sections thus rely on the clarity of performance on the higher-order requirements categorisations. So the first practical significance of the proposed decision system is identifying project-specific requirements using the visual aid based requirements taxonomy (see section 7.3.1) or process models (see *Figure*

5-6) to help distil understanding further prior to analysis. This brings structure to the process, but it also embeds a collaborative and participatory environment in the design process.

9.2.2.2 Uncertainty and Forecasting in FED

This research has demonstrated the practical implications of uncertainty on the realisation of project benefits (see sections 6.2.6 and 6.3.4). Uncertainty for instance impacts on the belief structure of decision making (see sections 2.2.4 and 5.5). The research in section 5.5 illustrated how an expanded knowledge frame results in further unknowns in an even more expanded frame with every new unknown brought to the decision-making setting. Every unknown can, therefore, make the decision-making problem more complex.

The modelling of uncertainty, however, does show consistency for user requirements decision making in accounting for uncertainty in the understanding of potential outcomes of benefits. FED uncertainty is a present feature and is by large contextual. An unstructured approach in quantifiably accounting for uncertainty in information affecting elements of its processes ultimately can impact on benefits delivery. Multiple and conflicting alternatives and inconclusive information due to uncertainty in the BoE can be analysed using incomplete decision matrices. With the ability to account for this uncertainty either through complete/incomplete, crisp of vague or dynamic information through the belief and plausibility structure, decision making is now able to analyse choice alternatives and trade-offs flexibly and more reliably. Conceptually, the state space in decision making, i.e. actions/decisions, the resulting lotteries and probabilities and outcomes, consequences/trade-offs and ultimately the benefits and utilities; is vital in understanding the conceptual dynamics of decision making. Critically, elements, patterns, interdependences, and boundary events are important to be empirically discerned for a particular stage of the process; in determining, for example, how far the role of the stakeholders is and its impact on the successful delivery of benefits in FED.

What this implies is that the decision support system can assist by applying the DS-T to the whole FoD, in order that decision-making can assess the level of confidence in the pronounced preferences for a given decision setting. With the knowledge of the housing alternatives and the intense dynamism in the project context for user benefits in case study two, the DS-T component of the decision support system was able to reveal high levels of uncertainty with the single-model social housing design approach. This increased when two or more models were considered (see section 5.2). The confidence level was, however, highest when the Very Low, Low and Medium-low housing design models were evaluated together. This suggested success in the assessment of the attributes required for social housing where particular constraints may bear on the requirements and their understanding (see section 7.3.1). DESIDE, therefore, for the first time in this case, brings to design practice the knowledge of awareness of unawareness as a way of focussing decision making on the utility of project benefits in FED.

Regarding FED, the research found that conventional practice has relied on rational approached merely based on the experience and intuition of decision-makers. Applying HMM to high order requirements integrated within the decision system brought an extra layer of awareness of changing user requirements in embedding resilience in design decisions. This is especially important for designers as it gave their decisions impetus and confidence in as far as exploring collaboration while assessing the performance of requirements of the design throughout its lifecycle. Benefits Realisation from a QFD-MAUT-DS-ANP as in DESIDE approach presents opportunities to focus the design process on the delivery of benefits through a collaborative and more structured approach.

9.2.2.3 Structured Decision Making in FED

The findings from both case study contexts reveal the importance of understanding the project context as stakeholder needs vary and change. The process of defining and managing of requirements and benefits in FED in the proposed system, therefore, comes with a significant degree of structure, unlike in conventional FED practice. The evaluation of the system revealed this was an immediate benefit as it can form a basis for downstream change and control processes. Having knowledge of how likely requirements can change, a level of confidence in the decisions made on the available alternatives, defined high order and possibly low order requirements and ranking of requirements based on the project-specific benefits in one integrated system brings structure to FED processes. Moreover, all the parameters accept the subjectivity of decision making, harness the context-specific dynamics and changing nature project requirements; rather than ignore or merely eliminate them in futility.

9.2.3 Limitations of the Research Decision Support System

The research sought to develop convergence on the key conceptualisations of Requirements Management and contextual uncertainty in Benefits Realisation through decision making in a FED perspective. While every endeavour has been taken to exhaustively explore the essential elements in informing a new decision system, their separate but wide bodies of knowledge mean this research may not have gone far enough. The research however narrowed on the main concepts through the exploration of relevant seminal works in building a unified understanding of the concepts. Recasting the concepts in a utilitarian perspective means exploring utility theory to greater depths. There is, however, a limited body of research on utility theory that is current which meant that the research relied on seminal works for instance by Keeney and Raiffa (1976) and Malak Jr et al. (2009) that may need developing to reflect advances elsewhere in research. Nonetheless, decision system was supplemented by the latest advances in probability theory while accepting that the seminal works still retained validity.

Design is a problem-solving process and solutions should be specific in addressing a specific problem. There is a limitation in this research of generalisability of both the results and attributes for analysis. The choice of case studies in this research may not fully reflect the contexts studied. The geopolitics in case study one is so wide that any generalisations from the results and perhaps the attributes may not be sufficient. Any future analysis using DESIDE may, therefore, have to go through a separate data collection and modelling to make the results relevant in addition to any need to reconfigure or redefine any constant attributes and parameters.

The nature of case studies also presented limitations in the cross-case analysis of the decision model. It should be highlighted that the wider methodological approaches the research adopted and the research strategy were a major contributing factor to the overall research rigour. The case study context one provided a wealth of data on the context-specific issues, but this was a cross-sectional study. Furthermore, the projects studied in the MCMV were across various sub projects and at various stages of development. The choice of participants was important in underscoring the various contextual attributes for analysis, but these participants, while all with knowledge of design and use of social housing in MCMV came from various backgrounds which could have affected the data for the analysis. In case study two, the project was a refurbishment, which means the data may not have reflected the full-scale dynamics as those represented by case study one. Despite the case study limitations, the research was able to capture the essential processes and dynamics representative of each context in a manner that supports analysis using the decision support system. Further case studies, perhaps a longitudinal study, could help in the future to contribute to further understanding any contextual strengths or weaknesses of the decision system and support its further development. This would still work well within the methodological and research strategy set out in this research.

One of the essential elements of support systems is to take away any cumbersomeness from decision making that may contribute to added complexity. One of the aims of the decision support system was to bring structure and model complex phenomena in evaluating design alternatives. From a practical basis, however, the decision system which is Microsoft excel workbook-based means data is manually inputted with no interoperability. Equations have been developed into the spreadsheet, meaning that any inadvertent alteration to one parameter may affect the overall results from the analysis. In addition to the general limitation of shared and collaborative analysis, this manual system adds an extra layer of complexity and cumbersomeness in computing for the various parameters. Maintaining the integrity of the spreadsheets is vital to ensure that there is consistency in the results.

Regarding the methodological approach, two case study contexts were used in the study. However, as seen during the evaluation and in preceding sections, the cases being mainly in the housing sector could have limited full understanding and context of DESIDE's capabilities as well as scope of the research itself (see section 8.5). The wider scope could have been potentially improved by studies in infrastructure or as suggested in the evaluation in urban planning and policy decision making. The subsequent evaluation of the system was also through questionnaires and guided interviews. The original intention was to organise workshops within the two study contexts, but this was revised due to the COVID-19 pandemic outbreak. The original approach could potentially have enhanced the value of the validation and evaluation process. Barring this and the time frame for this research, an additional third and alternative sector case study context could have brought extra rigour to the results.

9.2.4 Future Research

Three potential areas are identified for further research, concerned with i) the contextualisation of subjectivity during analysis alongside the adoption of the latest advances in this area of emergent body of knowledge and ii) parallel and longitudinal contextual studies. Regarding the first, this is to enhance the sensitivity analysis of the system by carrying out further studies to increase the reliability of forecasting and finally digitisation of the system to utilise the latest technologies in Internet of Things (IoT) and big data.

9.2.4.1 Subjectivity and Sensitivity Analysis

Using utilitarian concepts ensures that subjectivity of decision making is integrated rather than eliminated like in many rational systems in design decision making. This is, however, a developing area of research, particularly regarding the use of fuzzy sets to represent further the subjective nature of decision-makers. Further research into integrating the latest applications in subjective decision making, particularly on the weighting of alternatives is needed to improve the decision system in this area. Similarly, further study is also required in developing the transition and emission data for the HMM matrices. DESIDE has also adopted a sensitivity analysis, both at the level of attribute interdependency and at the probabilistic assessments of uncertainty. The author feels both areas could be developed further to, for example, integrate more robust consistency checks in the system. Additionally as highlighted in sections 6.2.7 and 6.3.2, a sensitivity analysis at the forecasting level would be necessary for highlighting specific areas of influencing parameters that could be adjusted as needed adding further to the rigour of the decision support system.

9.2.4.2 Further case studies and experiments

The author believes that the opportunities for the decision system are not limited to FED, social housing or indeed to any particular context a position supported by the system evaluation process. Further work is needed to explore what other areas the decision system could be applied to, for instance at the planning level of major infrastructure development plans through perhaps a retrospective assessment of design for their resilience to future requirement changes. In terms of the forecasting ability of the system, this is an area that again requires further experimentation to assess shifts in context factors affecting FED processes. Understanding these shifts will inform better configurations of the matrices in terms of block or isolated applications to contexts and how soon the data regularly needed to be updated.

9.2.4.3 Development of Application Software

It was earlier noted that the computations for analysis are currently in a workbook spreadsheet. There is an opportunity to further exploit the strengths of the decision system through the development of an online application that could improve data management to support real-time interoperability in analysis for similar or related decision settings. Digitisation of the system would also mean more resilient data updates to support the forecasting module of the decision system using HMM. This could, for example, mean that crime, attainment, development, geopolitical shifts, legislative changes, and related data can be updated swiftly for a particular context to better reflect perhaps through automation using IoT and big data. Such an application could also be used to retrospectively assess the resilience of designs before important future decisions like for local infrastructure development plans for communities or major planned refurbishments and retrofits with a real-time scoreboard and detailed analysis.

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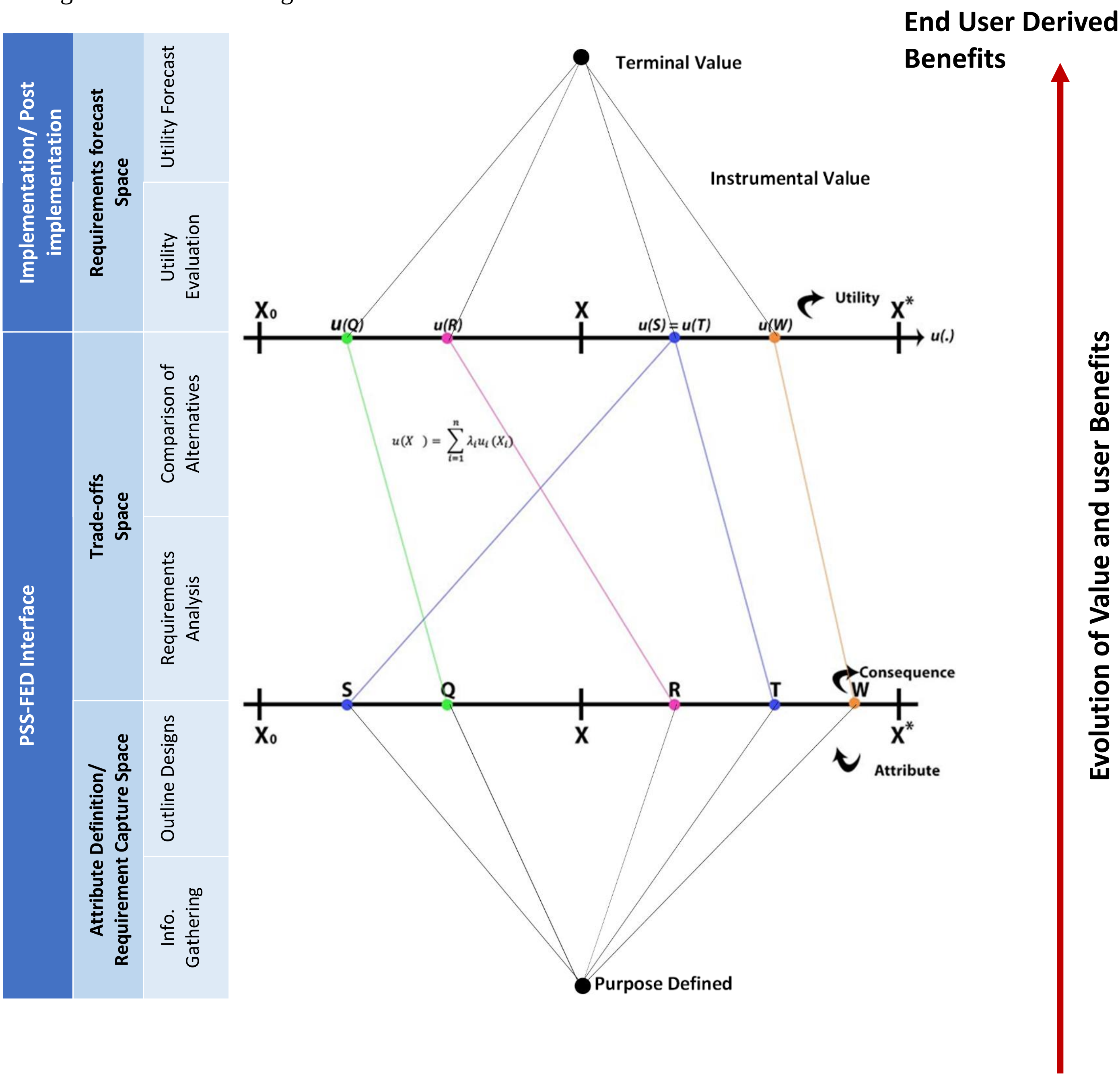
APPENDICES

Appendix A - A conceptual Illustration of Uncertainty and The Need for Requirements Management and Modelling



Appendix B - Questionnaire

About this Research:

Consent:

As a participant, you are entitled to a copy of the brief of this research that explains explicitly your role and how your consent is sought and can be withdrawn at will at any moment until 2 weeks of results publication. All this information is also available verbally should you need any further clarifications. A group presentation to any participating organisation is also available, through which major points of research interest can be presented. During the presentation, you have the opportunity to identify with the research and to change your mind should you wish to as to your consent.

Your Right to Withdraw your participation:

Data Capture and management and protection processes – Your participation is anonymous, and you are reminded of your right to withdraw your participation should you perceive the process to run counter to your prior understanding. We have a proactive data management processes, including locking away any data in a safe drawer and using encrypted email service.

Harm – While there is no prospect for physical harm to anyone as a result of this research, emotional harm is being considered. Should you feel in any way emotionally distressed as a result of your participation in this research reminded of your right to withdraw your participation should you perceive the process to run counter to your prior understanding.

I confirm that I have been given information in this form on ethical issues and that I understand my rights in regard to my participation in this research. (Electronic confirmation is sufficient).

Researcher: - Joas Serugga – University of Huddersfield, U.K., - Supervisors: Prof. Mike Kagioglou, Prof. Patricia Tzortzopoulos

PhD Research:

Title: A Decision Support System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts

Research Aim: To develop a Front-End Design decision-support System for Benefits Realisation in Dynamic Contexts

Objectives:

- To describe the state-of-the-art in Front End design and Requirements Management and their relationship to Benefits Realisation in project life cycles.

- To identify and describe current decision support tools for FED decision making and identify their limitations in accounting for dynamic and contextual factors that impact on Requirements Management.
- To Propose and describe an integrated FED decision support system based on probabilistic mathematical modelling
- To evaluate the proposed decision system through case studies with a view of assessing how it impacted on Benefits Realisation from a FED perspective

Questions for Research

Questions specific for End Users are marked **(A) -** Designers and technical Stakeholders **(B)**

Rating of Importance: You may rate importance factors according to the following scale
Not at all Important **(1), to** Extremely Important **(9)**

1. **What role are you in the Project Process?**

End-User	☐	Design Team	☐	Owner/Company	☐	Contractor	☐
Consultant	☐	Funding	☐	Authority/Specialist	☐	Other Stakeholder	☐

2. **How type of accommodation/occupancy is the project/home?**

Family 2-4 Occupants	☐	Single Occupancy	☐	Family of >4 Occupants	☐	Supported Living	☐

3. **Please Rate how the following influence home needs (Rate 1-9)**

Family/ Occupancy	☐	Economic/Finance	☐	Friends/community	☐
Sociocultural	☐	Environment	☐	Lifecycle Performance	☐
Technical/Specification	☐	Leadership/ politics	☐	Project Governance	☐

4. **Please Rate how important it is for the following for design needs. (Rate 1-9)**

Not at all Important **(1),………,** Important **(5),………..,** Extremely Important **(9)**
Economics Factors

Cost of Construction		Project Costs		Strategic value			
Sociocultural							
Mobility		Integrated Design		Culture/Community		Demographics	
Health and Safety							
Safety		Acoustics		Flow of Spaces		Hygiene/Health	
Security							
Technical Aspects							
Constructability		Legal/Compliance		Design Form		Collaboration	
Project Processes		Functional Design		Lead Times		Specification	
Lifecycle Performance							
Accessibility		Serviceability		Maintainability			
Occupancy							
Occupancy Levels/patterns		Financial Status		Social Status/Aspiration			
Environment							
Materials Use		Adaptability		Lifecycle costs			
Energy Performance				Physical Management			
Geopolitics							
Political Leadership				Legislation/Policy			
Governance							
Project Governance		Project Context		Stakeholder Management			

5. **Please Rate how the following influence user needs (Rate 1-9)**

Family/ Occupancy		Economic/Finance		Friends/community	
Sociocultural		Environment		Lifecycle Performance	
Technical/Specification		Leadership/ politics		Project Governance	

6. **Please Rate how important it is for the following for user needs. (Rate 1-9)**

Not at all Important **(1),………,** Important **(5),………..,** Extremely Important **(9)**							
Economics Factors							
Cost of Construction		Project Costs		Strategic value			
Sociocultural							
Mobility		Integrated Design		Culture/Community		Demographics	
Health and Safety							
Safety		Acoustics		Flow of Spaces		Hygiene/Health	
Security							
Technical Aspects							
Constructability		Legal/Compliance		Design Form		Collaboration	

Project Processes		Functional Design		Lead Times		Specification	
Lifecycle Performance							
Accessibility		Serviceability		Maintainability			
Occupancy							
Occupancy Levels/patterns		Financial Status		Social Status/Aspiration			
Environment							
Materials Use		Adaptability		Lifecycle costs			
Energy Performance				Physical Management			
Geopolitics							
Political Leadership				Legislation/Policy			
Governance							
Project Governance		Project Context		Stakeholder Management			

7. **How important is understanding requirements interdependences help in highlighting important project benefits (B)? (Rate 1-9)**

1		2		3		4		5		6		7	

8. **How Important is modelling requirements interdependences important in supporting** Benefits Realisation **(B)? (Rate 1-9)**

1		2		3		4		5		6		7	

9. **How do you manage user requirements during the design process (B)?**

Informal Discussions		**Structured discussions Qualitatively (tool)**		**A** Requirements Management **tool**	

10. **How do you make decisions during the design process (B)?**

Informal Discussions (Qualitatively)		Structured discussions Qualitatively (tool)		A decision support tool (Quantitatively)	

11. **How do you quantify, if at all, the quantitative requirements?**

Appendix C – Ethical Approval

THE UNIVERSITY OF HUDDERSFIELD

ADA Ethics Committee

POSTGRADATE RESEARCH STUDENT ETHICAL REVIEW FORM

Please complete and return via email to alex.thompson@hud.ac.uk along with the required documents (shown below).

SECTION A: TO BE COMPLETED BY THE APPLICANT

Before completing this section please refer to the Business School Research Ethics web pages which can be found under Resources on the Unilearn site (Ethics Policies and Procedures). Applicants should consult the appropriate ethical guidelines.

Please ensure that the statements in Section C are completed by the applicant (and supervisor for PGR students) prior to submission.

Researcher(s) details	Joas Serugga (U1769796)
Project title	A System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts
Award (where applicable)	PhD
Supervisor details (where applicable)	Prof. Mike Kagioglou, Prof. Patricia Tzortzopoulos
Project start date	8th/01/2018

SECTION B: PROJECT OUTLINE (TO BE COMPLETED IN FULL BY THE APPLICANT)

Aim / objectives of the study Aims and Objectives need to be clearly stated and in accord with the title of the study. (Sensitive subject areas which might involve distress to the participants will be referred to the Course Approval Panel).	The research aims to develop a system for Benefits Realisation in Front End Design (FED) of Construction Projects. Specific objectives include: I. To identify and describe current decision support tools for FED decision making and identify their limitations in accounting for dynamic and contextual factors that impact on Requirements Management. II. To Propose and describe an integrated mathematical based FED decision support framework for Requirements Management and forecasting, and uncertainty modelling based on utility theory for FED. III. To evaluate and validate the proposed framework through case studies with a view of supporting design decision making in FED. IV.
Brief overview of research methodology The methodology only needs to be explained in sufficient detail to show the approach used (e.g. survey) and explain the research methods to be used during the study.	An empirical study will be conducted with the stakeholders of a housing association. The main sources of evidence include: (i) open-ended and semi-structured interviews with architects and engineers involved in design, as well as client representatives e.g. housing association manager, council representative, and others; (ii) open-ended and semi-structured interviews with end users (iii) analysis of documents: 2D plans, 3D models, operational process descriptions, and different codes and regulations; and (iv) direct observations.
Does your study require any third-party permissions for study? If so, please give details, e.g., company permission	Management permission will be needed by the participating organisation (housing association) and will be arranged ahead of the case study
Participants Please outline who will participate in your research. If your research involves vulnerable groups (e.g. children, adults with learning disabilities), it must be referred to the Course Assessment Panel.	Participants will be selected based on their expertise, availability, and willingness to participate in the design processes. Participants will not involve anyone from vulnerable groups.
Access to participants Please give details about how participants will be identified and contacted.	Participants will be contacted by phone or/and e-mail. Participants will only be contacted as suggested by the housing association involved in the project. Participants will include professionals and social housing users (non-vulnerable adults).
How will your data be recorded and stored? Please confirm that as a minimum this will comply with the university data storage policy and the Data Protection Act. Please indicate also any further specific details.	Data will be collected and stored using digital audio recorders if the interviewees permit. In case they not, interviews will be undertaken in pairs to enable note taking. I confirm that all sensitive/ confidential data will be stored on a secure university system (i.e. K drive) Yes ✓ No ☐ (provide further details if No) Data will also be securely shared with researchers in collaborating HEI through box.
Informed consent. Please outline how you will obtain informed consent.	Participation in the research is voluntary. Consent of participants will be sought prior to interviews or observations. Participants will be provided with a letter explaining the purpose of the research, approach and dissemination strategy, and an accompanying Participant Consent Form.

	All participants will have the right to withdraw from the research at any time
Confidentiality Please outline the level of confidentiality you will offer respondents and how this will be respected. You should also outline about who will have access to the data and how it will be stored. (This should be included on information sheet.)	The confidentiality of the company and the individual participants will be respected. Any photographs containing faces, names, personal details, or signatures will be blurred or cropped to comply with participant confidentiality. Nobody other than the PhD researcher, the PhD. supervisors and members of the project team will have access to the data.
Anonymity Do you intend to offer anonymity? If so, please indicate how this will be achieved. NB for most projects' anonymity should be offered as standard unless there are compelling grounds not to.	All information collected will be strictly confidential and anonymised before the data is presented in any work, in compliance with the Data Protection Act and ethical research guidelines and principles. Commitments to ensure confidentiality of all information that can be used to identify participants will be removed from transcripts or concealed in write-ups. The projects, interviewees and participants will not be named on any research any research outputs publicly available, unless written consent is given by participants. All the content recorded from the interviews and meeting as well as any graphical artefact analysed will only be used for the purpose of this research.
Harm Please outline your assessment of the extent to which your research might induce psychological stress, anxiety, cause harm or negative consequences for the **participants** or the **researcher** (beyond the risks encountered in normal life). If more than minimal risk, you should outline what support there will be for participants. If you believe that that there is minimal likely harm, please articulate why you believe this to be so. If there is potential for harm to the researcher (physical or psychological) please include attach a risk assessment.	No potential ham is envisaged in the process of carrying out this research. However, all participants will be made aware of their right to withdraw should they in any way feel uncomfortable with any part of their participation.
Does the project include any security sensitive information? Please explain how processing of all security sensitive information will be in full compliance with the "Oversight of security - sensitive research material in UK universities: guidance (October 2012)" (Universities UK, recommended by the Association of Chief Police Officers)	No ☒ Yes ☐ If yes, please provide further information.

Retrospective applications. If your application for Ethics approval is retrospective, please explain why this has arisen. This application is not retrospective

SECTION C – SUMMARY OF ETHICAL ISSUES (TO BE COMPLETED BY THE APPLICANT)

Please give a summary of the ethical issues and any action that will be taken to address the issue(s).

Data Capture and management processes – Addressed by anonymity to all participants and case studies including allowing any participant to withdraw their participation should they perceive the process to run counter to their prior understanding. Harm – While there is not prospect for physical harm to anyone as a result of this research, emotional harm is being considered: Addressed by: allowing any participant to withdraw their participation should they perceive the process to run counter to their prior understanding. Data protection – issues relating to data and how its processed are anticipated - Addressed by anonymity to all participants and case studies and adopting a proactive data management processes including locking away any data in a safe drawer.

SECTION D – ADDITIONAL DOCUMENTS CHECKLIST (TO BE COMPLETED BY THE APPLICANT)

Please supply copies of all relevant supporting documentation electronically. If this is not available electronically, please provide explanation and supply hard copy.

I have included the following documents

Information sheet	Yes	✓	Not applicable	☐
Consent form	Yes	✓	Not applicable	☐
Letters	Yes	☐	Not applicable	✓
Questionnaire	Yes	☐	Not applicable	✓
Interview schedule	Yes	☐	Not applicable	☐

SECTION E – STATEMENT BY APPLICANT

I confirm that the information I have given in this form on ethical issues is correct. (Electronic confirmation is sufficient).

and (for PGR students only)

Affirmation by Supervisor (where applicable)
I can confirm that, to the best of my understanding, the information presented by the applicant is correct and appropriate to allow an informed judgement on whether further ethical approval is required

Supervisor name/signature: Prof. Mike Kagioglou,

Date: 12/11/2018

Supervisor name/signature: Prof. Patricia Tzortzopoulos

Date: 12/11/2018

Name of applicant (electronic is acceptable)

Joas Serugga

Date

05/11/2018

Research students/ Staff

Staff and Research students- All documentation must be submitted electronically to school research office (sadapgradmin@hud.ac.uk).
All enquiries should be directed to school research office (sadapgradmin@hud.ac.uk).

Participant Information Sheet

Appendix 1

Research Project Title: A Decision Support System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts

You are being invited to take part in a research project. Before you decide, it is important for you to understand why this research is being done and what it will involve. Please take time to read the following information and discuss it with others if you wish. Ask if there is anything that is not clear or if you would like more information. May I take this opportunity to thank you for taking time to read this.

What is the purpose of the project?
The main purpose of the study is to develop a Front-End Design decision-support System for Benefits Realisation in Dynamic Contexts. The research will do this first by exploring theoretical conceptualisations of Benefits Realisation, front end design, uncertainty and Requirements Management and forecasting. This understanding will support the development of a decision support system based on mathematical modelling able to model interdependences among requirements, support forecasting and model uncertainty within design process.

Why have I been chosen?
You have been chosen because our research subject is well aligned with your current position.

Do I have to take part?
Participation on this study is entirely voluntary, so please do not feel obliged to take part. Refusal will involve no penalty whatsoever and you may withdraw from the study at any stage without giving an explanation to the researcher.

What do I have to do?
You will be invited to take part in an interview. This should take no more than 60 minutes of your time.

Are there any disadvantages to taking part?
There should be no foreseeable disadvantages to your participation. If you are unhappy or have further questions at any stage in the process, please address your concerns initially to the researcher if this is appropriate. Alternatively, please contact Patricia Tzortzopoulos at the School of Art, Design and Architecture, University of Huddersfield. You have a right at all times to withdraw your participation without any recourse.

Will all my details be kept confidential?
All information which is collected will be strictly confidential and anonymised before the data is presented in any work, in compliance with the Data Protection Act and ethical research guidelines and principles.

What will happen to the results of the research study?

The results of this research will be written up in in research reports, conference and journal papers and dissertations/thesis. If you would like a copy please contact the researcher.

What happens to the data collected?
Data will be collected, stored and analysed in cloud-based platforms, which comply to the University Regulations
Will I be paid for participating in the research?
You will not be paid for participating in this research.
Where will the research be conducted?
The researcher is based in the Barbara Hepworth Building, PGR room, at the University of Huddersfield.
Who has reviewed and approved the study, and who can be contacted for further information?

Professor Patricia Tzortzopoulos
P.Tzortzopoulos@hud.ac.uk
+44 (0) 1484 471827

Name & Contact Details of Researcher:
Joas Serugga
07553231992, joas.serugga@hud.ac.uk

Participant Consent Form

Appendix 2

Title of Research Study: A Decision Support System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts
Name of Researcher: Joas Serugga

Participant Identifier Number:

☐ I confirm that I have read and understood the participant Information sheet related to this research, and have had the opportunity to ask questions.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.

☐ I understand that all my responses will be anonymised.

☐ I give permission for members of the research team to have access to my anonymised responses.

☐ I agree to take part in the above study

Name of Participant:
____

Signature of Participant: ________________________Date: __________________

Name of Researcher:
____

Signature of Researcher: _______________________ Date:
____

Researcher Consent Form

Appendix 3

This form is to be used when consent is sought from those responsible for an organisation or institution for research to be carried out with participants within that organisation or institution. This may include schools, colleges or youth work facilities.

Title of Research Study: A Decision Support System for Benefits Realisation in Front End Design of Construction Projects in Dynamic Contexts
Name of Researcher: Joas Serugga

Name of School/College/organisation: School of Art, Design and Architecture / University of Huddersfield

Describe i) the purpose of the research study

ii) the data collection methods to be used

iii) which pupils/groups/classes will be selected for this study.

The research aims To develop a Front-End Design decision-support System for Benefits Realisation in Dynamic Contexts. Specific objectives include: To identify and describe current decision support tools for FED decision making and identify their limitations in accounting for dynamic and contextual factors that impact on requirements management. To Propose and describe an integrated mathematical based FED decision support framework for requirements management and forecasting, and uncertainty modelling based on utility theory for FED. To evaluate and validate the proposed framework through case studies with a view of supporting design decision making in FED.
Interviews, questionnaires and observations will be the main data collection methods alongside documentary review to support any factual data important for modelling using the proposed decision system support .
Stakeholders in the participating organisation including designers, support services, decision makers such as in management and groups of residents will be the target participants for the research.

☐ I confirm that I give permission for this research to be carried out and that permission from all participants will be gained in line within my organisation's policy.

Name and position of authorised signatory:

____

Signature: ______________________________________ Date: ___________________

Name of Researcher:

____

Signature of Researcher: __________________________ Date: ___________________

Appendix D - Pairwise Comparison Design Requirements Interdependence

Table 55 Pairwise Comparison of Social Housing User Benefits Cost of Construction

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	0.5000	0.3333	3.0000	2.0000	2.0000	0.5000
AC	0.5000	1.0000	5.0000	5.0000	6.0000	5.0000	3.0000	3.0000
WK	2.0000	0.2000	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000
ED	3.0003	0.2000	0.3333	1.0000	2.0000	2.0000	2.0000	0.1670
FS	0.3333	0.1667	0.2500	0.5000	1.0000	2.0000	2.0000	0.1670
WF	0.5000	0.2000	0.3333	0.5000	0.5000	1.0000	1.0000	2.0000
CO	0.5000	0.3333	0.3333	0.5000	0.5000	1.0000	1.0000	0.5000
WB	2.0000	0.3333	2.0000	5.9880	5.9880	0.5000	2.0000	1.0000

Table 56 Pairwise Comparison of Social Housing User Benefits Project Costs

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	2.0000	0.5000	0.1670	2.0000	2.0000	0.5000
AC	0.5000	1.0000	3.0000	3.0000	3.0000	4.0000	3.0000	2.0000
WK	0.5000	0.3333	1.0000	1.0000	1.0000	2.0000	1.0000	0.5000
ED	2.0000	0.3333	1.0000	1.0000	1.0000	2.0000	1.0000	0.5000
FS	5.9880	0.3333	1.0000	1.0000	1.0000	1.0000	2.0000	0.3333
WF	0.5000	0.2500	0.5000	0.5000	1.0000	1.0000	3.0000	0.5000
CO	0.5000	0.3333	1.0000	1.0000	0.5000	0.3333	1.0000	0.5000
WB	2.0000	0.5000	2.0000	2.0000	3.0003	2.0000	2.0000	1.0000

Table 57 Pairwise Comparison of Social Housing User Benefits Strategic Value

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	3.0000	4.0000	2.0000	2.0000	2.0000	0.3333
AC	0.2500	1.0000	7.0000	6.0000	7.0000	5.0000	5.0000	0.2000
WK	0.3333	0.1429	1.0000	2.0000	4.0000	3.0000	3.0000	0.5000
ED	0.2500	0.1667	0.5000	1.0000	5.0000	3.0000	2.0000	0.3333
FS	0.5000	0.1429	0.2500	0.2000	1.0000	2.0000	2.0000	0.2500
WF	0.5000	0.2000	0.3333	0.3333	0.5000	1.0000	4.0000	0.2500
CO	0.5000	0.2000	0.3333	0.5000	0.5000	0.2500	1.0000	0.2500
WB	3.0003	5.0000	2.0000	3.0003	4.0000	4.0000	4.0000	1.0000

Table 58 Pairwise Comparison of Social Housing User Benefits Mobility

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	3.0000	7.0000	5.0000	7.0000	3.0000	3.0000	0.2000
AC	0.3333	1.0000	4.0000	4.0000	5.0000	4.0000	6.0000	0.1667
WK	0.1429	0.2500	1.0000	4.0000	4.0000	0.3333	4.0000	0.2500
ED	0.2000	0.2500	0.2500	1.0000	2.0000	0.5000	4.0000	0.2500
FS	0.1429	0.2000	0.2500	0.5000	1.0000	3.0000	2.0000	0.2500

WF	0.3333	0.2500	3.0000	2.0000	0.3333	1.0000	2.0000	0.2500
CO	0.3333	0.1667	0.2500	0.2500	0.5000	0.5000	1.0000	0.2000
WB	5.0000	5.9988	4.0000	4.0000	4.0000	4.0000	5.0000	1.0000

Table 59 Pairwise Comparison of Social Housing User Benefits Integrated Design

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	0.3333	3.0000	0.2000	6.0000	2.0000	2.0000	0.3333
AC	3.0000	1.0000	6.0000	4.0000	4.0000	5.0000	6.0000	0.2500
WK	0.3333	0.1667	1.0000	3.0000	4.0000	0.3333	2.0000	0.5000
ED	5.0000	0.2500	0.3333	1.0000	3.0000	0.3333	2.0000	0.3333
FS	0.1667	0.2500	0.2500	0.3333	1.0000	0.5000	2.0000	0.2500
WF	0.5000	0.2000	3.0000	3.0000	2.0000	1.0000	4.0000	0.2500
CO	0.5000	0.1667	0.5000	0.5000	0.5000	0.2500	1.0000	0.5000
WB	3.0000	4.0000	2.0000	3.0000	4.0000	4.0000	2.0000	1.0000

Table 60 Pairwise Comparison of Social Housing User Benefits Culture/Community

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	4.0000	4.0000	3.0000	5.0000	0.3333	2.0000	0.3333
AC	0.2500	1.0000	7.0000	7.0000	7.0000	0.1667	4.0000	0.2500
WK	0.2500	0.1429	1.0000	3.0000	4.0000	0.3333	3.0000	0.5000
ED	0.3333	0.1429	0.3333	1.0000	5.0000	0.3333	2.0000	0.3333
FS	0.2000	0.1429	0.2500	0.2000	1.0000	0.5000	2.0000	0.2500
WF	3.0000	6.0000	3.0000	3.0000	2.0000	1.0000	4.0000	0.2500
CO	0.5000	0.2500	0.3333	0.5000	0.5000	0.2500	1.0000	0.2500
WB	3.0000	4.0000	2.0000	3.0000	4.0000	4.0000	4.0000	1.0000

Table 61 Pairwise Comparison of Social Housing User Benefits Demographics

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	3.0000	3.0000	5.0000	6.0000	0.5000	2.0000	0.3333
AC	0.3333	1.0000	4.0000	4.0000	4.0000	4.0000	5.0000	2.0000
WK	0.3333	0.2500	1.0000	2.0000	4.0000	0.5000	3.0000	0.5000
ED	0.2000	0.2500	0.5000	1.0000	5.0000	0.2500	2.0000	0.3333
FS	0.1667	0.2500	0.2500	0.2000	1.0000	0.5000	2.0000	0.2500
WF	2.0000	0.2500	2.0000	4.0000	2.0000	1.0000	3.0000	0.2500
CO	0.5000	0.2000	0.3333	0.5000	0.5000	0.3333	1.0000	0.2500
WB	3.0000	0.5000	2.0000	3.0000	4.0000	4.0000	4.0000	1.0000

Table 62 Pairwise Comparison of Social Housing User Benefits Safety

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	0.2500	4.0000	6.0000	4.0000	3.0000	3.0000	0.5000
AC	4.0000	1.0000	4.0000	3.0000	3.0000	3.0000	4.0000	0.2500
WK	0.2500	0.2500	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000
ED	0.1667	0.3333	0.3333	1.0000	5.0000	3.0000	2.0000	0.3333

FS	0.2500	0.3333	0.2500	0.2000	1.0000	2.0000	2.0000	0.2500
WF	0.3333	0.3333	0.3333	0.3333	0.5000	1.0000	3.0000	0.2500
CO	0.3333	0.2500	0.3333	0.5000	0.5000	0.3333	1.0000	0.3333
WB	2.0000	4.0000	2.0000	3.0000	4.0000	4.0000	3.0000	1.0000

Table 63 Pairwise Comparison of Social Housing User Benefits Ambience

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	4.0000	3.0000	4.0000	6.0000	2.0000	2.0000	0.3333
AC	0.2500	1.0000	4.0000	5.0000	4.0000	4.0000	4.0000	0.2000
WK	0.3333	0.2500	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000
ED	0.2500	0.2000	0.3333	1.0000	5.0000	0.3333	2.0000	0.3333
FS	0.1667	0.2500	0.2500	0.2000	1.0000	0.5000	2.0000	0.2500
WF	0.5000	0.2500	0.3333	3.0000	2.0000	1.0000	4.0000	0.2500
CO	0.5000	0.2500	0.3333	0.5000	0.5000	0.2500	1.0000	0.2500
WB	3.0000	5.0000	2.0000	3.0000	4.0000	4.0000	4.0000	1.0000

Table 64 Pairwise Comparison of Social Housing User Benefits Space Flow

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	3.0000	3.0000	5.0000	5.0000	2.0000	2.0000	0.3333
AC	0.3333	1.0000	4.0000	4.0000	5.0000	3.0000	4.0000	0.2500
WK	0.3333	0.2500	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000
ED	0.2000	0.2500	0.3333	1.0000	5.0000	3.0000	2.0000	0.3333
FS	0.2000	0.2000	0.2500	0.2000	1.0000	2.0000	2.0000	0.2500
WF	0.5000	0.3333	0.3333	0.3333	0.5000	1.0000	4.0000	0.2500
CO	0.5000	0.2500	0.3333	0.5000	0.5000	0.2500	1.0000	0.5000
WB	3.0000	4.0000	2.0000	3.0000	4.0000	4.0000	2.0000	1.0000

Table 65 Pairwise Comparison of Social Housing User Benefits Hygiene/Health

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	3.0000	4.0000	4.0000	4.0000	2.0000	2.0000	0.3333
AC	0.3333	1.0000	5.0000	4.0000	4.0000	3.0000	4.0000	0.2500
WK	0.2500	0.2000	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000
ED	0.2500	0.2500	0.3333	1.0000	5.0000	3.0000	2.0000	0.3333
FS	0.2500	0.2500	0.2500	0.2000	1.0000	2.0000	2.0000	0.3333
WF	0.5000	0.3333	0.3333	0.3333	0.5000	1.0000	4.0000	0.3333
CO	0.5000	0.2500	0.3333	0.5000	0.5000	0.2500	1.0000	0.2000
WB	3.0000	4.0000	2.0000	3.0000	3.0000	3.0000	5.0000	1.0000

Table 66 Pairwise Comparison of Social Housing User Benefits Security

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	0.2500	3.0000	3.0000	5.0000	3.0000	3.0000	0.3333
AC	4.0000	1.0000	5.0000	5.0000	5.0000	4.0000	3.0000	0.2500
WK	0.3333	0.2000	1.0000	3.0000	4.0000	3.0000	3.0000	0.5000

ED	0.3333	0.2000	0.3333	1.0000	5.0000	3.0000	2.0000	0.3333
FS	0.2000	0.2000	0.2500	0.2000	1.0000	2.0000	2.0000	0.2500
WF	0.3333	0.2500	0.3333	0.3333	0.5000	1.0000	4.0000	0.2500
CO	0.3333	0.3333	0.3333	0.5000	0.5000	0.2500	1.0000	0.3333
WB	3.0000	4.0000	2.0000	3.0000	4.0000	4.0000	3.0000	1.0000

Table 67 Pairwise Comparison of Social Housing User Benefits Constructability

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	3.0000
AC	0.5000	1.0000	3.0000	2.0000	3.0000	2.0000	2.0000	3.0000
WK	0.5000	0.3333	1.0000	3.0000	4.0000	3.0000	3.0000	2.0000
ED	0.5000	0.5000	0.3333	1.0000	5.0000	3.0000	2.0000	3.0000
FS	0.5000	0.3333	0.2500	0.2000	1.0000	2.0000	2.0000	4.0000
WF	0.5000	0.5000	0.3333	0.3333	0.5000	1.0000	2.0000	3.0000
CO	0.5000	0.5000	0.3333	0.5000	0.5000	0.5000	1.0000	2.0000
WB	0.3333	0.3333	0.5000	0.3333	0.2500	0.3333	0.5000	1.0000

Table 68 Pairwise Comparison of Social Housing User Benefits Legal/Compliance

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	4.0000	6.0000	5.0000	6.0000	5.0000	3.0000	3.0000
AC	0.2500	1.0000	7.0000	7.0000	7.0000	6.0000	5.0000	4.0000
WK	0.1667	0.1429	1.0000	3.0000	4.0000	3.0000	3.0000	2.0000
ED	0.2000	0.1429	0.3333	1.0000	5.0000	3.0000	2.0000	3.0000
FS	0.1667	0.1429	0.2500	0.2000	1.0000	2.0000	2.0000	4.0000
WF	0.2000	0.1667	0.3333	0.3333	0.5000	1.0000	4.0000	3.0000
CO	0.3333	0.2000	0.3333	0.5000	0.5000	0.2500	1.0000	4.0000
WB	0.3333	0.2500	0.5000	0.3333	0.2500	0.3333	0.2500	1.0000

Table 69 Pairwise Comparison of Social Housing User Benefits Design Form

	MT	**AC**	**WK**	**ED**	**FS**	**WF**	**CO**	**WB**
MT	1.0000	2.0000	2.0000	2.0000	3.0000	2.0000	2.0000	3.0000
AC	0.5000	1.0000	5.0000	6.0000	5.0000	5.0000	6.0000	3.0000
WK	0.5000	0.2000	1.0000	3.0000	2.0000	3.0000	3.0000	2.0000
ED	0.5000	0.1667	0.3333	1.0000	5.0000	3.0000	2.0000	3.0000
FS	0.3333	0.2000	0.5000	0.2000	1.0000	2.0000	2.0000	3.0000
WF	0.5000	0.2000	0.3333	0.3333	0.5000	1.0000	2.0000	3.0000
CO	0.5000	0.1667	0.3333	0.5000	0.5000	0.5000	1.0000	4.0000
WB	0.3333	0.3333	0.5000	0.3333	0.3333	0.3333	0.2500	1.0000

Table 70 Pairwise Comparison of Social Housing User Benefits Collaboration

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	2.0000	4.0000	4.0000	2.0000	2.0000	5.0000
AC	0.2500	1.0000	5.0000	5.0000	3.0000	5.0000	6.0000	4.0000
WK	0.5000	0.2000	1.0000	3.0000	4.0000	3.0000	3.0000	2.0000
ED	0.2500	0.2000	0.3333	1.0000	5.0000	3.0000	2.0000	3.0000
FS	0.2500	0.3333	0.2500	0.2000	1.0000	2.0000	2.0000	4.0000
WF	0.5000	0.2000	0.3333	0.3333	0.5000	1.0000	4.0000	4.0000
CO	0.5000	0.1667	0.3333	0.5000	0.5000	0.2500	1.0000	6.0000
WB	0.2000	0.2500	0.5000	0.3333	0.2500	0.2500	0.1667	1.0000

Table 71 Pairwise Comparison of Social Housing User Benefits Project Processes

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	1.0000	3.0000	4.0000	4.0000	4.0000	2.0000
AC	0.5000	1.0000	6.0000	4.0000	3.0000	4.0000	6.0000	4.0000
WK	1.0000	0.1667	1.0000	3.0000	4.0000	3.0000	3.0000	4.0000
ED	0.3333	0.2500	0.3333	1.0000	4.0000	4.0000	4.0000	4.0000
FS	0.2500	0.3333	0.2500	0.2500	1.0000	4.0000	4.0000	3.0000
WF	0.2500	0.2500	0.3333	0.2500	0.2500	1.0000	3.0000	4.0000
CO	0.2500	0.1667	0.3333	0.2500	0.2500	0.3333	1.0000	4.0000
WB	0.5000	0.2500	0.2500	0.2500	0.3333	0.2500	0.2500	1.0000

Table 72 Pairwise Comparison of Social Housing User Benefits Functional Design

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	3.0000	4.0000	2.0000	5.0000	4.0000	6.0000
AC	0.5000	1.0000	7.0000	6.0000	6.0000	7.0000	7.0000	6.0000
WK	0.3333	0.1429	1.0000	3.0000	4.0000	3.0000	3.0000	2.0000
ED	0.2500	0.1667	0.3333	1.0000	5.0000	3.0000	2.0000	3.0000
FS	0.5000	0.1667	0.2500	0.2000	1.0000	2.0000	2.0000	4.0000
WF	0.2000	0.1429	0.3333	0.3333	0.5000	1.0000	6.0000	6.0000
CO	0.2500	0.1429	0.3333	0.5000	0.5000	0.1667	1.0000	5.0000
WB	0.1667	0.1667	0.5000	0.3333	0.2500	0.1667	0.2000	1.0000

Table 73 Pairwise Comparison of Social Housing User Benefits Lead Times

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	3.0000	5.0000	8.0000	2.0000	2.0000	3.0000
AC	0.5000	1.0000	3.0000	3.0000	6.0000	6.0000	6.0000	7.0000
WK	0.3333	0.3333	1.0000	5.0000	4.0000	4.0000	4.0000	6.0000
ED	0.2000	0.3333	0.2000	1.0000	2.0000	2.0000	4.0000	5.0000
FS	0.1250	0.1667	0.2500	0.5000	1.0000	2.0000	2.0000	2.0000
WF	0.5000	0.1667	0.2500	0.5000	0.5000	1.0000	5.0000	6.0000
CO	0.5000	0.1667	0.2500	0.2500	0.5000	0.2000	1.0000	7.0000
WB	0.3333	0.1429	0.1667	0.2000	0.5000	0.1667	0.1429	1.0000

Table 74 Pairwise Comparison of Social Housing User Benefits Specification

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	2.0000	4.0000	2.0000	3.0000	5.0000	5.0000
AC	0.5000	1.0000	5.0000	5.0000	4.0000	7.0000	6.0000	8.0000
WK	0.5000	0.2000	1.0000	2.0000	3.0000	3.0000	4.0000	4.0000
ED	0.2500	0.2000	0.5000	1.0000	2.0000	3.0000	4.0000	4.0000
FS	0.5000	0.2500	0.3333	0.5000	1.0000	4.0000	4.0000	5.0000
WF	0.3333	0.1429	0.3333	0.3333	0.2500	1.0000	4.0000	7.0000
CO	0.2000	0.1667	0.2500	0.2500	0.2500	0.2500	1.0000	4.0000
WB	0.2000	0.1250	0.2500	0.2500	0.2000	0.1429	0.2500	1.0000

Table 75 Pairwise Comparison of Social Housing User Benefits Accessibility

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	4.0000	4.0000	5.0000	5.0000	3.0000	4.0000
AC	0.5000	1.0000	4.0000	2.0000	3.0000	4.0000	5.0000	4.0000
WK	0.2500	0.2500	1.0000	2.0000	5.0000	3.0000	3.0000	4.0000
ED	0.2500	0.5000	0.5000	1.0000	3.0000	3.0000	4.0000	2.0000
FS	0.2000	0.3333	0.2000	0.3333	1.0000	2.0000	2.0000	4.0000
WF	0.2000	0.2500	0.3333	0.3333	0.5000	1.0000	3.0000	4.0000
CO	0.3333	0.2000	0.3333	0.2500	0.5000	0.3333	1.0000	5.0000
WB	0.2500	0.2500	0.2500	0.5000	0.2500	0.2500	0.2000	1.0000

Table 76 Pairwise Comparison of Social Housing User Benefits Serviceability

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	2.0000	3.0000	2.0000	3.0000	2.0000	4.0000
AC	0.5000	1.0000	5.0000	4.0000	3.0000	6.0000	5.0000	7.0000
WK	0.5000	0.2000	1.0000	2.0000	3.0000	3.0000	2.0000	4.0000
ED	0.3333	0.2500	0.5000	1.0000	2.0000	3.0000	2.0000	4.0000
FS	0.5000	0.3333	0.3333	0.5000	1.0000	3.0000	2.0000	4.0000
WF	0.3333	0.1667	0.3333	0.3333	0.3333	1.0000	4.0000	6.0000
CO	0.5000	0.2000	0.5000	0.5000	0.5000	0.2500	1.0000	5.0000
WB	0.2500	0.1429	0.2500	0.2500	0.2500	0.1667	0.2000	1.0000

Table 77 Pairwise Comparison of Social Housing User Benefits Maintainability

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	4.0000	3.0000	4.0000	4.0000	3.0000	4.0000
AC	0.2500	1.0000	5.0000	4.0000	5.0000	6.0000	5.0000	6.0000
WK	0.2500	0.2000	1.0000	2.0000	3.0000	3.0000	3.0000	4.0000
ED	0.3333	0.2500	0.5000	1.0000	3.0000	4.0000	2.0000	4.0000
FS	0.2500	0.2000	0.3333	0.3333	1.0000	2.0000	2.0000	3.0000
WF	0.2500	0.1667	0.3333	0.2500	0.5000	1.0000	3.0000	5.0000
CO	0.3333	0.2000	0.3333	0.5000	0.5000	0.3333	1.0000	4.0000
WB	0.2500	0.1667	0.2500	0.2500	0.3333	0.2000	0.2500	1.0000

Table 78 Pairwise Comparison of Social Housing User Benefits Occupancy Level/Patterns

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	6.0000	3.0000	3.0000	4.0000	4.0000	4.0000	4.0000
AC	0.1667	1.0000	5.0000	4.0000	7.0000	6.0000	6.0000	6.0000
WK	0.3333	0.2000	1.0000	2.0000	5.0000	4.0000	4.0000	5.0000
ED	0.3333	0.2500	0.5000	1.0000	2.0000	2.0000	3.0000	3.0000
FS	0.2500	0.1429	0.2000	0.5000	1.0000	5.0000	5.0000	6.0000
WF	0.2500	0.1667	0.2500	0.5000	0.2000	1.0000	7.0000	8.0000
CO	0.2500	0.1667	0.2500	0.3333	0.2000	0.1429	1.0000	7.0000
WB	0.2500	0.1667	0.2000	0.3333	0.1667	0.1250	0.1429	1.0000

Table 79 Pairwise Comparison of Social Housing User Benefits Financial Status

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	4.0000	2.0000	6.0000	5.0000	3.0000	5.0000
AC	0.2500	1.0000	4.0000	4.0000	5.0000	4.0000	2.0000	5.0000
WK	0.2500	0.2500	1.0000	2.0000	4.0000	5.0000	2.0000	4.0000
ED	0.5000	0.2500	0.5000	1.0000	3.0000	4.0000	2.0000	4.0000
FS	0.1667	0.2000	0.2500	0.3333	1.0000	1.0000	2.0000	5.0000
WF	0.2000	0.2500	0.2000	0.2500	1.0000	1.0000	5.0000	5.0000
CO	0.3333	0.5000	0.5000	0.5000	0.5000	0.2000	1.0000	4.0000
WB	0.2000	0.2000	0.2500	0.2500	0.2000	0.2000	0.2500	1.0000

Table 80 Pairwise Comparison of Social Housing User Benefits Social Status

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	3.0000	2.0000	3.0000	3.0000	4.0000	4.0000
AC	0.5000	1.0000	6.0000	6.0000	5.0000	6.0000	6.0000	6.0000
WK	0.3333	0.1667	1.0000	3.0000	6.0000	5.0000	5.0000	6.0000
ED	0.5000	0.1667	0.3333	1.0000	4.0000	5.0000	5.0000	4.0000
FS	0.3333	0.2000	0.1667	0.2500	1.0000	5.0000	4.0000	5.0000
WF	0.3333	0.1667	0.2000	0.2000	0.2000	1.0000	4.0000	4.0000
CO	0.2500	0.1667	0.2000	0.2000	0.2500	0.2500	1.0000	4.0000
WB	0.2500	0.1667	0.1667	0.2500	0.2000	0.2500	0.2500	1.0000

Table 81 Pairwise Comparison of Social Housing User Benefits Political Leadership

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	3.0000	3.0000	3.0000	3.0000	3.0000	4.0000	3.0000
AC	0.3333	1.0000	4.0000	4.0000	6.0000	6.0000	4.0000	4.0000
WK	0.3333	0.2500	1.0000	2.0000	4.0000	4.0000	4.0000	5.0000
ED	0.3333	0.2500	0.5000	1.0000	4.0000	5.0000	5.0000	4.0000
FS	0.3333	0.1667	0.2500	0.2500	1.0000	3.0000	4.0000	4.0000
WF	0.3333	0.1667	0.2500	0.2000	0.3333	1.0000	4.0000	4.0000
CO	0.2500	0.2500	0.2500	0.2000	0.2500	0.2500	1.0000	4.0000
WB	0.3333	0.2500	0.2000	0.2500	0.2500	0.2500	0.2500	1.0000

Table 82 Pairwise Comparison of Social Housing User Benefits Legislation/Compliance

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	3.0000	3.0000	3.0000	4.0000	4.0000	3.0000
AC	0.5000	1.0000	3.0000	2.0000	3.0000	6.0000	4.0000	5.0000
WK	0.3333	0.3333	1.0000	2.0000	3.0000	4.0000	3.0000	4.0000
ED	0.3333	0.5000	0.5000	1.0000	2.0000	3.0000	3.0000	4.0000
FS	0.3333	0.3333	0.3333	0.5000	1.0000	4.0000	4.0000	4.0000
WF	0.2500	0.1667	0.2500	0.3333	0.2500	1.0000	4.0000	4.0000
CO	0.2500	0.2500	0.3333	0.3333	0.2500	0.2500	1.0000	3.0000
WB	0.3333	0.2000	0.2500	0.2500	0.2500	0.2500	0.3333	1.0000

Table 83 Pairwise Comparison of Social Housing User Benefits Energy Performance

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	2.0000	2.0000	5.0000	4.0000	2.0000	5.0000
AC	0.2500	1.0000	3.0000	2.0000	6.0000	6.0000	3.0000	4.0000
WK	0.5000	0.3333	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
ED	0.5000	0.5000	1.0000	1.0000	2.0000	2.0000	3.0000	3.0000
FS	0.2000	0.1667	1.0000	0.5000	1.0000	4.0000	3.0000	4.0000
WF	0.2500	0.1667	1.0000	0.5000	0.2500	1.0000	3.0000	4.0000
CO	0.5000	0.3333	1.0000	0.3333	0.3333	0.3333	1.0000	3.0000
WB	0.2000	0.2500	1.0000	0.3333	0.2500	0.2500	0.3333	1.0000

Table 84 Pairwise Comparison of Social Housing User Benefits Lifecycle Costs

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	7.0000	2.0000	2.0000	5.0000	3.0000	3.0000	2.0000
AC	0.1429	1.0000	3.0000	2.0000	7.0000	6.0000	4.0000	5.0000
WK	0.5000	0.3333	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
ED	0.5000	0.5000	1.0000	1.0000	1.0000	2.0000	2.0000	3.0000
FS	0.2000	0.1429	1.0000	1.0000	1.0000	4.0000	2.0000	3.0000
WF	0.3333	0.1667	1.0000	0.5000	0.2500	1.0000	2.0000	4.0000
CO	0.3333	0.2500	1.0000	0.5000	0.5000	0.5000	1.0000	2.0000
WB	0.5000	0.2000	1.0000	0.3333	0.3333	0.2500	0.5000	1.0000

Table 85 Pairwise Comparison of Social Housing User Benefits Physical Management

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	3.0000	2.0000	1.0000	2.0000	3.0000	3.0000	3.0000
AC	0.3333	1.0000	3.0000	2.0000	3.0000	4.0000	4.0000	4.0000
WK	0.5000	0.3333	1.0000	2.0000	2.0000	3.0000	2.0000	3.0000
ED	1.0000	0.5000	0.5000	1.0000	2.0000	3.0000	1.0000	2.0000
FS	0.5000	0.3333	0.5000	0.5000	1.0000	3.0000	3.0000	3.0000
WF	0.3333	0.2500	0.3333	0.3333	0.3333	1.0000	2.0000	4.0000
CO	0.3333	0.2500	0.5000	1.0000	0.3333	0.5000	1.0000	5.0000
WB	0.3333	0.2500	0.3333	0.5000	0.3333	0.2500	0.2000	1.0000

Table 86 Pairwise Comparison of Social Housing User Benefits Materials Use

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	3.0000
AC	0.5000	1.0000	6.0000	5.0000	4.0000	6.0000	4.0000	6.0000
WK	0.5000	0.1667	1.0000	2.0000	2.0000	3.0000	2.0000	2.0000
ED	0.5000	0.2000	0.5000	1.0000	1.0000	1.0000	1.0000	1.0000
FS	0.5000	0.2500	0.5000	1.0000	1.0000	3.0000	2.0000	4.0000
WF	0.5000	0.1667	0.3333	1.0000	0.3333	1.0000	3.0000	5.0000
CO	0.5000	0.2500	0.5000	1.0000	0.5000	0.3333	1.0000	4.0000
WB	0.3333	0.1667	0.5000	1.0000	0.2500	0.2000	0.2500	1.0000

Table 87 Pairwise Comparison of Social Housing User Benefits Adaptability

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	2.0000	4.0000	4.0000	3.0000	4.0000	2.0000	5.0000
AC	0.5000	1.0000	3.0000	3.0000	4.0000	6.0000	4.0000	5.0000
WK	0.2500	0.3333	1.0000	2.0000	4.0000	4.0000	3.0000	5.0000
ED	0.2500	0.3333	0.5000	1.0000	1.0000	3.0000	2.0000	4.0000
FS	0.3333	0.2500	0.2500	1.0000	1.0000	3.0000	2.0000	5.0000
WF	0.2500	0.1667	0.2500	0.3333	0.3333	1.0000	4.0000	5.0000
CO	0.5000	0.2500	0.3333	0.5000	0.5000	0.2500	1.0000	3.0000
WB	0.2000	0.2000	0.2000	0.2500	0.2000	0.2000	0.3333	1.0000

Table 88 Pairwise Comparison of Social Housing User Benefits Project Governance

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	1.0000	3.0000	3.0000	2.0000	3.0000	2.0000	4.0000
AC	1.0000	1.0000	2.0000	2.0000	3.0000	4.0000	3.0000	4.0000
WK	0.3333	0.5000	1.0000	3.0000	2.0000	3.0000	3.0000	3.0000
ED	0.3333	0.5000	0.3333	1.0000	3.0000	3.0000	2.0000	3.0000
FS	0.5000	0.3333	0.5000	0.3333	1.0000	4.0000	2.0000	4.0000
WF	0.3333	0.2500	0.3333	0.3333	0.2500	1.0000	2.0000	4.0000
CO	0.5000	0.3333	0.3333	0.5000	0.5000	0.5000	1.0000	5.0000
WB	0.2500	0.2500	0.3333	0.3333	0.2500	0.2500	0.2000	1.0000

Table 89 Pairwise Comparison of Social Housing User Benefits Project Context

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	4.0000	5.0000	6.0000	4.0000	4.0000	4.0000
AC	0.2500	1.0000	3.0000	3.0000	6.0000	6.0000	4.0000	5.0000
WK	0.2500	0.3333	1.0000	2.0000	5.0000	5.0000	3.0000	5.0000
ED	0.2000	0.3333	0.5000	1.0000	3.0000	4.0000	4.0000	3.0000
FS	0.1667	0.1667	0.2000	0.3333	1.0000	4.0000	3.0000	4.0000
WF	0.2500	0.1667	0.2000	0.2500	0.2500	1.0000	4.0000	5.0000
CO	0.2500	0.2500	0.3333	0.2500	0.3333	0.2500	1.0000	7.0000
WB	0.2500	0.2000	0.2000	0.3333	0.2500	0.2000	0.1429	1.0000

Table 90 Pairwise Comparison of Social Housing User Benefits Stakeholder Management

	MT	AC	WK	ED	FS	WF	CO	WB
MT	1.0000	4.0000	3.0000	3.0000	3.0000	4.0000	3.0000	4.0000
AC	0.2500	1.0000	6.0000	5.0000	5.0000	6.0000	5.0000	6.0000
WK	0.3333	0.1667	1.0000	2.0000	2.0000	3.0000	2.0000	3.0000
ED	0.3333	0.2000	0.5000	1.0000	1.0000	2.0000	1.0000	1.0000
FS	0.3333	0.2000	0.5000	1.0000	1.0000	5.0000	3.0000	5.0000
WF	0.2500	0.1667	0.3333	0.5000	0.2000	1.0000	4.0000	5.0000
CO	0.3333	0.2000	0.5000	1.0000	0.3333	0.2500	1.0000	5.0000
WB	0.2500	0.1667	0.3333	1.0000	0.2000	0.2000	0.2000	1.0000

Appendix E - Requirements Forecasting in Case Study Context Two

Table 91 Computing for Design Requirements in HOQ Relationship Matrix for Case Study B

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16)	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
c	9	9	9	7	4	8	7	5	5	3	6	4	7	7	8	8	7	7	8	8	4	7	8	7	8	9	6	5	7	9	3	9	3	7	6	7
ral	5	5	7	7	6	9	9	7	6	6	7	7	2	4	8	8	4	6	7	5	5	5	5	7	6	9	7	8	5	8	2	8	6	7	8	6
d	1	3	4	1	6	7	4	9	8	7	8	9	6	8	5	5	3	7	5	7	6	8	8	5	1	0	2	8	8	8	6	8	4	2	2	2
l	8	9	7	6	9	8	7	8	9	9	8	6	9	8	9	9	9	9	9	9	8	9	8	4	0	8	0	8	9	9	9	9	9	8	8	8
ce	6	7	7	7	5	4	5	5	7	5	6	2	6	5	7	6	6	4	7	7	4	7	9	3	6	3	0	5	8	9	4	8	0	1	1	1
y	2	2	2	8	3	7	7	7	7	6	7	8	1	7	7	8	3	9	3	6	6	7	5	9	8	8	3	6	8	8	2	8	7	1	1	1
al	7	7	7	7	6	5	7	7	6	3	5	5	1	9	2	4	2	5	6	6	5	5	4	6	8	7	9	9	7	6	3	7	5	7	8	7
nt	5	5	6	7	7	9	2	7	9	7	7	6	7	7	8	8	7	7	7	7	8	8	7	6	3	5	7	8	9	9	9	9	5	2	6	1
ce	6	6	2	1	3	3	1	2	1	1	1	1	5	8	7	7	8	4	9	5	1	4	2	1	0	0	0	2	1	3	0	5	4	9	9	9
	153.38	145.95	126.07	159.01	98.74	121.76	120.77	95.79	108.39	79.63	97.35	64.62	80.73	132.13	145.32	154.17	128.91	119.64	149.44	127.52	92.41	116.04	101.25	107.53	126.63	160.48	92.34	112.94	123.94	143.90	61.09	151.90	100.64	125.74	140.82	120.44
tial	0.0992				0.1167				0.1040				0.2421				0.0722				0.0920				0.0479				0.1356				0.0903			
	149.44	148.61	132.56	153.23	111.52	137.62	127.04	117.55	126.11	96.49	116.67	88.10	96.47	149.31	156.08	163.47	133.67	134.66	159.42	142.78	104.55	134.68	121.46	116.86	123.05	151.33	92.43	130.30	140.56	161.77	74.44	169.39	106.49	127.09	140.73	121.87
	0.0924				0.1137				0.1170				0.2439				0.0774				0.0840				0.0478				0.1401				0.0837			
	136.93	141.70	139.53	153.39	121.36	150.10	136.05	137.92	146.29	114.78	137.31	111.76	102.29	150.15	152.73	159.46	122.42	143.92	150.40	149.55	119.54	147.06	139.88	128.86	126.44	151.17	99.29	147.51	160.26	176.50	92.96	178.55	107.58	109.81	123.19	104.57
	0.0858				0.1151				0.1330				0.2322				0.0834				0.0834				0.0507				0.1470				0.0693			
	137.41	145.07	144.55	153.47	129.24	159.29	140.47	149.81	156.79	124.08	147.88	123.80	110.71	160.35	159.10	165.57	126.15	152.74	156.80	158.57	127.27	157.57	150.70	134.91	126.62	149.62	101.55	157.92	170.55	186.91	101.19	188.87	112.12	111.80	125.26	106.50
	0.0835				0.1140				0.1374				0.2328				0.0852				0.0804				0.0508				0.1486				0.0672			
	150.17	159.17	148.71	152.57	137.40	168.00	141.49	157.08	160.75	127.43	151.83	128.39	124.46	182.95	177.16	183.52	145.74	163.88	180.36	172.56	129.94	169.57	157.48	136.72	123.02	145.23	99.09	164.56	174.41	196.17	101.50	203.48	121.28	133.26	146.84	127.92
	0.0841				0.1101				0.1333				0.2444				0.0839				0.0744				0.0484				0.1464				0.0749			
	150.36	137.88	142.50	148.88	128.08	158.89	138.64	152.19	159.29	125.68	150.34	127.16	107.91	155.66	152.70	159.00	117.13	150.93	148.65	156.06	127.90	157.04	152.40	134.23	122.99	144.85	99.68	159.42	172.89	187.30	103.34	187.24	107.45	100.60	114.27	95.24
	0.0856				0.1141				0.1419				0.2280				0.0869				0.0799				0.0515				0.1506				0.0616			
	150.44	160.31	150.38	152.50	139.89	170.75	142.62	160.61	163.91	130.17	154.94	131.86	127.15	186.02	178.99	185.25	146.94	166.37	182.41	175.27	132.28	172.69	160.74	138.37	122.91	144.61	99.95	167.74	177.48	199.26	104.17	206.55	122.51	133.94	147.67	128.56
	0.0836				0.1098				0.1344				0.2444				0.0844				0.0736				0.0485				0.1468				0.0744			
	150.47	160.46	150.61	152.43	140.22	171.07	142.70	161.03	164.29	130.49	155.31	132.26	127.52	186.38	179.18	185.42	147.08	166.63	182.67	175.59	132.55	173.06	161.15	138.51	122.82	144.45	100.06	168.14	177.84	199.61	104.54	206.91	122.61	134.02	147.79	128.64
	0.0835				0.1098				0.1346				0.2445				0.0845				0.0735				0.0485				0.1469				0.0743			
		Economic				Sociocultural				Health and Safety			Technical				Lifecycle Performance			Family				Geopolitical				Environment						Governance		

Appendix F – Utilitarian Assessment for Case Study Context Two

Table 92 DQFD relationship Matrix for User and Design Requirements

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26)	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT		1		9	1	4	5	1	5		2	1		1	1		2	5	3	7	2	4	4	8	3	7	2	3	5	3	4	4	7	4	5	5
AC	6	7	7	5	2	3	6	4	6	6	6	5	6	5	6	5	5	8	6	8	5	5	5	8	5	2	1	3	8	8	4	8	7	3	6	2
WK			2	5		3	4	2			2	2		1		3		4	1		5			5	4	3	2	5	1	2			6	2		3
ED				5		5	6	2	1		6	1		1		2	2	3			4			5	4	3	2	3					4			2
FS			1	4	2		6	3	2		2	2				2			2		2			7	9	2		2	3				2	1		3
WF		5	3	3	5	2	5	5	6		6	6		4		5	3	6		5		2	3	7	3		2	3	3	4	4	4	5	5		5
CO	6	6	8	5		9	8	5	2		3	5	2	4		5	4	5	4			1	1	5		4	4	4		3	1	2		3	5	3
WB	5	6	6	6	5	4	2	8	7	2	7	7		2	1	1		6	2	6	1	5	6	9	3	2	5	5	3	3	6	6	5	2	4	2
Weighted	2.1566	3.1263	3.3591	5.2990	1.8513	3.7096	5.2690	3.6971	3.6713	1.0927	4.2525	3.5779	1.0853	2.2545	1.1060	2.8485	2.0423	4.6487	2.3365	3.3704	2.4452	2.1951	2.4304	6.7967	3.9471	2.9182	2.1972	3.4635	3.0133	2.9422	2.4032	3.0877	4.5717	2.4892	2.5891	3.1082
Normalised	0.0194	0.0281	0.0302	0.0476	0.0166	0.0333	0.0473	0.0332	0.0330	0.0098	0.0382	0.0321	0.0097	0.0202	0.0099	0.0256	0.0183	0.0417	0.0210	0.0303	0.0220	0.0197	0.0218	0.0610	0.0354	0.0262	0.0197	0.0311	0.0271	0.0264	0.0216	0.0277	0.0411	0.0224	0.0233	0.0279

Table 93 Initial Decision Matrix for the Design and User Requirements Pairwise Comparison

Weights	0.0194	0.0281	0.0302	0.0476	0.0166	0.0333	0.0473	0.0332	0.0330	0.0098	0.0382	0.0321	0.0097	0.0202	0.0099	0.0256	0.0183	0.0417	0.0210	0.0303	0.0220	0.0197	0.0218	0.0610	0.0354	0.0262	0.0197	0.0311	0.0271	0.0264	0.0216	0.0277	0.0411	0.0224	0.0233	0.0279
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26)	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT	0.1088	0.1190	0.1541	0.2266	0.1312	0.1594	0.1885	0.1975	0.1945	0.1934	0.1845	0.1634	0.1729	0.2521	0.1601	0.2037	0.1770	0.2014	0.1964	0.1833	0.2438	0.1661	0.2244	0.2000	0.2460	0.1573	0.1832	0.2039	0.2391	0.2433	0.1861	0.1557	0.2151	0.1887	0.2386	0.2097

AC	0.2736	0.2283	0.2643	0.1902	0.2581	0.2161	0.2202	0.2021	0.1955	0.1957	0.1959	0.2396	0.1783	0.2846	0.2966	0.2482	0.2402	0.3022	0.2455	0.2788	0.2046	0.2753	0.2681	0.2426	0.2071	0.2609	0.2337	0.2172	0.2415	0.2738	0.2206	0.3164	0.2280	0.1986	0.2107	0.2873
WK	0.1603	0.0859	0.1174	0.1085	0.1000	0.0991	0.1048	0.1362	0.1313	0.1367	0.1357	0.1322	0.1819	0.1246	0.1384	0.1417	0.1615	0.1229	0.1863	0.1352	0.1611	0.1372	0.1367	0.1485	0.1517	0.1894	0.1640	0.1566	0.0653	0.0665	0.1431	0.1233	0.1685	0.1572	0.1610	0.1132
ED	0.1027	0.1034	0.1029	0.0656	0.1081	0.0768	0.0863	0.1105	0.0823	0.1099	0.1104	0.1073	0.1657	0.1121	0.1412	0.1255	0.1510	0.1101	0.1113	0.1142	0.1241	0.1144	0.1254	0.0834	0.1251	0.1430	0.1600	0.1271	0.1243	0.1070	0.1138	0.0604	0.1039	0.1308	0.1196	0.0590
FS	0.0616	0.1482	0.0533	0.0570	0.0419	0.0368	0.0418	0.0571	0.0402	0.0553	0.0570	0.0536	0.1111	0.0746	0.0869	0.0851	0.1103	0.0755	0.0607	0.1190	0.0877	0.1020	0.0758	0.1248	0.0816	0.1140	0.1036	0.1286	0.1326	0.1201	0.1224	0.1192	0.1104	0.1258	0.0960	0.1345
WF	0.0579	0.0849	0.0598	0.0712	0.1231	0.1803	0.1312	0.0552	0.0987	0.0657	0.0666	0.0615	0.0883	0.0728	0.0741	0.0922	0.0787	0.1083	0.1051	0.1023	0.0837	0.1093	0.0873	0.1198	0.1058	0.0722	0.0819	0.0909	0.0972	0.0900	0.0888	0.1103	0.0975	0.0844	0.0829	0.0960
CO	0.0448	0.0605	0.0297	0.0248	0.0346	0.0290	0.0327	0.0325	0.0312	0.0348	0.0321	0.0315	0.0630	0.0544	0.0706	0.0785	0.0555	0.0589	0.0745	0.0486	0.0692	0.0739	0.0599	0.0644	0.0618	0.0452	0.0514	0.0502	0.0653	0.0592	0.0922	0.0787	0.0545	0.0861	0.0721	0.0723
WB	0.1902	0.1698	0.2185	0.2561	0.2030	0.2026	0.1945	0.2089	0.2264	0.2085	0.2178	0.2110	0.0387	0.0248	0.0322	0.0250	0.0260	0.0208	0.0200	0.0185	0.0257	0.0219	0.0224	0.0164	0.0209	0.0181	0.0222	0.0254	0.0346	0.0401	0.0331	0.0360	0.0222	0.0285	0.0192	0.0281
Root of Squares	0.4102	0.3821	0.4159	0.4221	0.4060	0.4044	0.4004	0.4020	0.4045	0.3982	0.3990	0.4065	0.3845	0.4325	0.4144	0.4018	0.4000	0.4248	0.4082	0.4123	0.4035	0.4044	0.4173	0.4028	0.4052	0.4119	0.4016	0.3968	0.4095	0.4215	0.3862	0.4208	0.4032	0.3847	0.4040	0.4196
Weights	**0.0194**	**0.0281**	**0.0302**	**0.0476**	**0.0166**	**0.0333**	**0.0473**	**0.0332**	**0.0330**	**0.0098**	**0.0382**	**0.0321**	**0.0097**	**0.0202**	**0.0099**	**0.0256**	**0.0183**	**0.0417**	**0.0210**	**0.0303**	**0.0220**	**0.0197**	**0.0218**	**0.0610**	**0.0354**	**0.0262**	**0.0197**	**0.0311**	**0.0271**	**0.0264**	**0.0216**	**0.0277**	**0.0411**	**0.0224**	**0.0233**	**0.0279**

Table 94 Normalised MOORA decision matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26)	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT	0.2652	0.3115	0.3704	0.5370	0.3231	0.3941	0.4708	0.4913	0.4807	0.4858	0.4625	0.4019	0.4497	0.5829	0.3862	0.5069	0.4424	0.4743	0.4811	0.4446	0.6042	0.4106	0.5379	0.4967	0.6072	0.3817	0.4563	0.5140	0.5838	0.5771	0.4819	0.3701	0.5334	0.4904	0.5908	0.4997
AC	0.6670	0.5975	0.6354	0.4506	0.6358	0.5343	0.5499	0.5026	0.4832	0.4915	0.4910	0.5894	0.4637	0.6579	0.7156	0.6177	0.6005	0.7114	0.6014	0.6762	0.5071	0.6808	0.6425	0.6023	0.5111	0.6333	0.5820	0.5475	0.5897	0.6497	0.5712	0.7518	0.5654	0.5162	0.5215	0.6845
WK	0.3908	0.2247	0.2824	0.2570	0.2463	0.2450	0.2618	0.3389	0.3247	0.3434	0.3401	0.3251	0.4731	0.2881	0.3340	0.3527	0.4038	0.2894	0.4564	0.3279	0.3992	0.3393	0.3277	0.3688	0.3744	0.4598	0.4084	0.3948	0.1596	0.1577	0.3704	0.2930	0.4178	0.4087	0.3985	0.2698
ED	0.2504	0.2707	0.2475	0.1554	0.2663	0.1899	0.2154	0.2749	0.2034	0.2759	0.2768	0.2639	0.4309	0.2592	0.3408	0.3122	0.3775	0.2591	0.2726	0.2770	0.3075	0.2828	0.3005	0.2069	0.3087	0.3470	0.3984	0.3203	0.3036	0.2539	0.2945	0.1434	0.2578	0.3398	0.2960	0.1406
FS	0.1502	0.3878	0.1281	0.1350	0.1032	0.0910	0.1043	0.1419	0.0994	0.1389	0.1429	0.1319	0.2890	0.1724	0.2098	0.2119	0.2757	0.1777	0.1488	0.2887	0.2172	0.2521	0.1816	0.3099	0.2014	0.2768	0.2579	0.3240	0.3238	0.2849	0.3168	0.2834	0.2738	0.3269	0.2375	0.3204
WF	0.1412	0.2222	0.1438	0.1686	0.3032	0.4458	0.3277	0.1374	0.2440	0.1651	0.1668	0.1514	0.2295	0.1684	0.1787	0.2295	0.1966	0.2549	0.2575	0.2481	0.2075	0.2701	0.2092	0.2974	0.2611	0.1753	0.2040	0.2291	0.2374	0.2135	0.2298	0.2622	0.2418	0.2194	0.2052	0.2288
CO	0.1092	0.1583	0.0714	0.0588	0.0851	0.0718	0.0817	0.0809	0.0771	0.0873	0.0804	0.0775	0.1639	0.1257	0.1704	0.1954	0.1387	0.1386	0.1826	0.1179	0.1716	0.1826	0.1434	0.1600	0.1525	0.1096	0.1280	0.1266	0.1596	0.1404	0.2387	0.1870	0.1351	0.2237	0.1785	0.1722
WB	0.4636	0.4443	0.5253	0.6069	0.4999	0.5009	0.4859	0.5196	0.5597	0.5237	0.5459	0.5191	0.1007	0.0574	0.0776	0.0623	0.0650	0.0489	0.0491	0.0448	0.0637	0.0542	0.0538	0.0408	0.0516	0.0440	0.0552	0.0641	0.0845	0.0950	0.0857	0.0856	0.0551	0.0740	0.0476	0.0670

Table 95 Weighted Normalised MOORA decision matrix

Weights	**0.0168**	**0.0243**	**0.0261**	**0.0578**	**0.0117**	**0.0464**	**0.0410**	**0.0288**	**0.0286**	**0.0085**	**0.0331**	**0.0278**	**0.0084**	**0.0264**	**0.0086**	**0.0222**	**0.0159**	**0.0362**	**0.0182**	**0.0262**	**0.0353**	**0.0171**	**0.0189**	**0.0538**	**0.0524**	**0.0543**	**0.0171**	**0.0270**	**0.0235**	**0.0229**	**0.0187**	**0.0240**	**0.0356**	**0.0194**	**0.0430**	**0.0242**
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26)	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT	0.0051	0.0087	0.0112	0.0256	0.0054	0.0131	0.0223	0.0163	0.0159	0.0048	0.0177	0.0129	0.0044	0.0118	0.0038	0.0130	0.0081	0.0198	0.0101	0.0135	0.0133	0.0081	0.0117	0.0303	0.0215	0.0100	0.0090	0.0160	0.0158	0.0152	0.0104	0.0103	0.0219	0.0110	0.0137	0.0139
AC	0.0129	0.0168	0.0192	0.0214	0.0106	0.0178	0.0260	0.0167	0.0159	0.0048	0.0187	0.0189	0.0045	0.0133	0.0071	0.0158	0.0110	0.0297	0.0126	0.0205	0.0111	0.0134	0.0140	0.0368	0.0181	0.0166	0.0115	0.0170	0.0160	0.0172	0.0123	0.0208	0.0232	0.0115	0.0121	0.0191
WK	0.0076	0.0063	0.0085	0.0122	0.0041	0.0082	0.0124	0.0113	0.0107	0.0034	0.0130	0.0104	0.0046	0.0058	0.0033	0.0090	0.0074	0.0121	0.0096	0.0099	0.0088	0.0067	0.0072	0.0225	0.0133	0.0121	0.0081	0.0123	0.0043	0.0042	0.0080	0.0081	0.0172	0.0091	0.0093	0.0075
ED	0.0049	0.0076	0.0075	0.0074	0.0044	0.0063	0.0102	0.0091	0.0067	0.0027	0.0106	0.0085	0.0042	0.0052	0.0034	0.0080	0.0069	0.0108	0.0057	0.0084	0.0068	0.0056	0.0066	0.0126	0.0109	0.0091	0.0079	0.0100	0.0082	0.0067	0.0064	0.0040	0.0106	0.0076	0.0069	0.0039
FS	0.0029	0.0109	0.0039	0.0064	0.0017	0.0030	0.0049	0.0047	0.0033	0.0014	0.0055	0.0042	0.0028	0.0035	0.0021	0.0054	0.0051	0.0074	0.0031	0.0087	0.0048	0.0050	0.0040	0.0189	0.0071	0.0073	0.0051	0.0101	0.0088	0.0075	0.0068	0.0079	0.0112	0.0073	0.0055	0.0089
WF	0.0027	0.0062	0.0043	0.0080	0.0050	0.0149	0.0155	0.0046	0.0080	0.0016	0.0064	0.0049	0.0022	0.0034	0.0018	0.0059	0.0036	0.0106	0.0054	0.0075	0.0046	0.0053	0.0046	0.0182	0.0093	0.0046	0.0040	0.0071	0.0064	0.0056	0.0050	0.0073	0.0099	0.0049	0.0048	0.0064
CO	0.0021	0.0044	0.0022	0.0028	0.0014	0.0024	0.0039	0.0027	0.0025	0.0009	0.0031	0.0025	0.0016	0.0025	0.0017	0.0050	0.0025	0.0058	0.0038	0.0036	0.0038	0.0036	0.0031	0.0098	0.0054	0.0029	0.0025	0.0039	0.0043	0.0037	0.0052	0.0052	0.0055	0.0050	0.0041	0.0048
WB	0.0090	0.0125	0.0158	0.0289	0.0083	0.0167	0.0230	0.0173	0.0185	0.0051	0.0208	0.0167	0.0010	0.0012	0.0008	0.0016	0.0012	0.0020	0.0010	0.0014	0.0014	0.0011	0.0012	0.0025	0.0018	0.0012	0.0011	0.0020	0.0023	0.0025	0.0018	0.0024	0.0023	0.0017	0.0011	0.0019
S_j^-	0.0246	0.0355	0.0394	0.0583	0.0239	0.0493	0.0645	0.0385	0.0424	0.0116	0.0460	0.0405	0.0077	0.0179	0.0097	0.0233	0.0158	0.0424	0.0191	0.0293	0.0171	0.0198	0.0198	0.0574	0.0292	0.0223	0.0166	0.0261	0.0247	0.0253	0.0191	0.0305	0.0354	0.0181	0.0180	0.0274
S_j^+	0.0226	0.0380	0.0332	0.0544	0.0170	0.0330	0.0537	0.0441	0.0391	0.0131	0.0497	0.0386	0.0176	0.0289	0.0143	0.0404	0.0300	0.0559	0.0323	0.0441	0.0373	0.0289	0.0325	0.0941	0.0583	0.0413	0.0325	0.0522	0.0414	0.0374	0.0367	0.0354	0.0664	0.0400	0.0396	0.0392
S_j	-0.0021	0.0025	-0.0062	-0.0039	-0.0069	-0.0163	-0.0109	0.0056	-0.0033	0.0015	0.0038	-0.0019	0.0099	0.0110	0.0047	0.0171	0.0142	0.0135	0.0133	0.0147	0.0202	0.0091	0.0128	0.0367	0.0291	0.0189	0.0159	0.0261	0.0167	0.0120	0.0176	0.0049	0.0310	0.0219	0.0216	0.0118
Sums	0.0472	0.0735	0.0725	0.1128	0.0409	0.0824	0.1182	0.0826	0.0815	0.0246	0.0957	0.0791	0.0253	0.0468	0.0240	0.0637	0.0459	0.0983	0.0514	0.0734	0.0544	0.0487	0.0523	0.1515	0.0875	0.0636	0.0491	0.0784	0.0661	0.0627	0.0559	0.0659	0.1018	0.0581	0.0576	0.0665
Interval (0.1)	0.0979	0.1025	0.0938	0.0961	0.0931	0.0837	0.0891	0.1056	0.0967	0.1015	0.1038	0.0981	0.1099	0.1110	0.1047	0.1171	0.1142	0.1135	0.1133	0.1147	0.1202	0.1091	0.1128	0.1367	0.1291	0.1189	0.1159	0.1261	0.1167	0.1120	0.1176	0.1049	0.1310	0.1219	0.1216	0.1118
Rank %	72%	75%	69%	70%	68%	61%	65%	77%	71%	74%	76%	72%	80%	81%	77%	86%	84%	83%	83%	84%	88%	80%	82%	100%	94%	87%	85%	92%	85%	82%	86%	77%	96%	89%	89%	82%
		0.2943		0.3620						0.5056							0.8985					0.3421			0.3847		0.2420				0.5823				0.3552	
Category Rank		33%		40%						56%							100%					38%			43%		27%				65%				40%	

Table 96 Weighted Normalised COPRAS decision matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26)	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT	0.0021	0.0033	0.0046	0.0108	0.0022	0.0053	0.0089	0.0066	0.0064	0.0019	0.0070	0.0052	0.0017	0.0051	0.0016	0.0052	0.0032	0.0084	0.0041	0.0055	0.0054	0.0033	0.0049	0.0122	0.0087	0.0041	0.0036	0.0063	0.0065	0.0064	0.0040	0.0043	0.0088	0.0042	0.0055	0.0059
AC	0.0053	0.0064	0.0080	0.0090	0.0043	0.0072	0.0104	0.0067	0.0064	0.0019	0.0075	0.0077	0.0017	0.0058	0.0029	0.0064	0.0044	0.0126	0.0052	0.0084	0.0045	0.0054	0.0059	0.0148	0.0073	0.0068	0.0046	0.0068	0.0065	0.0072	0.0048	0.0088	0.0094	0.0044	0.0049	0.0080
WK	0.0031	0.0024	0.0035	0.0052	0.0017	0.0033	0.0050	0.0045	0.0043	0.0013	0.0052	0.0042	0.0018	0.0025	0.0014	0.0036	0.0030	0.0051	0.0039	0.0041	0.0035	0.0027	0.0030	0.0091	0.0054	0.0050	0.0032	0.0049	0.0018	0.0018	0.0031	0.0034	0.0069	0.0035	0.0037	0.0032
ED	0.0020	0.0029	0.0031	0.0031	0.0018	0.0026	0.0041	0.0037	0.0027	0.0011	0.0042	0.0034	0.0016	0.0023	0.0014	0.0032	0.0028	0.0046	0.0023	0.0035	0.0027	0.0023	0.0027	0.0051	0.0044	0.0037	0.0032	0.0040	0.0034	0.0028	0.0025	0.0017	0.0043	0.0029	0.0028	0.0016
FS	0.0012	0.0042	0.0016	0.0027	0.0007	0.0012	0.0020	0.0019	0.0013	0.0005	0.0022	0.0017	0.0011	0.0015	0.0009	0.0022	0.0020	0.0032	0.0013	0.0036	0.0019	0.0020	0.0017	0.0076	0.0029	0.0030	0.0020	0.0040	0.0036	0.0032	0.0026	0.0033	0.0045	0.0028	0.0022	0.0038
WF	0.0011	0.0024	0.0018	0.0034	0.0020	0.0060	0.0062	0.0018	0.0033	0.0006	0.0025	0.0020	0.0009	0.0015	0.0007	0.0024	0.0014	0.0045	0.0022	0.0031	0.0018	0.0022	0.0019	0.0073	0.0038	0.0019	0.0016	0.0028	0.0026	0.0024	0.0019	0.0031	0.0040	0.0019	0.0019	0.0027
CO	0.0009	0.0017	0.0009	0.0012	0.0006	0.0010	0.0015	0.0011	0.0010	0.0003	0.0012	0.0010	0.0006	0.0011	0.0007	0.0020	0.0010	0.0025	0.0016	0.0015	0.0015	0.0015	0.0013	0.0039	0.0022	0.0012	0.0010	0.0016	0.0018	0.0016	0.0020	0.0022	0.0022	0.0019	0.0017	0.0020
WB	0.0037	0.0048	0.0066	0.0122	0.0034	0.0067	0.0092	0.0069	0.0075	0.0020	0.0083	0.0068	0.0004	0.0005	0.0003	0.0006	0.0005	0.0009	0.0004	0.0006	0.0006	0.0004	0.0005	0.0010	0.0007	0.0005	0.0004	0.0008	0.0009	0.0011	0.0007	0.0010	0.0009	0.0006	0.0004	0.0008

Sums	0.0194	0.0281	0.0302	0.0476	0.0166	0.0333	0.0473	0.0332	0.0330	0.0098	0.0382	0.0321	0.0097	0.0202	0.0099	0.0256	0.0183	0.0417	0.0210	0.0303	0.0220	0.0197	0.0218	0.0610	0.0354	0.0262	0.0197	0.0311	0.0271	0.0264	0.0216	0.0277	0.0411	0.0224	0.0233	0.0279
Rj	0.0101	0.0136	0.0164	0.0246	0.0097	0.0200	0.0258	0.0155	0.0172	0.0046	0.0183	0.0165	0.0030	0.0077	0.0040	0.0093	0.0063	0.0180	0.0078	0.0121	0.0069	0.0080	0.0082	0.0231	0.0118	0.0092	0.0067	0.0104	0.0101	0.0107	0.0074	0.0128	0.0143	0.0070	0.0073	0.0115
Pj	0.0093	0.0145	0.0138	0.0230	0.0069	0.0134	0.0215	0.0177	0.0158	0.0052	0.0198	0.0157	0.0068	0.0125	0.0059	0.0162	0.0120	0.0237	0.0132	0.0182	0.0151	0.0117	0.0136	0.0379	0.0236	0.0170	0.0131	0.0207	0.0170	0.0158	0.0142	0.0149	0.0268	0.0154	0.0160	0.0164
	98.97	73.74	61.10	40.61	102.96	50.12	38.71	64.61	58.27	216.86	54.52	60.77	336.08	129.21	249.95	106.96	158.13	55.55	128.57	82.68	144.99	124.78	121.27	43.25	84.52	108.65	150.03	96.39	98.99	93.70	135.30	77.94	70.06	143.61	137.50	87.09
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Qi	0.0093	0.0145	0.0138	0.0230	0.0069	0.0134	0.0215	0.0177	0.0158	0.0052	0.0199	0.0157	0.0068	0.0125	0.0059	0.0162	0.0120	0.0238	0.0132	0.0182	0.0151	0.0117	0.0136	0.0379	0.0236	0.0170	0.0131	0.0207	0.0170	0.0158	0.0142	0.0149	0.0268	0.0154	0.0160	0.0164
Rank %	24%	38%	36%	61%	18%	35%	57%	47%	42%	14%	52%	41%	18%	33%	16%	43%	32%	63%	35%	48%	40%	31%	36%	100%	62%	45%	34%	55%	45%	42%	37%	39%	71%	41%	42%	43%
Category Qi		0.0376		0.0648						0.0743							0.1086					0.0404			0.0786		0.0338				0.0886				0.0478	
%age Category		35%		60%						68%							100%					37%			72%		31%				82%				44%	

Appendix G – DS Uncertainty Modelling for Requirements

Table 97 Second Level Combination with Work Criterion

		0.015504		**0.155039**		**0.488372**		**0.139535**		**0.046512**		**0.124031**		**0.023256**		**0.007752**	
		A		D		H		F		BF		CEG		CDEF		O	
EH	{}	0.0052	{}	0.0517	H	0.162791	{}	0.0465	{}	0.0155	E	0.041344	E	0.007752	EH	0.002584	
BF	{}	0.0044	{}	0.0443	{}	0.1395	F	0.039867	BF	0.013289	{}	0.0354	F	0.006645	BF	0.002215	{} =
AD	A	0.002953	D	0.029531	{}	0.0930	{}	0.0266	{}	0.0089	{}	0.0236	D	0.00443	AD	0.001477	0.5932
G	{}	0.0022	{}	0.022148	{}	0.0698	{}	0.0199	{}	0.0066	G	0.017719	{}	0.003322	G	0.001107	
Θ	A	0.000738	D	0.007383	H	0.023256	F	0.006645	BF	0.002215	CEG	0.005906	CDEF	0.001107	Θ	0.000369	

Table 98 Third Level Combination with Education Criterion

		0.009074		**0.101633**		**0.12069**		**0.130672**		**0.043557**		**0.45735**		**0.00363**		**0.043557**		**0.006352087**		**0.014519**		**0.002722**		**0.000907**	
		A		D		E		F		G		H		AD		BF		EH		CEG		CDEF		O	
H	{}	0.0035	{}	0.0395	{}	0.0469	{}	0.050817	{}	0.016939	H	0.177858	{}	0.0014	{}	0.016939	H	0.002470256	{}	0.005646	{}	0.001059	H	0.000353	
BCFG	{}	0.0030	{}	0.0339	{}	0.0402	F	0.043557	G	0.014519	{}	0.1525	{}	0.0012	BF	0.014519	{}	0.002117362	CG	0.00484	CF	0.000907	BCFG	0.000302	{} =
A	A	0.002017	{}	0.0226	{}	0.0268	{}	0.029038	{}	0.009679	{}	0.1016	A	0.000807	{}	0.009679	{}	0.001411575	{}	0.003226	{}	0.000605	A	0.000202	0.6204
Θ	A	0.000504	D	0.005646	E	0.006705	F	0.00726	G	0.00242	H	0.025408	AD	0.000202	BF	0.00242	EH	0.000352894	CEG	0.000807	CDEF	0.000151	Θ	5.04E-05	

Table 99 Fourth Level Combination with Financial Status Criterion

		0.009296		**0.014874**		**0.017663**		**0.133865**		**0.044622**		**0.542895**		**0.000531**		**0.044622**		**0.002390438**		**0.012749**		**0.00093**		**0.002125**		**0.000796813**		**0.000398406**		**0.000132802**	
		A		D		E		F		G		H		AD		BF		CF		CG		EH		CEG		BCFG		CDEF		O	
B	{}	0.0030	{}	0.0047	{}	0.0056	{}	0.0426	{}	0.0142	{}	0.1727	{}	0.0002	B	0.0142	{}	0.0008	{}	0.0041	{}	0.0003	{}	0.0007	B	0.0003	{}	0.0001	B	0.0000	{} =
F	{}	0.0025	{}	0.0041	{}	0.0048	F	0.0365	{}	0.0122	{}	0.1481	{}	0.0001	F	0.0122	F	0.0007	{}	0.0035	{}	0.0003	{}	0.0006	F	0.0002	F	0.0001	F	0.0001	0.5805
ADGH	A	0.0021	D	0.0034	{}	0.0040	{}	0.0304	G	0.0101	H	0.1234	A	0.0001	{}	0.0101	{}	0.0005	G	0.0029	H	0.0002	G	0.0005	F	0.0002	D	0.0001	ADGH	0.0000	
C	{}	0.0013	{}	0.0020	{}	0.0024	{}	0.0183	{}	0.0061	{}	0.0740	{}	0.0001	{}	0.0061	C	0.0003	C	0.0017	{}	0.0001	C	0.0003	C	0.0001	C	0.0001	C	0.0000	
Θ	A	0.0004	D	0.0007	E	0.0008	F	0.0061	G	0.0020	H	0.0247	AD	0.0000	BF	0.0020	CF	0.0001	CG	0.0006	EH	0.0000	CEG	0.0001	BCFG	0.0000	CDEF	0.0000	Θ	0.0000	

Table 100 Fifth Level Combination with Welfare Criterion

		0.0060		**0.0338**		**0.0057**		**0.0099**		**0.0019**		**0.1324**		**0.0371**		**0.3530**		**0.0001**		**0.0048**		**0.0003**		**0.0014**		**0.0001**		**0.0002**		**0.0001**		**0.0001**		**0.0000**		**0.0000**	
		A		B		C		D		E		F		G		H		AD		BF		CF		CG		EH		CEG		ADGH		BCFG		CDEF		O	**{} =**
B	{}	0.0038	B	0.0215	{}	0.0037	{}	0.0063	{}	0.0012	{}	0.0842	{}	0.0236	{}	0.2246	{}	0.0000	B	0.0031	{}	0.0002	{}	0.0009	{}	0.0001	{}	0.0001	{}	0.0001	B	0.0001	{}	0.0000	B	0.0000	**0.4824**
ACDEG	A	0.0016	A	0.0092	C	0.0016	D	0.0027	E	0.0005	{}	0.0361	G	0.0101	{}	0.0963	AD	0.0000	{}	0.0013	C	0.0001	CG	0.0004	E	0.0000	CEG	0.0001	ADG	0.0000	CG	0.0000	CDE	0.0000	ACDEG	0.0000	
Θ	A	0.0005	B	0.0031	C	0.0005	D	0.0009	E	0.0002	F	0.0120	G	0.0034	H	0.0321	AD	0.0000	BF	0.0004	CF	0.0000	CG	0.0001	EH	0.0000	CEG	0.0000	ADGH	0.0000	BCFG	0.0000	CDEF	0.0000	Θ	0.0000	

Table 101 Sixth Level Combination with Community Criterion

		0.0221		**0.0535**		**0.0042**		**0.0069**		**0.0013**		**0.0232**		**0.0260**		**0.0620**		**0.0000**		**0.0008**		**0.0000**		**0.0010**		**0.0000**		**0.0001**		**0.0002**		**0.0000**		**0.0000**		**0.0000**		**0.0000**		**0.0000**		**0.0000**	
		A		B		C		D		E		F		G		H		AD		BF		CF		CG		EH		ADG		CEG		CDE		ADGH		BCFG		CDEF		ACDEG		O	
B	{}	0.0119	B	0.0288	{}	0.0022	{}	0.0037	{}	0.0007	{}	0.0125	{}	0.0140	{}	0.0334	{}	0.0000	B	0.0005	{}	0.0000	{}	0.0006	{}	0.0000	{}	0.0000	{}	0.0001	{}	0.0000	{}	0.0000	B	0.0000	{}	0.0000	{}	0.0000	B	0.0000	
ADFH	A	0.0051	{}	0.0123	{}	0.0010	D	0.0016	{}	0.0003	F	0.0054	{}	0.0060	H	0.0143	AD	0.0000	F	0.0002	F	0.0000	{}	0.0002	H	0.0000	AD	0.0000	{}	0.0000	D	0.0000	ADH	0.0000	F	0.0000	DF	0.0000	AD	0.0000	ADFH	0.0000	{} =

CE	{}	0.0034	{}	0.0082	C	0.0006	{}	0.0011	E	0.0002	{}	0.0036	{}	0.0040	{}	0.0095	{}	0.0000	{}	0.0001	C	0.0000	C	0.0002	E	0.0000	{}	0.0000	CE	0.0000	CE	0.0000	{}	0.0000	{}	0.0000	CE	0.0000	E	0.0000	CE	0.0000	0.1291
Θ	A	0.0017	B	0.0041	C	0.0003	D	0.0005	E	0.0001	F	0.0018	G	0.0020	H	0.0048	AD	0.0000	BF	0.0001	CF	0.0000	CG	0.0001	EH	0.0000	ADG	0.0000	CEG	0.0000	CDE	0.0000	ADGH	0.0000	BCFG	0.0000	CDEF	0.0000	ACDEG	0.0000	Θ	0.0000	

Table 102 Translated Total Weighted Relation Matrix of Design Requirements

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
MT	40%	52%	58%	88%	51%	74%	86%	95%	86%	93%	85%	68%	95%	89%	54%	82%	74%	67%	80%	66%	100%	60%	84%	82%	100%	60%	78%	94%	99%	89%	84%	49%	94%	95%	100%	73%
	100%	100%	100%	74%	100%	100%	100%	97%	86%	94%	90%	100%	98%	100%	100%	100%	100%	100%	100%	100%	84%	100%	100%	100%	84%	100%	100%	100%	100%	100%	100%	100%	100%	100%	88%	100%
WK	59%	38%	44%	42%	39%	46%	48%	65%	58%	66%	62%	55%	100%	44%	47%	57%	67%	41%	76%	48%	66%	50%	51%	61%	62%	73%	70%	72%	27%	24%	65%	39%	74%	79%	67%	39%
ED	38%	45%	39%	26%	42%	36%	39%	53%	36%	53%	51%	45%	91%	39%	48%	51%	63%	36%	45%	41%	51%	42%	47%	34%	51%	55%	68%	59%	51%	39%	52%	19%	46%	66%	50%	21%
FS	23%	65%	20%	22%	16%	17%	19%	27%	18%	27%	26%	22%	61%	26%	29%	34%	46%	25%	25%	43%	36%	37%	28%	51%	33%	44%	44%	59%	55%	44%	55%	38%	48%	63%	40%	47%
	21%	37%	23%	28%	48%	83%	60%	26%	44%	32%	31%	26%	49%	26%	25%	37%	33%	36%	43%	37%	34%	40%	33%	49%	43%	28%	35%	42%	40%	33%	40%	35%	43%	43%	35%	33%
CO	16%	26%	11%	10%	13%	13%	15%	16%	14%	17%	15%	13%	35%	19%	24%	32%	23%	19%	30%	17%	28%	27%	22%	27%	25%	17%	22%	23%	27%	22%	42%	25%	24%	43%	30%	25%
	70%	74%	83%	100%	79%	94%	88%	100%	100%	100%	100%	88%	21%	9%	11%	10%	11%	7%	8%	7%	11%	8%	8%	7%	9%	7%	9%	12%	14%	15%	15%	11%	10%	14%	8%	10%

Table 103 Preference for Design requirements focal elements decision alternatives

F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
B- 7 w	B-7 w	B-7 w	AB-7 w	B-7 w	B-7 w	B-6 w	B-7 w	B-7 w	B-7 w	B-6 w	B-7 w	C-6 w	B-7 w	B-6 w	B-7 w	B-7 w	B-7 w	B-7 w	B-6 w	A-7 w	B-7 w	B-7 w	B-7 w	A-7 w	B-7 w	B-7 w	B-6 w	AB-7 w	B-7 w	B-6 w	B-7 w	AB-7 w	AB-6 w	A-7 w	B-7 w
C- 5 w	A-5 w	A-5 w	C-6 w	A-6 w	A-5 w	A-4 w	A-6 w	A-5 w	A-5 w	A-5 w	A-5 w	ABD-5 w	A-5 w	A-5 w	A-5 w	A-6 w	A-6 w	A-6 w	A-5 w	B-5 w	A-6 w	A-5 w	A-5 w	B-6 w	C-5 w	AC-5 w	A-5 w	DE-6 w	A-5 w	A-5 w	A-5 w	C-6 w	C-5 w	B-6 w	A-5 w
AD- 3w	CD-3 w	CD-3 w	DE-3 w	C-4 w	CD-4 w	CD-3 w	C-4 w	C-3 w	CD-3 w	C-3 w	C-4 w	E-4 w	C-3 w	CD-2 w	CD-4 w	CD-4 w	C-3 w	C-5 w	CDE-4w	C-3 w	C-4 w	C-3 w	C-4 w	C-5 w	A-4 w	D-4 w	C-4 w	F-3 w	E-4 w	C-4 w	CEF-3w	DEF-3w	DE-3 w	C-4 w	E-3 w
Θ - 1w	Θ -1 w	Θ -- 1w	Θ -- 1w	DF-2 w	Θ -1 w	Θ -1 w	D-2 w	D-2 w	Θ -1 w	D-2 w	D-2 w	F-3 w	D-2 w	Θ -1 w	EFD-2w	E-3 w	DF-2 w	DF-3 w	F-3 w	DE-2 w	DF-2 w	D-2 w	E-3 w	D-3 w	D-3 w	E-3 w	DE-3 w	Θ -1 w	DF-3 w	DE-3 w	Θ -1 w	Θ -1 w	FG-2 w	D-3 w	CF-2 w
				Θ -- 1w			Θ -1 w	Θ -1 w		Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w		Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w	Θ -1 w	F-2 w	F-2 w	E-2 w	Θ -1 w	F-2 w		Θ -1 w	FG-2 w			Θ - 1 w	E-2 w	Θ -1 w
																							Θ -1 w	Θ -1 w	Θ -1 w		Θ -1 w			Θ -1 w				Θ -1 w	

Table 104 Design Requirements Initial Fused Matrix

F1		F2		F3		F4		F5		F6		F7		F8		F9		F10		F11		F12	
Weights	0.0168		0.0243		0.0261		0.0578		0.0117		0.0464		0.0410		0.0288		0.0286		0.0085		0.0331		0.0278
B	0.1175	B	0.1703	B	0.1830	AB	0.4043	B	0.0818	B	0.3245	B	0.2460	B	0.2014	B	0.2000	B	0.0595	B	0.1986	B	0.1949
C	0.0839	A	0.1217	A	0.1307	C	0.3466	A	0.0701	A	0.2318	A	0.1640	A	0.1726	A	0.1429	A	0.0425	A	0.1655	A	0.1392
AD	0.0504	CD	0.0730	CD	0.0784	DE	0.1733	C	0.0467	CD	0.1854	CD	0.1230	C	0.1151	C	0.0857	CD	0.0255	C	0.0993	C	0.1114
Θ	0.0168	Θ	0.0243	Θ	0.0261	Θ	0.0578	DF	0.0234	Θ	0.0464	Θ	0.0410	D	0.0575	D	0.0571	Θ	0.0085	D	0.0662	D	0.0557
								Θ	0.0117					Θ	0.0288	Θ	0.0286			Θ	0.0331	Θ	0.0278

F13		F14		F15		F16		F17		F18		F19		F20		F21		F22		F23		F24	
	0.0084		0.0264		0.0086		0.0222		0.0159		0.0362		0.0182		0.0262		0.0353		0.0171		0.0189		0.0538
C	0.0507	B	0.1848	B	0.0516	B	0.1552	B	0.1113	B	0.2533	B	0.1273	B	0.1574	A	0.2469	B	0.1196	B	0.1324	B	0.3766
ABD	0.0422	A	0.1320	A	0.0430	A	0.1108	A	0.0954	A	0.2171	A	0.1091	A	0.1312	B	0.1764	A	0.1025	A	0.0946	A	0.2690
E	0.0338	C	0.0792	CD	0.0172	CD	0.0887	CD	0.0636	C	0.1085	C	0.0909	CDE	0.1049	C	0.1058	C	0.0683	C	0.0567	C	0.2152
F	0.0253	D	0.0528	Θ	0.0086	EFG	0.0443	E	0.0477	DF	0.0724	DF	0.0546	F	0.0787	DE	0.0705	DF	0.0342	D	0.0378	E	0.1614
Θ	0.0084	Θ	0.0264			Θ	0.0222	Θ	0.0159	Θ	0.0362	Θ	0.0182	Θ	0.0262	Θ	0.0353	Θ	0.0171	Θ	0.0189	F	0.1076
																						Θ	0.0538

F25		F26		F27		F28		F29		F30		F31		F32		F33		F34		F35		F36	
	0.0524		0.0543		0.0171		0.0270		0.0235		0.0229		0.0187		0.0240		0.0356		0.0194		0.0430		0.0242
A	0.3665	B	0.3803	B	0.1197	B	0.1617	AB	0.1642	B	0.1603	B	0.1122	B	0.1682	AB	0.2491	AB	0.1162	A	0.3010	B	0.1693
B	0.3141	C	0.2716	AC	0.0855	A	0.1348	DE	0.1407	A	0.1145	A	0.0935	A	0.1202	C	0.2135	C	0.0969	B	0.2580	A	0.1209
C	0.2618	A	0.2173	D	0.0684	C	0.1078	F	0.0704	E	0.0916	C	0.0748	CEF	0.0721	DEF	0.1067	DE	0.0581	C	0.1720	E	0.0726
D	0.1571	D	0.1630	E	0.0513	DE	0.0809	Θ	0.0235	DF	0.0687	DE	0.0561	Θ	0.0240	Θ	0.0356	FG	0.0387	D	0.1290	CF	0.0484
F	0.1047	E	0.1087	Θ	0.0171	F	0.0539			Θ	0.0229	FG	0.0374					Θ	0.0194	E	0.0860	Θ	0.0242
Θ	0.0524	Θ	0.0543			Θ	0.0270					Θ	0.0187							Θ	0.0430		

Table 105 Design Requirements Normalised Fused Matrix

F1		F2		F3		F4		F5		F6		F7		F8		F9		F10		F11		F12	
	0.2685		0.3893		0.4183		0.9819		0.2337		0.7880		0.5741		0.5755		0.5143		0.1361		0.5626		0.5291
B	0.4375	B	0.4375	B	0.4375	AB	0.4118	B	0.3500	B	0.4118	B	0.4286	B	0.3500	B	0.3889	B	0.4375	B	0.3529	B	0.3684
C	0.3125	A	0.3125	A	0.3125	C	0.3529	A	0.3000	A	0.2941	A	0.2857	A	0.3000	A	0.2778	A	0.3125	A	0.2941	A	0.2632
AD	0.1875	CD	0.1875	CD	0.1875	DE	0.1765	C	0.2000	CD	0.2353	CD	0.2143	C	0.2000	C	0.1667	CD	0.1875	C	0.1765	C	0.2105

F13		F14		F15		F16		F17		F18		F19		F20		F21		F22		F23		F24	
	0.1605		0.4753		0.1205		0.4212		0.3338		0.6874		0.4000		0.4984		0.6349		0.3417		0.3405		1.1837
C	0.3158	B	0.3889	B	0.4286	B	0.3684	B	0.3333	B	0.3684	B	0.3182	B	0.3158	A	0.3889	B	0.3500	B	0.3889	B	0.3182
ABD	0.2632	A	0.2778	A	0.3571	A	0.2632	A	0.2857	A	0.3158	A	0.2727	A	0.2632	B	0.2778	A	0.3000	A	0.2778	A	0.2273
E	0.2105	C	0.1667	CD	0.1429	CD	0.2105	CD	0.1905	C	0.1579	C	0.2273	CDE	0.2105	C	0.1667	C	0.2000	C	0.1667	C	0.1818

ϴ	0.0625	ϴ	0.0625	ϴ	0.0625	ϴ	0.0588	DF	0.1000	ϴ	0.0588	ϴ	0.0714	D	0.1000	D	0.1111	ϴ	0.0625	D	0.1176	D	0.1053
								ϴ	0.0500					ϴ	0.0500	ϴ	0.0556			ϴ	0.0588	ϴ	0.0526

F	0.1579	D	0.1111	ϴ	0.0714	EFG	0.1053	E	0.1429	DF	0.1053	DF	0.1364	F	0.1579	DE	0.1111	DF	0.1000	D	0.1111	E	0.1364
ϴ	0.0526	ϴ	0.0556			ϴ	0.0526	ϴ	0.0476	ϴ	0.0526	ϴ	0.0455	ϴ	0.0526	ϴ	0.0556	ϴ	0.0500	ϴ	0.0556	F	0.0909
																						ϴ	0.0455

F25		F26		F27		F28		F29		F30		F31		F32		F33		F34		F35		F36	
	1.2566		1.1952		0.3420		0.5660		0.3987		0.4580		0.3928		0.3845		0.6049		0.3293		0.9889		0.4354
A	0.2917	B	0.3182	B	0.3500	B	0.2857	AB	0.4118	B	0.3500	B	0.2857	B	0.4375	AB	0.4118	AB	0.3529	A	0.3043	B	0.3889
B	0.2500	C	0.2273	AC	0.2500	A	0.2381	DE	0.3529	A	0.2500	A	0.2381	A	0.3125	C	0.3529	C	0.2941	B	0.2609	A	0.2778
C	0.2083	A	0.1818	D	0.2000	C	0.1905	F	0.1765	E	0.2000	C	0.1905	CEF	0.1875	DEF	0.1765	DE	0.1765	C	0.1739	E	0.1667
D	0.1250	D	0.1364	E	0.1500	DE	0.1429	ϴ	0.0588	DF	0.1500	DE	0.1429	ϴ	0.0625	ϴ	0.0588	FG	0.1176	D	0.1304	CF	0.1111
F	0.0833	E	0.0909	ϴ	0.0500	F	0.0952			ϴ	0.0500	FG	0.0952					ϴ	0.0588	E	0.0870	ϴ	0.0556
ϴ	0.0417	ϴ	0.0455			ϴ	0.0476					ϴ	0.0476							ϴ	0.0435		

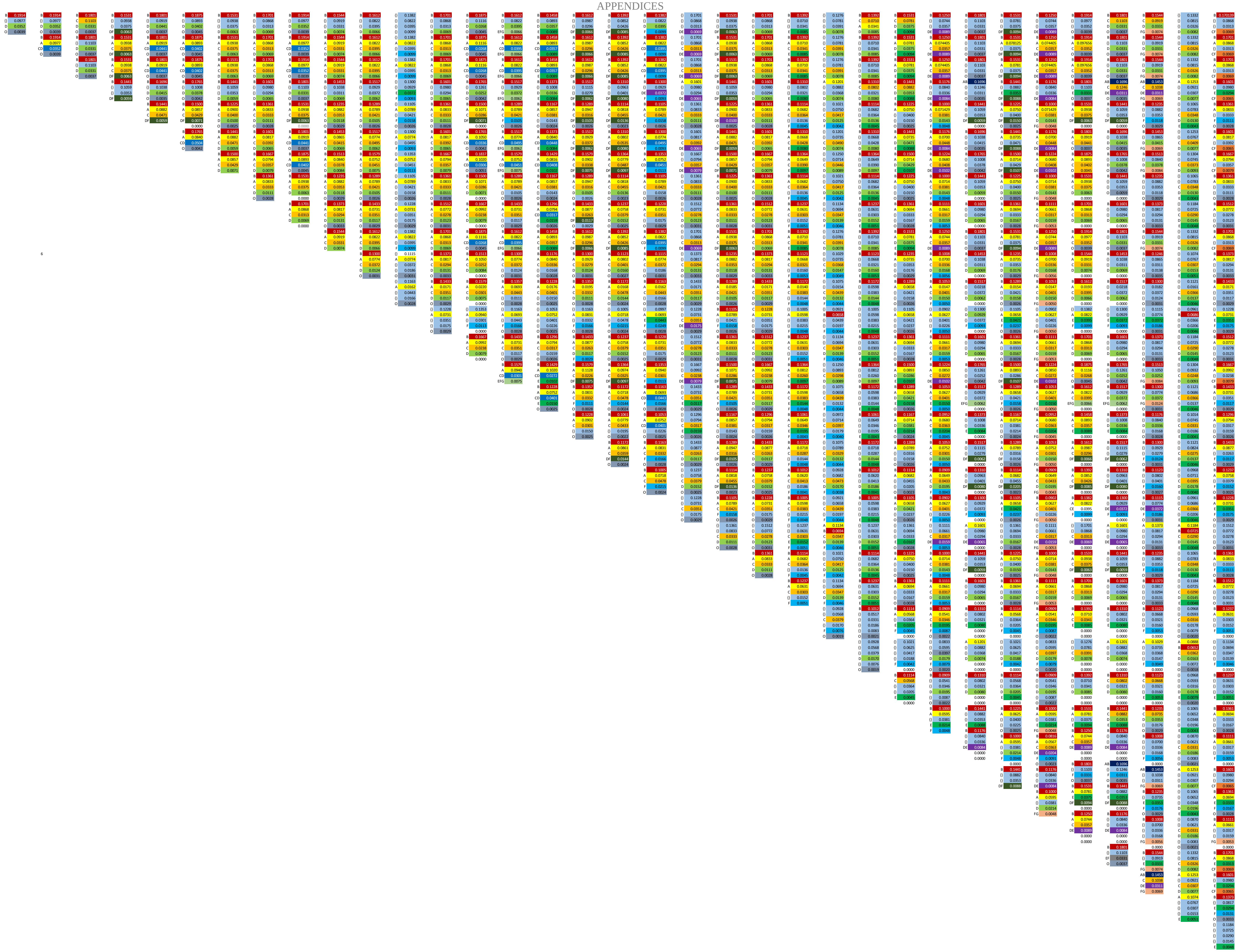


Figure 0-1 Detailed Analysis for User Requirements Uncertainty Modelling

H	0.1639	H	0.1014	H	0.1184	{}	0.0968	{}	0.1937	{}	0.1639	{}	0.1121
F	0.0602	BF	0.0745	BF	0.0870	F	0.0711	{}	0.0711	F	0.0602	{}	0.0686
{}	0.0334	D	0.0414	{}	0.0483	DF	0.0494	D	0.0198	{}	0.0334	D	0.0458
CEG	0.0134	G	0.0248	CEG	0.0097	C	0.0237	{}	0.3427	CEG	0.0134	CE	0.0183
		O	0.0021	H	0.2094	O	0.0020	DEG	0.0629	{}	0.2899	O	0.0023
		H	0.1795	CFG	0.0769	{}	0.1713	A	0.0140	DF	0.0533	{}	0.1984
		F	0.0659	A	0.0342	F	0.0629	{}	0.2121	{}	0.0237	G	0.0607
		A	0.0293	O	0.0043	A	0.0350	{}	0.0779	O	0.0059	{}	0.0324
		G	0.0110	H	0.1296	C	0.0105	AD	0.0173	{}	0.1795	ACEF	0.0081
				BF	0.0952	{}	0.1061	{}	0.2475	F	0.0659	{}	0.1228
				A	0.0423	F	0.0779	CG	0.0909	{}	0.0293	{}	0.0752
				G	0.0079	AD	0.0433	A	0.0202	G	0.0110	D	0.0401
						{}	0.0195	B	0.2025	{}	0.2094	CE	0.0150
						O	0.0022	{}	0.0744	F	0.0769	O	0.0025
						{}	0.1237	ADGH	0.0207	{}	0.0342	{}	0.1433
						F	0.0909			O	0.0043	G	0.0877
						A	0.0505			B	0.1713	{}	0.0468
						C	0.0076			F	0.0629	ACEF	0.0058
										{}	0.0350	B	0.1172
										C	0.0105	{}	0.0718
										B	0.3427	D	0.0478
										AD	0.0629	C	0.0144
										CEG	0.0140	O	0.0024
												B	0.2344
												G	0.0718
												D	0.0191
												B	0.1984
												{}	0.0607
												{}	0.0324
												ACEF	0.0081

Figure 0-2 Detailed Analysis for User Requirements Uncertainty Modelling

Appendix H – Evaluation Questionnaire

Evaluation Questionnaire

Rating of Importance: You may rate importance factors according to the following scale
Not at all Important **(1),………,** Important **(5),………..,** Extremely Important **(9)**

1. What role are you in the Project Process?

End-User		**Project Team**		**Authority/Compliance**		**Contractor Team**	
Funding		**Care/Support**		**Other Stakeholder**			

2. What Experience do have you in similar project environment (B)?

No. Of Years		**N/A**	

3. How are the following factors likely to influence home or user needs (Rate 1-9)?

Family/ Occupancy		**Economic/Finance**		**Friends/community**	
Sociocultural		**Environment**		**Lifecycle Performance**	
Technical/Specification		**Leadership/ politics**		**Project Governance**	

4. Please Rate the Decision Support Systems capabilities in highlighting the following areas of design decision making and the project. (Rate 1-9)

Not at all Important **(1),………,** Important **(5),………..,** Extremely Important **(9)**							
Economics Factors							
Cost of Construction		Project Costs		Strategic value			
Sociocultural							
Mobility		Integrated Design		Culture/Community		Demographics	
Health and Safety							
Safety		Acoustics		Flow of Spaces		Hygiene/Health	
Security							
Technical Aspects							
Constructability		Legal/Compliance		Design Form		Collaboration	
Project Processes		Functional Design		Lead Times		Specification	
Lifecycle Performance							
Accessibility		Serviceability		Maintainability			
Occupancy							
Occupancy Levels/patterns		Financial Status		Social Status/Aspiration			
Environment							
Materials Use		Adaptability		Lifecycle costs			
Energy Performance				Physical Management			

Geopolitics						
Political Leadership				Legislation/Policy		
Governance						
Project Governance		Project Context		Stakeholder Management		

5. How important are the following assessments in influencing the nature of design process? (Rate 1-9)

Project Outcomes		**Emergent Requirements**		**Confidence in design decisions**		**Causes and effects in outcomes**	

6. How has the decision support system supported assessments of the following for the purpose of assisting design decisions and process? (Rate 1-9)

Project Outcomes		**Emergent Requirements**		**Confidence in design decisions**		**Causes and effects in outcomes**	

7. How do you rate the decision support system in the following (Rate 1-9)?

Integrating many project attributes		**Coping with Emergent Requirements**		**Ranking of attributes**		**Causes and effects in outcomes**	

8. How do you rate the relevance of the following components of the decision support system (Rate 1-9)?

Outcomes Ranker		**Cause-Effect Graphs**		**Uncertainty assessment for requirements**		**Change in Requirements Assessment**	

9. In your view, has DESIDE support the following? (Rate 1-9)

Aim of the Research		**Research Objectives**		**Comprehensive Decision Making**		**Simple and Clear Decision Making**	

10. Rate the Proposed Decision System and its Structure to any alternative you have used previously and comment on any change you would propose

The System Compared to alternatives		**Structure of System**	

Appendix I - Reviewed Studies by Year, methodology, Sector and Requirements Factors identified

Author	Methodology	Sector	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36
Leśniak and Zima (2018)	Evaluative Study	Construction	✓	✓	✓																																	
Tezel et al. (2018)	Qualitative Survey Study	Construction		✓	✓																												✓					
Hwang et al. (2018)	Qualitative Survey Study	Construction			✓														✓											✓								
Callegari et al. (2018)	Evaluative Study	Construction	✓	✓	✓																✓												✓					✓
Kruger et al. (2018)	Qualitative Survey Study	Product Service Systems																✓																				
Boton (2018)	Case Study	Construction													✓			✓																		✓		
Knauss et al. (2018)	Qualitative Survey Study	IT																✓																		✓		✓
Hujainah et al. (2018)	Literature Review	IT																																		✓		✓
Śladowski (2018)	Case Study	Construction																																				
Jansson et al. (2018)	Qualitative Survey Study	Construction													✓		✓												✓	✓						✓		
Smyth et al. (2018)	Case Study (Interpretive)	Construction			✓			✓																														
Chesbrough et al. (2018)	Evaluative Study	New Product Development																✓																				
Chalhoub and Ayer (2018)	Evaluative Study	Construction			✓													✓	✓																			
Sindhu et al. (2018)	Qualitative Documentary Study	Construction	✓												✓																					✓		
Du et al. (2018b)	Evaluative Study	Construction			✓																												✓					
Du et al. (2018a)	Literature Review	Construction	✓	✓	✓																															✓		
Choi et al. (2018)	Evaluative Study	Construction			✓																										✓		✓	✓				
Garcia-Ceballos et al. (2018)	Evaluative Study	Construction			✓																														✓		✓	
Hu (2018)	Case Study	Construction			✓																														✓			
Wang et al. (2018)	Evaluative Study	Construction																																				
Liao et al. (2018)	Evaluative Study	Construction						✓																														
Volk et al. (2018)	Case Study	Construction																				✓																✓
Eleftheriadis et al. (2018)	Evaluative Study	Construction			✓													✓											✓	✓								
Thew and Sutcliffe (2018)	Evaluative Study	IT						✓									✓	✓											✓									
Han et al. (2018)	Exploratory Case Study	Engineering Design																				✓																
Müller et al. (2017)	Evaluative Study	IT			✓					✓				✓									✓													✓	✓	
ul Musawir et al. (2017)	Qualitative Survey Study	Construction			✓																																	
Pegoraro and Paula (2017)	Systematic Literature Review	Construction			✓													✓		✓											✓		✓					
Rodrigues and Freire (2017)	Evaluative Study	Construction			✓																					✓											✓	
Carrizo et al. (2017)	Evaluative Study	IT																✓																	✓			
Abeywickrama and Ovaska (2017)	Literature Review	IT																																				
Goh and Loosemore (2017)	Qualitative Survey Study	Construction																✓									✓									✓		
Koh (2017)	Evaluative Study	Construction																																				
Papadonikolaki et al. (2017)	mixed method approach plus caste study	Construction																✓																				
Akcay et al. (2017)		Construction			✓																															✓	✓	✓
Sinesilassie et al. (2017)	Qualitative Survey Study	Construction							✓												✓									✓						✓	✓	
Locatelli et al. (2017)	Evaluative Case Study	Construction		✓	✓			✓													✓												✓			✓		✓
Lin et al. (2017)	Qualitative Survey Study	Construction						✓										✓																✓				✓
Cavka et al. (2017)	Qualitative Survey Study	Construction			✓					✓				✓		✓		✓		✓			✓	✓							✓							
Sleiman et al. (2017)	Evaluative Study	Construction					✓																													✓		
Cardenas et al. (2017)	Evaluative Study	Construction			✓													✓																		✓		
Wiese et al. (2017)	Evaluative Study	IT																✓																			✓	
Hastie et al. (2017)	Case Study, Survey	Construction													✓			✓												✓							✓	
Sanderson and Winch (2017)	Evaluative Study	Construction																✓																		✓		✓
Mok et al. (2017)	Case Study	Construction			✓			✓									✓	✓		✓									✓							✓		✓
Samset (2017)	Literature Review	Construction			✓																												✓					
Eckart et al. (2017)	Literature Review	Construction						✓									✓																					
Saoud et al. (2017)	Case Study, Survey	Construction																✓													✓							
Clarke et al. (2017)	Evaluative Study	Construction																	✓																			
Oraee et al. (2017)	Systematic Literature Review	Construction																✓										✓					✓					
Vernet and Coste (2017)	Evaluative Study	Construction			✓			✓																												✓		
Buchmann and Karagiannis (2017)	Evaluative Study	IT			✓													✓		✓																		
Shin et al. (2017)	Evaluative Study	Construction			✓									✓				✓																				✓
Revellino and Mouritsen (2017)	Evaluative Study	Construction																✓											✓									
Rowlinson (2017)	Literature Review	Construction																	✓												✓							
Pal et al. (2017)	Case Study	Construction																													✓			✓		✓		✓
Sousa-Zomer and Miguel (2017)	Qualitative Documentary Study	Product Service Systems				✓				✓													✓	✓	✓													
Heikkilä et al. (2017)	Qualitative Survey Study	IT			✓																												✓		✓			
Galle et al. (2017)	Evaluative Study	Construction			✓																												✓					
Shen et al. (2017)	Case Study	Construction														✓		✓												✓								
Brioso et al. (2017)	Action Research	Construction			✓																											✓	✓					
Dias et al. (2017)		Construction																																				
Kpamma et al. (2017)	Evaluative Study	Construction																✓	✓														✓					
Hollberg and Ruth (2016)	Quantitative Model analysis	Construction																																✓				
del Caño et al. (2016)	Evaluative Study	Construction														✓																				✓		✓
Haddadi et al. (2016)	Literature Review	Construction																																				✓
Davies and Brady (2016)	Evaluative Study	Construction			✓													✓																			✓	
Immonen et al. (2016)	Evaluative Study	IT			✓													✓													✓							
Nielsen et al. (2016)	Evaluative Study	Construction															✓		✓																	✓	✓	
Jussila et al. (2016)	Case Study	Construction			✓													✓																				

Dave et al. (2016)	Design Science Research	Construction															✓											✓		✓					
Roux et al. (2016)	Case Study	Construction			✓																							✓	✓		✓					
Delmastro et al. (2016)	Evaluative Study	Construction																										✓								
Kemp and Scholl (2016)	Case Study	Construction						✓																												
Addison et al. (2016)	Case Study	Health			✓	✓		✓				✓																								
Bacciotti et al. (2016)	Qualitative Documentary Study	New Product Development			✓																															
Malekitabar et al. (2016)	Qualitative Documentary Study	Construction								✓			✓																					✓		✓
Wei et al. (2016)	Evaluative Study	Construction			✓			✓																				✓	✓		✓	✓				
Palm and Reindl (2016)	Evaluative Study	Construction			✓																	✓					✓								✓	✓
Samset and Volden (2016)	Case Study	Construction															✓										✓	✓	✓		✓					
Ferreira et al. (2016)	Evaluative Study	Construction			✓																														✓	
Surlan et al. (2016)	Qualitative Survey Study	Construction			✓				✓								✓																	✓	✓	
Müller et al. (2016)	Qualitative Survey Study	Construction			✓																															
Dias et al. (2016)	Case Study	Engineering Design			✓												✓										✓	✓								✓
Osei–Kyei and Chan (2016)	Evaluative Study	Construction	✓	✓	✓													✓								✓										
Bayram et al. (2016)	Evaluative Study	Construction		✓	✓																															
Ledoux et al. (2016)	Evaluative Study	Engineering Design			✓												✓		✓															✓		
Hoła et al. (2015)	Evaluative Study	Construction			✓																							✓			✓			✓		
Vezzoli et al. (2015)	Evaluative Study	Product Service Systems			✓			✓				✓					✓	✓								✓										
Plewa et al. (2015)	Evaluative Study	New Product Development			✓																												✓			
Lung et al. (2015)	Case Study	IT			✓																															
Dagan and Isaac (2015)	Action Research	Construction								✓								✓															✓	✓		
Koh et al. (2015)	Case Study	Engineering Design																																		
Li et al. (2015)	Literature Review	Construction	✓	✓	✓																															
Inayat et al. (2015)	Case Study	IT							✓								✓											✓	✓		✓				✓	
Buyle et al. (2015)	Case Study	Construction	✓	✓	✓																															
Singhaputtangkul and Low (2015a)	Case Study	Construction												✓																						
Almeida et al. (2015)	Evaluative Study	Construction			✓							✓					✓	✓				✓									✓					✓
Russell-Smith and Lepech (2015)	Case Study	Construction		✓													✓																			
Serra and Kunc (2015)	Survey	IT			✓																															
Jung et al. (2015)	Evaluative Study	Construction			✓																								✓		✓					
Lu et al. (2015b)	Literature Review	Construction			✓																						✓	✓						✓		
Shackleton et al. (2014)	Case Study	Construction			✓			✓									✓																			
Too and Weaver (2014)	Literature Review	Construction			✓												✓											✓							✓	✓
Locatelli et al. (2014)	Literature Review	Construction																																		
Tserng et al. (2014)	Action Research	Construction																		✓																✓
Kw Wong et al. (2014)	Case Study	Construction			✓												✓							✓					✓		✓					
Chiu et al. (2014)	Evaluative Study	Construction			✓																				✓											
Pignataro et al. (2014)	Case Study	Construction																	✓		✓	✓							✓							
Shaikh et al. (2014)	Literature Review	Construction									✓																							✓		
Pemsel et al. (2014)	Literature Review	Construction			✓																													✓		
De Schepper et al. (2014)	Comparative Case Study	Construction			✓												✓											✓		✓	✓					
Shackleton et al. (2014)	Case Study	Construction			✓												✓							✓		✓			✓		✓	✓		✓		✓
Thomson et al. (2013)	Evaluative Study	Construction	✓		✓											✓	✓		✓	✓									✓		✓					
Himpe et al. (2013)	Case Study	Construction																					✓				✓							✓		✓
Hellström et al. (2013)	Exploratory Case Study	Construction																																	✓	
Lu and Hao (2013)	Case Study	Construction															✓																			
Im et al. (2013)	Qualitative Survey Study	New Product Development			✓												✓		✓									✓			✓					
Hsueh et al. (2013)	Evaluative Study	Construction	✓		✓			✓																												
Williams et al. (2013)	Literature Review	Construction			✓												✓								✓											✓
Rezgui et al. (2013)	Case Study	Construction													✓																					
Lin (2013)	Action Research	Construction			✓																										✓					
Shen et al. (2013)	Case Study	Construction									✓						✓						✓											✓		
Ghosh et al. (2012)	Case Study	Construction			✓												✓																	✓		
Belkadi et al. (2012)	Evaluative Study	Engineering Design			✓		✓										✓																	✓	✓	
Sanderson (2012)	Literature Review	Construction			✓																								✓							
Liu et al. (2012)	Case Study	Construction																																✓		
Tang et al. (2012)	Literature Review	Construction			✓												✓	✓																		
Elf et al. (2012)	Evaluative Study	Construction										✓					✓	✓																	✓	
Abduh et al. (2012)	Case Study	Construction			✓																													✓		✓
Chakraborty (2011)	Case Study	Construction			✓																															
Cavieres et al. (2011)	Quantitative Model analysis	Construction												✓							✓								✓							
Hopfe and Hensen (2011)	Evaluative Study	Construction																																		
Gasafi and Weil (2011)	Case Study	Construction																✓											✓							
Jay and Bowen (2011)	Qualitative Survey Study	Construction		✓				✓					✓						✓							✓										
Yang et al. (2011)		Construction			✓												✓																			
Lin et al. (2011)	Evaluative Study	Construction			✓												✓	✓											✓		✓					
Leckner and Zmeureanu (2011)	Evaluative Study	Construction			✓																													✓		
Chandra and Loosemore (2011)	Case Study	Construction															✓																			
Singh et al. (2011)	Case Study, Interviews	Construction												✓			✓																			
Baalousha and Çelik (2011)	Evaluative Study	Construction	✓	✓	✓																														✓	
Wolter and Meinel (2010)	Evaluative Study	IT			✓												✓																✓			
Adeyeye et al. (2010)	Evaluative Study	Construction																																		
Gu and London (2010)	Qualitative Evaluative Research	Construction															✓																			
Almeida et al. (2010)	Evaluative Study	Construction			✓				✓								✓															✓				
Razavi and Haas (2010)	Evaluative Study	Construction																✓																		
Luo et al. (2010)	Evaluative Study	Construction			✓						✓						✓	✓	✓													✓	✓			

Chen et al. (2010b)	Literature Review	Construction	✓				✓		✓					
Romani et al. (2010)	Evaluative Study	IT									✓	✓	✓	
van de Kar and Den Hengst (2009))	Qualitative Survey Study	IT						✓						✓
Chung et al. (2009)	Literature Review	Construction						✓						
Yeung et al. (2009)	Case Study	Construction		✓				✓						
Elf and Malmqvist (2009)	Evaluative Study	Construction		✓				✓						✓
Jallow et al. (2008)	Qualitative Survey Study	Construction		✓				✓						
Ross et al. (2008)	Evaluative Study	Construction		✓										
Yu et al. (2008)	Qualitative Survey Study	Construction						✓						
Baxter et al. (2008)	Case Study	Engineering Design		✓								✓		✓
Moodley et al. (2008)	Evaluative Study	Construction		✓	✓	✓		✓				✓		✓
George et al. (2008)	Qualitative Survey Study	Construction												✓
Agouridas et al. (2008)	Case Study/Action research	New Product Development		✓				✓		✓				

Appendix J - Reviewed Studies by Year, Sector and Decision Method and Techniques identified

Author	Journal	Decision Method	Sector	Main Technique	Study Type	Technique 2	Technique 3	Technique 4
Alkahtani et al. (2019)	Advances in Mechanical Engineering	MCDM	Supply Chain	AHP	Case Study	TOPSIS		
Jalilzadehazhari et al. (2019)	Buildings	MCDM	Construction	AHP	Case Study	BIM		
Yoon et al. (2019)	Journal of Cleaner Production	MCDM	Construction	CBA	Evaluative			
Chen et al. (2019b)	Journal of Cleaner Production	MCDM	PSS	DEMATEL	Evaluative	ANP		
D'Agostino et al. (2019)	Energy Strategy Reviews	MCDM	Energy	MAUT	Evaluative			
Chen et al. (2019a)	Advances in Civil Engineering	Explanatory	Construction	Model-Based	Case Study			
Kültür et al. (2019)	Buildings	Explanatory	Construction	Model-Based	Evaluative			
Zhang et al. (2019b).	Journal of Cleaner Production	MCDM	Engineering Design	QFD	Case Study	Fuzzy sets		
Li et al. (2019)	Computers and Industrial Engineering	MCDM	Engineering Design	QFD	Evaluative	Unigram model		
Zhang et al. (2019b)	Journal of Cleaner Production	MCDM	Engineering Design	QFD	Evaluative	Fuzzy Sets		
Zhang (2019)	Journal of Intelligent Manufacturing	MCDM	NDP	QFD	Evaluative	DEA		
Buchanan et al. (2019)	Environment Systems and Decisions	Explanatory	Engineering Design	Set-based design	Evaluative			
Small et al. (2019)	Journal of Défense Modelling and Simulation	Explanatory	NDP	Set-based design	Evaluative			
Wade et al. (2019)	Environment Systems and Decisions	Hybrid	Engineering Design	Set based design	Evaluative	probability trees		
Ammar et al. (2019)	Concurrent Engineering Research and Applications	Hybrid	NDP	Set-based design		Other		
Rempling et al. (2019).	Automation in Construction	Hybrid	Construction	Set-based design				
Kabirifar and Mojtahedi (2019).	Buildings	MCDM	Construction	TOPSIS	Case Study			
Navarro et al. (2019)	Advances in Civil Engineering	MCDM	Construction	TOPSIS	Literature Review	AHP	PROMETHEE	COPRAS
Imran et al. (2019)	Decision Science Letters	MCDM	Construction	partial least square structural equation modelling technique	Case Study			
Zanni et al. (2019)	Buildings	Visual	Construction	BIM	Evaluative	IDEF		
Lorenzi and Ferreira (2018)	International Journal of Quality and Reliability Management	Visual	NDP	A3 Reports	Case Study	FMEA		
Alshamrani et al. (2018)	Buildings	MCDM	Construction	AHP	Case Study	MUAT		
Arroyo et al. (2018)	Energy and Buildings	MCDM	Construction	CBA	Case Study			
Hashemkhani Zolfani et al. (2018)	Alexandria Engineering Journal	MCDM	Construction	MOORA	Case Study			
Antoniou and Aretoulis (2018)	International Journal of Management and Decision Making	MCDM	Construction	PROMETHEE	Case Study			
Eleftheriadis et al. (2018)	Advanced Engineering Informatics	MCDM	Manufacturing	QFD	Case Study	BIM		
Fargnoli et al. (2018)	Journal of Cleaner Production	MCDM	NDP	QFD	Case Study			
Liao **Wu and Liao (2018)**	Information Fusion	MCDM	NDP	QFD	Case Study	ORESTE		
Gotzamani et al. (2018a)	International Journal of Quality and Reliability Management	MCDM		QFD	Evaluative	MMC	AHP	
Eleftheriadis and Hamdy (2018)	Buildings	MCDM	Construction	QFD	-	BIM		
Rapp et al. (2018)	Systems Engineering	Hybrid	NDP	Set-based design	Comparative Study			
Saaty and De Paola (2017)	Buildings	MCDM	Construction	AHP	Evaluative			
Kpamma et al. (2017)	Engineering, Construction and Architectural Management	Explanatory	Construction	CBA	Case Study			
Kamara (2017).	Built Environment Project and Asset Management	Explanatory		Design Quality Indicator				
Guarini et al. (2017)	Buildings	MCDM	NDP	MACBETH	Evaluative	ANP	MUAT	
Della Spina et al. (2017)	Buildings	Explanatory	Construction	Model-Based	Case Study		-	
Chokhachian et al. (2017)	Buildings	Explanatory	Construction	Model-Based	Case Study		-	
Fregonara et al. (2017)	Buildings	Explanatory	Construction	Model-Based	Evaluative		-	
Kang (2017)	Energies	Hybrid	Construction	Model-Based	Evaluative		-	
El Sawalhi and El Agha (2017)	Journal of Construction in Developing Countries	MCDM	Construction	MUAT	Case Study		-	
Dehe and Bamford (2017)	Production Planning and Control	MCDM	Construction	QFD	Case Study		-	
Cho J., Chun J., Kim I., Choi J.	Mathematical Problems in Engineering	MCDM	Engineering Design	QFD	Evaluative	TOPSIS	-	
Liu A., Hu H., Zhang X., Lei D.	IEEE Transactions on Engineering Management	MCDM	NDP	QFD	Evaluative	Fuzzy Sets		-
Mastura et al. (2017)	International Journal of Advanced Manufacturing Technology	MCDM	Automotive	QFD	Evaluative	AHP	-	-
Sousa-Zomer and Cauchick-Miguel (2017)	International Journal of Advanced Manufacturing Technology	MCDM	PSS	QFD	Evaluative	AHP	-	-
Moghimi et al. (2017)	Journal of Building Engineering	MCDM	Construction	QFD	Survey Study	Means-End Chain		-
Singhaputtangkul (2017)	Smart and Sustainable Built Environment	MCDM	Construction	QFD	Survey Study		-	-
Chen et al. (2017)	European Journal of Operational Research	MCDM	NDP	QFD	Evaluative	Fuzzy Sets		-
Unal et al. (2017)	Structural and Multidisciplinary Optimization	Hybrid	Construction	Set-based design	Evaluative		-	
Lanjewar et al. (2016)	Decision Science Letters	MCDM	Energy	AHP	Evaluative	Graph Theory	PROMETHEE	

Ignatius et al. (2016)	Journal of Civil Engineering and Management	MCDM	Construction	AHP	Review	-	-	-
Arroyo et al. (2016b)	Energy and Buildings	MCDM	Construction	CBA	Case Study		-	-
Arroyo et al. (2016a)	Energy and Buildings	MCDM	Construction	CBA	Survey Study	WRC	-	-
Kundakcı and Işık (2016)	Decision Science Letters	MCDM	Industry	COPRAS	Evaluative	MACBETH	-	-
Cattaneo et al. (2016)	Buildings	Explanatory	Construction	Model-Based	Evaluative		-	-
Ceballos et al. (2016)	Progress in Artificial Intelligence	MCDM	Construction	MOORA	Comparative Study	TOPSIS	VIKOR.	
Wu et al. (2016)	Energies	MCDM	Automotive	PROMETHEE	Case Study	ANP	VIKOR.	-
Jia et al. (2016)	International Journal of Production Research	MCDM	Engineering Design	QFD	Case Study	Fuzzy Sets		-
Afshari et al. (2016)	Cogent Engineering	MCDM	NDP	QFD	Evaluative			
Alemam and Li (2016)	Concurrent Engineering Research and Applications	MCDM	Engineering Design	QFD	Evaluative			
Li and Song (2016)	Mathematical Problems in Engineering	MCDM	PSS	QFD	Evaluative	VIKOR	Rough Numbers	
Wang et al. (2016b)	Computers and Industrial Engineering	MCDM	NDP	QFD	Evaluative	Fuzzy Sets		
Wang et al. (2016c)	Symmetry	MCDM	Engineering Design	QFD	Evaluative	QUALIFLEX		
Wey and Wei (2016)	Social Indicators Research	MCDM	Construction	QFD	Evaluative	ANP		
Venkata Subbaiah et al. (2016)	Journal of The Institution of Engineers (India): Series C	MCDM	Engineering Design	QFD	Evaluative	ANP	-	-
Miranda De Souza and Borsato (2016)	Journal of Cleaner Production	Explanatory	NDP	Set-based design	Evaluative	Stage-Gate Model		-
Ding et al. (2016)	Mathematical Problems in Engineering	MCDM	Supply Chain	TOPSIS	Case Study		-	-
Tian et al. (2016)	Advances in Mechanical Engineering	MCDM	Automotive	AHP	Evaluative			-
Yang et al. (2015)	Mathematical Problems in Engineering	MCDM	NDP	ANP	Evaluative	Fuzzy Sets		
Arroyo et al. (2015)	Journal of Construction Engineering and Management	MCDM	Construction	CBA	Evaluative	AHP	-	-
Talebanpour and Javadi (2015)	Decision Science Letters	MCDM	Manufacturing	DEMATEL	Survey Study	SAW		-
Chohan et al. (2015)	Open House International	Explanatory	Construction	DQI	Case Study		-	-
Konstantinou (2015)	Buildings	Explanatory	Construction	Model-Based	Evaluative		-	-
Hosseini Motlagh et al. (2015)	he International Journal of Advanced Manufacturing Technology	MCDM	Engineering Design	PROMETHEE	Evaluative	QFD	-	-
Jiang et al. (2015)	International Journal of Production Research	MCDM	Engineering Design	QFD	Case Study			
Franceschini et al. (2015a)	International Journal of Production Research	MCDM	NDP	QFD	Evaluative			
Franceschini et al. (2015b)	Research in Engineering Design	MCDM	NDP	QFD	Evaluative	Yager’s algorithm		
Kim et al. (2015)	Sustainability (Switzerland)	MCDM	PSS	QFD	Evaluative	AHP		
Luo et al. (2015)	IEEE Transactions on Systems, Man, and Cybernetics: Systems	MCDM	NDP	QFD	Evaluative	Cluster Analysis		
Singhaputtangkul and Low (2015b)	Buildings	MCDM	Construction	QFD	Survey Study	Fuzzy Sets		
Yu et al. (2015)	Journal of Cleaner Production	MCDM	NDP	QFD	Case Study			
Jin et al. (2015)	Engineering Applications of Artificial Intelligence	MCDM	NDP	QFD	Comparative Study			
Ochoa (2014)	Journal of Cleaner Production	Explanatory	Construction	LPS	Case Study			
Chen and Chen (2014)	International Journal of Production Research	MCDM	NDP	QFD	Evaluative			
Goodfellow et al. (2014)	Process Safety and Environmental Protection	MCDM	Construction	QFD	Evaluative			
Ji et al. (2014)	International Journal of Production Research	MCDM	Engineering Design	QFD	Evaluative	Kano's model		
Liu et al. (2014)	Neurocomputing	MCDM	NDP	QFD	Evaluative	Fuzzy Sets		
Liu et al. (2014)	Neurocomputing	MCDM	NDP	QFD	Evaluative	Statistical		
Zaim et al. (2014)	Expert Systems with Applications	MCDM	NDP	QFD	Evaluative	AHP		
Zhao et al. (2014)	Computers and Industrial Engineering	MCDM	NDP	QFD	Evaluative	functional analysis		
Ko and Chen (2014)	International Journal of Production Research	MCDM	NDP	QFD	Evaluative	Fuzzy Sets		
Zhong S., Zhou J., Chen Y.	Neurocomputing	MCDM	Engineering Design	QFD	Evaluative			
Canbaz et al. (2014)	IEEE Transactions on Systems, Man, and Cybernetics: Systems	Explanatory	Engineering Design	Set-based design	Evaluative	Monte Carlo		
Hannapel and Vlahopoulos (2014)	Structural and Multidisciplinary Optimization	Hybrid	Engineering Design	Set-based design	Evaluative			
Kennedy et al. (2014)	Systems Engineering	Explanatory	Engineering Design	Set-based design	Evaluative	Design Structure Matrix		
Jain and Raj (2013)	Global Journal of Flexible Systems Management	MCDM	Manufacturing	AHP	Survey Study	TOPSIS	PROMETHEE	
Cook et al. (2013)	Landscape Journal	Explanatory	Construction	DQI	Case Study			
Al-Ashaab et al. (2013)	Concurrent Engineering	Explanatory	NDP	Set-based design	Evaluative			
Wang et al. (2013)	Engineering with Computers	Hybrid	NDP	Set-based design	Evaluative			
Yannou et al. (2013a)	Journal of Engineering Design	Explanatory	NDP	Set-based design	Evaluative			
Thomson et al. (2013)	Engineering, Construction and Architectural Management	Explanatory	Construction	Model-Based	Evaluative			
Rybkowski et al. (2012)	Health Environments Research and Design Journal	Explanatory	Construction	LPS	Evaluative	Set-Based Design		
Lee et al. (2012)	Automation in Construction	Hybrid	Construction	Set-based design	Case Study	AHP		

Sacks et al. (2010)	Automation in Construction	Explanatory	Construction	Last Planner System		BIM
Inoue et al. (2010)	Concurrent Engineering Research and Applications	Hybrid	Engineering Design	Set-based design	Evaluative	
Qureshi et al. (2014)	Engineering Applications of Artificial Intelligence	Explanatory	Engineering Design	Set-based design	Evaluative	
Shahan and Seepersad (2010)	Concurrent Engineering Research and Applications	Hybrid	Engineering Design	Set-based design	Evaluative	Trial-and-error Design Process
Avigad and Moshaiov (2010)	journal of Engineering Design	Hybrid		Set-Based Design	Evaluative	Pareto Analysis
Avigad and Moshaiov (2009)	Journal of Engineering Design	Explanatory	Engineering Design	Set-based design	Evaluative	
Malak Jr et al. (2009)	CAD Computer Aided Design	Hybrid	Engineering Design	Set based design	Evaluative	MAUT
Singer et al. (2009)	Naval Engineers Journal	Explanatory	Engineering Design	Set based design	Evaluative	