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Improving Productivity in Building Construction – by Repetitions in Products, Processes, and Organisations

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PREFACE

This dissertation is the result of an industrial Ph.D. project conducted in the Management Engineering Department at the Technical University of Denmark (DTU). The Ph.D. project is designed as an industrial Ph.D., meaning that industry partner both supports the project financially and hosts the research. The main stakeholders of this project are:

- DTU Management Engineering, an academic institution and programme that also provides the academic supervision for the execution of this Ph.D. project;
- MT Højgaard A/S (MTH), an industrial partner, which is one of the leading general contractor companies in Denmark with approximately $1 Billion yearly turnover and about 4,000 employees;
- The Danish Agency for Science, Technology and Innovation, a government agency setting the rules of industrial Ph.Ds. as well as promoting them through financial support; and
- Knud Højgaards Fond, a private foundation named after the civil engineer Knud Højgaard who co-founded Højgaard & Schultz A/S in 1918. Knud Højgaards Fond financially supports this Ph.D. project.

The main advisor is Associate Professor Christian Thuesen. The company advisors are Lars Fuhr Pedersen for the first half of the Ph.D. and Peter Bo Olsen for the second half. Professor Iris Tommelein from the University of California, Berkeley, USA, contributed to and supervised a six-month research stay related to the Ph.D. project.

The dissertation comprises the overall research process, the theoretical background, seven academic articles that constitute the study's solution set and finally the contribution to the body of knowledge.

It might be relevant to emphasise that, as the author of this thesis, I have worked 10 years in the construction industry and mostly onsite. My experience—in companies of various size from Small and Medium Enterprises (SME) holding projects as subcontractors in mostly fast developing countries like Qatar and Turkey to a general contractor leading the construction industry in Denmark—is reflected in thesis.

I also found the great opportunity to get feedback theoretically in the inspiring academic atmosphere of DTU and the University of California, Berkeley, during my visit as a guest researcher. The valuable guidance and feedback from supervisors and colleagues have played a crucial role in the completion of this thesis.

Baris Bekdik

Copenhagen, 2016

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I feel very fortunate that I had the opportunity to conduct an industrial Ph.D. in collaboration with DTU, Management Engineering, and MTH. It is without doubt, however, that this journey would not have been possible without the support and encouragement from colleagues, friends, and family.

I would like to start by thanking my supervisor Associate Professor Christian Thuesen, who has showed confidence in me in difficult times and who has shared his great enthusiasm about the field with inspiring insights to my project.

I would also like to thank my company co-supervisor Peter Bo Olsen for challenging my limits and for adding so much value to the project and to my personal development that followed the Ph.D. journey. Many thanks also go to former company co-supervisor Lars Fuhr Pedersen who helped me get off to a good start and who was very supportive along the way.

Special thanks Lea Urup, for sharing the similar industrial Ph.D. path with me and facilitating many follow-up meetings along the way. To Ole Berard and Rolf Büchmann-Slorup, thank you guys for shaping the project and for your valuable support from the very beginning. Without you paving the path as first generation Ph.D.s, my project would not be possible.

During my time as a Ph.D. student, I had the privilege of being part of the University of California, Berkeley, as a visiting scholar. I would like to thank Professor Iris Tommelein for this wonderful opportunity, and for the great insights she provided me during my stay.

I would also like to send my regards to the reference group members who followed my Ph.D. research closely with quarterly meetings. I am grateful for your input and support. Thank you to Torben Biilmann, CEO at MTH; Christian Koch, Professor at Chalmers; Christine Thorsen, Board Member at MTH; Erik Villads Hansen, Senior Project Manager at MTH; and Flemming Frandsen, Vice President at Knud Højgaards Fond.

Finally, I want to thank my family for being everything to me in this life. Dede and Anane alongside father and mom, and surely Lea Svane, Aslan Bjørn, and Alice Defne—you are my whole life.

Baris Bekdik

SUMMARY

This thesis builds on several studies with connection to the lack of productivity in building construction. It seeks to enhance the conditions for improving productivity in the fragmented building construction industry, by exploring how a modular thinking of products, processes and organisations can be reapplied on new building construction projects. Complexity theory is used for diagnosis and modularity theory for the remedy towards the high degree of complexity, which is seen as the root of unproductivity. Design Research Methodology is followed to structure and organise the different studies of the thesis into descriptive study I, exploratory study, prescriptive study and descriptive study II stages. In the descriptive study I the status quo of public hospital building in Denmark is investigated in order to demonstrate the high degree of complexity impeding flow and hindering a better utilisation of the repetitions effect across projects. In the first part of the exploratory study, a general contractor's attitudes and experiences with modularity in building projects are examined in order to highlight the many pitfalls and potential difficulties that modular designs represent from the practitioner's perspective. In the second part of the exploratory study, examples of the fragmented kinds of modular applications around the world are compiled in order to demonstrate the inconsistent use, but still universal appeal that the approach carries with respect to building construction. Next, the prescriptive study first tests two applications of the Qualitative Comparative Analysis (QCA), one relating to the tender result and one relating to the occurrence of a dispute. The QCA is presented as a tool to utilize the repetitions effect across projects to predict processes and make choices accordingly, thus avoiding undesirable outcomes. The first part of the descriptive study II tests an activity-clustering tool, the Design Structure Matrix (DSM), which allows one to split the construction process into separate modules, making dependencies clear. Together, the two tools represent methods of increasing productivity by taking advantage of the patterns existing within and across projects. Finally, the second part of the descriptive study II shows how a mapping of the complete product and information flow throughout the whole building process can highlight the chances to implement modularity and thereby increase productivity further. Taken together, the studies pave the road for breaking down the overall project organisation into smaller parts and thus preparing it for modularisation. All in all, this thesis aims to show the potential of modularity not only at product level, but also at the process and organisation levels in building construction. Although the gain may not be immediately visible, it is worth the effort for all parties involved to zoom out before each project start, visualise the iterative patterns and possible pathways of modular solutions in the specific project environment and then set off together. With an eye to taking advantage of the repetitions occurring within and across projects, this thesis advocates that processes and organisations can be made remarkably more productive and that there is a great unused potential in the projects' inherent repetitions effect.

DANSK SAMMENFATNING

Denne afhandling bygger på flere studier vedrørende manglen på produktivitet i byggebranchen. Den søger at skærpe vilkårene for at forbedre produktivitet i byggebranchen ved at udforske, hvordan en modulær tilgang til produkter, processer og organisationer kan genanvendes på nye byggeprojekter. Kompleksitetsteori bruges til diagnosticering og modularitet teori til behandling af den høje kompleksitetsgrad, hvilken ses som roden til produktivitetsproblemet. Til at strukturere og organisere afhandlingens forskellige studier bruges *Design Research Methodology*: *descriptive study I, exploratory study, prescriptive study* og *descriptive study II.* I *descriptive study I* undersøges status på det offentlige hospitalsbyggeri i Danmark for at demonstrere, hvordan den høje grad af kompleksitet forhindrer flow samt en bedre udnyttelse af gentagelseseffekten på tværs af projekter, der ligner hinanden. I første del af *exploratory study* analyseres en entreprenørs holdninger og erfaringer med modularitet for at fremhæve de mange fælder og potentielle vanskeligheder, som modulære designs repræsenterer fra den udførendes perspektiv. I anden del af *exploratory study* samles eksempler på de fragmenterede former for modulære anvendelser af designs rundt om i verden for at vise den inkonsistente brug, men dog universelle appel, som den modulære tilgang har i byggebranchen. Derefter afprøver det *prescriptive study* først to anvendelser af Qualitative Comparative Analysis (QCA), der omhandler henholdsvis resultat af tilbud og forekomst af konflikt. QCA præsenteres som et værktøj til udnyttelse af gentagelseseffekten på tværs af projekter, fordi det gør det muligt, at forudse processer og derudfra træffe de vigtige valg, så uønskede projektresultater kan undgås. Første del af *descriptive study II* afprøver et værktøj til gruppering af aktiviteter, Design Structure Matrix (DSM), hvilket via en blotlæggelse af afhængigheder gør det muligt at bryde byggeprocessen ned i moduler. Sammen udgør de to værktøjer nye metoder til at øge produktivitet ved at udnytte de gentagelsesmønstre, der kan ses i - og på tværs af - projekter. Endelig viser anden del af *descriptive study II*, hvordan en kortlægning af hele produkt- og informations flowet i en byggeproces kan fremhæve mulighederne for at implementere modularitet og dermed yderligere øge produktiviteten. Samlet set baner studierne vej for en nedbrydning af den samlede projektorganisation i mindre dele, hvorved der dannes grundlag for en modularisering. Overordnet ønsker afhandlingen at vise modularitetens potentiale i byggebranchen, ikke bare på produktniveau, men også på proces- og organisationsniveau. Selvom gevinsten ikke er middelbart synlig, er det indsatsen værd for alle involverede parter før projektstart at zoome ud, identificere og visualisere gentagelsesmønstre og mulige åbninger for modulære løsninger på det specifikke projekt i det specifikke projektmiljø. Med øje for at udnytte de gentagelser, der forekommer i - og på tværs af - projekter taler denne afhandling for, at processer og organisationer kan blive markant mere produktive og at der ligger et stort uudnyttet potentiale i projekternes iboende gentagelseseffekt.

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LIST OF ABBREVIATIONS

AIA	: The American Institute of Architects
BIM	: Building Information Modelling
BLS	: The U.S. Bureau of Labor Statistics
DRM	: Design Research Methodology
CPM	: Critical Path Method
DFMA	: Design for Manufacturing and Assembly
DSM	: Design Structure Matrix
DTU	: Technical University of Denmark
EPOC	: Engineering Project Organisations Conference
EU	: European Union
GDP	: Gross Domestic Product
IPD	: Integrated Project Delivery
MDM	: Multi Domain Matrix
MEP	: Mechanical Electrical and Plumbing
MIP	: Modularity in Production
MID	: Modularity in Design
MIU	: Modularity in Use
MTH	: MT Højgaard A / S
OECD	: The Organisation for Economic Co-operation and Development
PERT	: Program Evaluation and Review Technique
PM	: Project Manager
RQ	: Research Question
SME	: Small and Medium Enterprises
QCA	: Qualitative Comparative Analysis
UK	: United Kingdom
USA	: United States of America
VDC	: Virtual Design in Construction
VSM	: Value Stream Mapping

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READER'S GUIDELINE

In this short section an overview of the thesis and the descriptions of the different chapters in this thesis are outlined. Then, a complete roadmap of the thesis is shared in Figure 1.

Chapter 1: Introductory section, the research problem is defined along with its background. Then, the research scope and context are outlined. Next, the research question and sub-questions answered in different studies throughout the thesis are introduced.

Chapter 2 discusses the scientific philosophy of the research and the applied research methodology. The chapter presents the design science research approach and describes how it is applied in the Ph.D. study. Mixed method research, combining qualitative and quantitative methods for data collection, is introduced in the research design subsection. Different data analysis methods applied to different types of data also are described.

Chapter 3 introduces complexity theory and describes the complexity of building projects. Then, modularity theory is introduced as the main theory to approach the research problem. Following the investigation of the modularity theory in different industries, modularity at product, process, and organisation domains is elaborated. Finally, modularity in building industry is outlined.

Chapter 4 analysis section presents the findings of the studies belonging to different stages of the research. These are:

- Descriptive study I building an understanding of the productivity problem with multi-case analysis in building industry.
- Exploratory studies presenting the state-of-the-art analysis of modularisation in the building industry through multiple cases and building explanations, and matching patterns within and across the cases studied.
- Prescriptive study assuming the existence of repetitions across the 'unique' building projects is used to a way to meet the objectives to operationalise the modularity.
- Descriptive study II presents the suggestions to operationalise modularity into building construction with two different case studies.

Chapter 5 discusses the findings of the different studies presented in Chapter 4. Then a common interpretation of the results subtracted from different stages of the analysis is drawn. Furthermore, the implications for practice and research are outlined.

Chapter 6 concludes the thesis. The study is summarised, the key findings and contributions are presented, and the research is evaluated. The chapter ends with suggestions for future research.

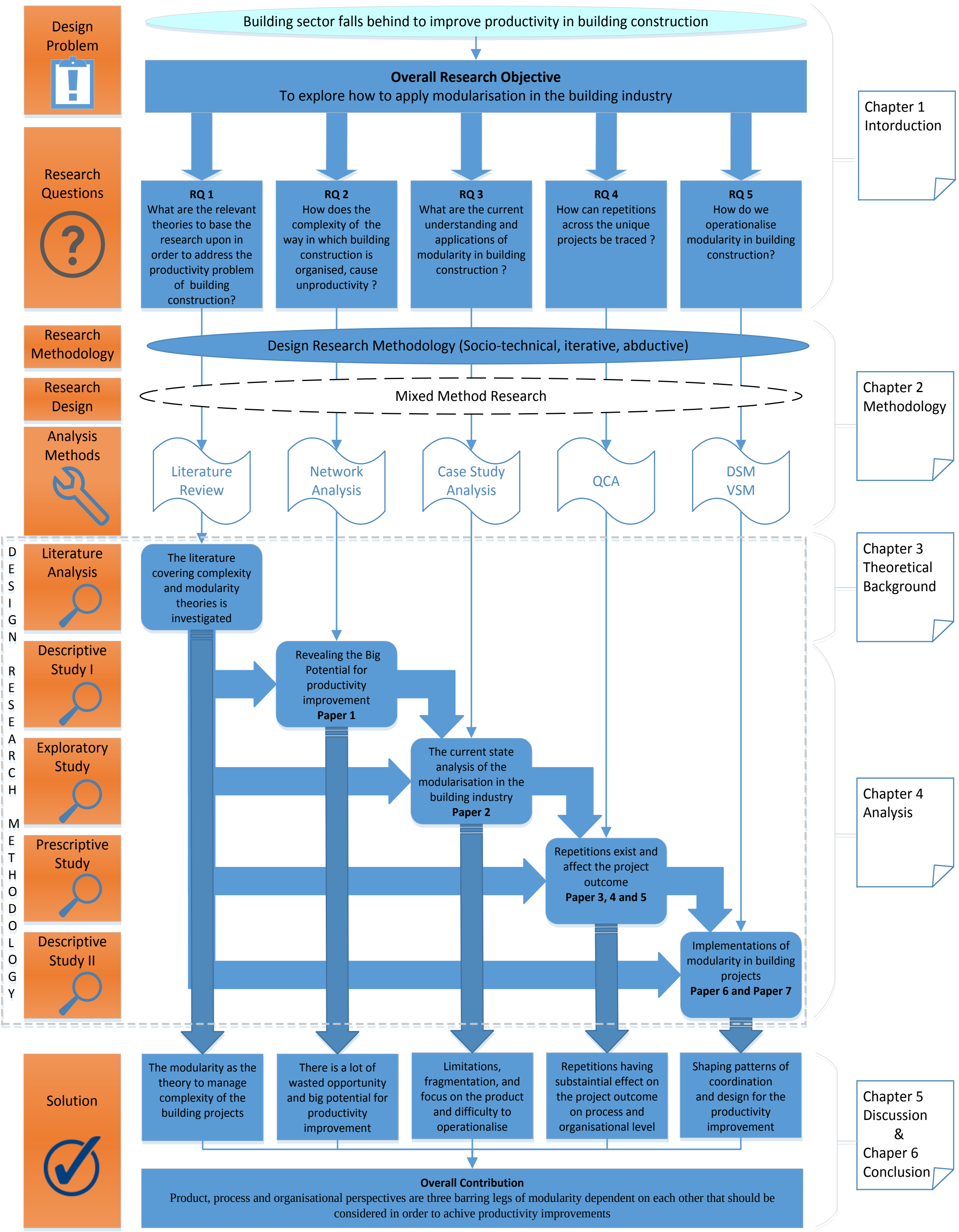


Figure 1. The Structure of the thesis

‘The real voyage of discovery consists not in seeking new landscapes, but in having new eyes’. Marcel Proust

1 Introduction

This chapter introduces the motivation, background, and framing of this thesis. First, the objective and overall motivation for the research is described. Then the scope, context, and limitations of the research are defined. Finally, the main and sub-research questions are presented.

1.1 Objective and Motivation

The objective of the study is to explore the application of modularisation in the building industry.

This thesis takes its point of departure in the productivity problem of the construction industry. Construction industry hosts the typical examples of project-based organizations (Chinowsky, 2011) working in dynamic environments and short term collaboration patterns. After the projects are terminated project teams are usually dissolved (Bower, 2003) and therefore the transfer of the valuable experience gained during the project execution is limited. Basically, in every new construction project many things are reinvented again and again causing the same mistakes being repeated over and over again.

The purpose of this study is to explore in what ways modularization may help this problem. By breaking down products, processes and organisations into components and modules, the thesis advocates, a handover of comprised work and experience is made possible and building processes may be made more efficient. I choose the building industry as my field, because of its repetitive nature as compared to, for example, infrastructure construction. It will be my argument that modularization can increase productivity in specific instances within the building sector and that these instances deserve attention due to the potential they open for comparable processes to be enhanced and boosted. These instances cover different processes such as tendering, design, building in the long life cycle of building projects. Although examples derive mainly from Denmark, cases from different geographies and contexts are included in the studied so that more general perspective of the problem studied can be attained.

1.1.1 Productivity in construction industry

At macro level, the building industry is considered to be one of the key industries in the general economy. The construction sector typically comprises 8-10 % of the Gross Domestic Profit (GDP) of a Western economy (McGeorge & Palmer, 2002). A 10 % improvement in construction performance can represent a 2.5 % increase in GDP (McGeorge & Palmer, 2002). There is, therefore, no doubt that improving productivity in the building industry will contribute positively to the general economy.

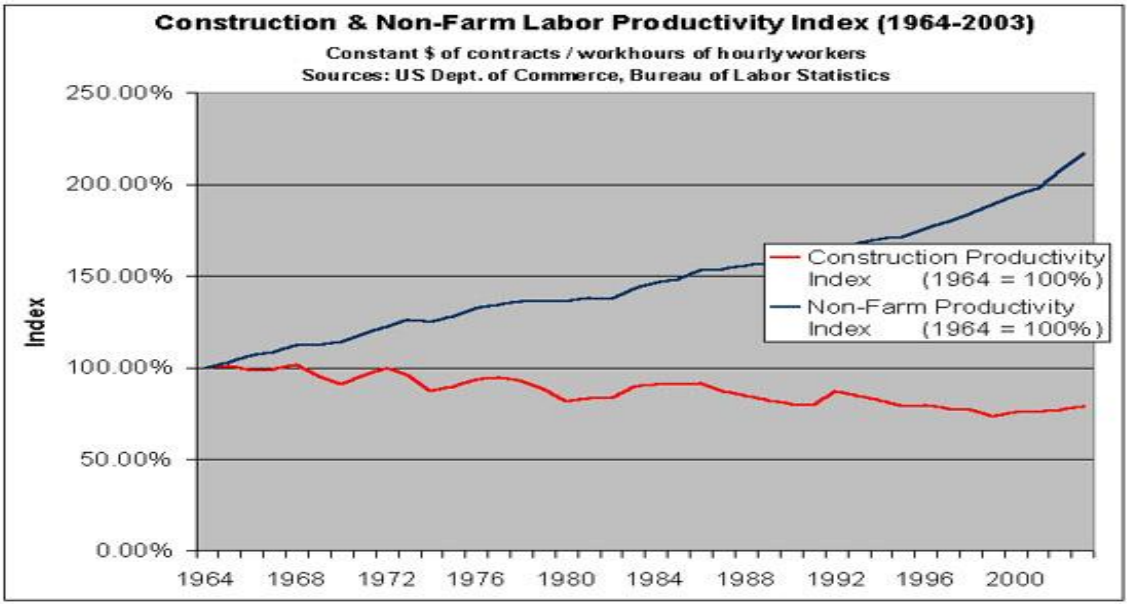


Figure 2. Index of construction labour productivity in the USA (1964-2012) based on various deflators in comparison to labour productivity in all nonfarm industries (Teicholz, 2013).

However, the building industry unfortunately suffers from decades of long unproductivity while other nonfarming industries, such as the automotive and manufacturing industries, have steadily improved their productivity (Figure 2). According to the Organisation for Economic Co-operation and Development's (OECD) definition, 'productivity' is defined as a ratio between the output volume and the volume of inputs (OECD, 2016). In this definition, input can be any resource used to create goods and services, and output is the quantity of goods and services produced. Similarly, the U.S. Bureau of Labor Statistics (BLS) defines productivity as a measure of economic performance that indicates how efficiently inputs are converted into outputs. Labour productivity is measured at two levels. At the macroeconomic level, labour productivity is measured by GDP at market prices and at constant prices per hour worked (OECD, 2016). At the industry level, labour productivity is measured as gross value added at basic prices and constant prices per hour worked (OECD, 2016).

According to Teicholz, the BLS productivity statistics indicate a productivity decline for many decades in the construction sector (Figure 2). Teicholz (2013) calculates the decline trend for the given period to be -0.32% per year, while nonfarm industries show a trend upwards by 3.06% per year (Figure 1, blue line). Similar to the tendency in the USA, a decline in construction productivity has been detected in most countries according to the labour and multi-labour productivity factors (Abdel-Wahab & Vogl, 2011).

A recent OECD (2016) publication shows the contribution of different industries to the overall productivity growth. As seen in Figure 3, the contribution of construction to the productivity growth is very little or non-existent in many countries. In France, the tendency is even worse because construction productivity is found to be negative while other industries push the productivity upwards. Some new members of the European Union (EU), such as Latvia and Lithuania, enjoy higher productivity improvements in all industries, including the construction industry. However, the construction industry contribution is still smaller than other industries. Greece is the only example where the construction industry provides a positive growth while the other industries experience a decline in productivity.

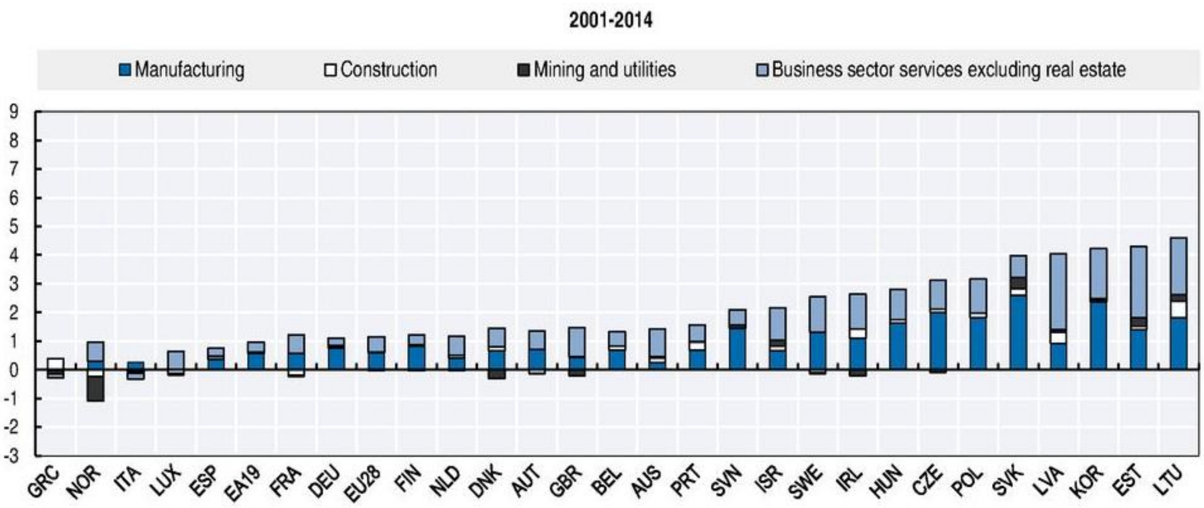


Figure 3. Industry contribution to business sector productivity growth (OECD, 2016).

There may be various reasons for low productivity measurement in the construction sector. In the USA, these reasons are assumed to be insufficient data, improper statistical methods, and a variety of problems in the industry (Teicholz, 2013). In Denmark, a recent report published by Produktivitets Kommissionen claims that it is not possible to compare productivity data in the case of the construction industry with other industries (Produktivitets Kommissionen, 2013). The report provides three reasons for this claim.

First, different countries undertook large infrastructure investments in different decades, which affect the productivity measurements because of the extensive machinery usage in those projects. Second, it is difficult to draw a framework that will work universally in the construction sector because it is so big that it almost affects every sub-industry. Third, there is the variance within the sector because infrastructure works are so different from building construction in terms of labour requirements. Moreover, the report states that 'almost all construction companies undertake different types of works—such as infrastructure, renovation, and building projects simultaneously—making productivity estimation and measurement further difficult'(Produktivitets Kommissionen, 2013, p63). The report concludes that a comparison is not possible for these reasons (Produktivitets Kommissionen, 2013).

Despite the complexity of the data and inaccuracy of the statistics reflecting the real picture, one thing is clear: low productivity is a problem in the construction industry (Gottlieb & Haugbølle, 2010; Changali et al., 2015) and the lack of labour productivity impacts costs, schedule, scope, and quality, too (Allen, 1985).

Construction productivity falls remarkably behind compared to other production industries, and has been attracting the attention of academia and government agencies for a long time. In addition to the recent reports about construction productivity mentioned above, three very influential reports have been published in the U.K. 'Rethinking Construction', also known as ‘the Egan report’, states ‘clients have generally been dissatisfied with the output of the construction industry in terms of cost, quality, timing, and safety’ (Egan, 1998).

Before the Egan report, ‘Constructing the Team’ was published in 1994. Often referred to as ‘the Latham report’, the UK government commissioned the report to investigate the perceived problems with the construction industry, which the report’s author, Sir Michael Latham, described as ‘ineffective’, ‘adversarial’, ‘fragmented’ and ‘incapable of delivering for its customers’ (Latham, 1994).

Back in 1966, a team of architects, contractors, subcontractors, material suppliers, unions, academicians, quantity surveyors, specialty contractors, and government agencies published a report called ‘Interdependence and Uncertainty’. The work, commonly known as ‘the Crichton report’, touched upon the problems of the construction industry separating it from other production industries. Today, the main issues raised in ‘the Crichton report’ are still valid in the building process and organisation described in ‘Interdependence and Uncertainty’ 50 years ago: ‘Interdependence vs. autonomous way of working’ and ‘uncertainty both internal and external’ (Crichton, 1966).

The problems might be outlined long ago. However, debate about the relationship between productivity in general and construction industry productivity in particular is ongoing (Gottlieb & Haugbølle, 2010; Teicholz, 2013; Produktivitets Kommissionen, 2013; Danish Government Report, 2014; Changali et al., 2015). Furthermore, recently, in a book about the future of the construction industry, similar causes for the productivity problem to have been identified as ‘silo type of working’ by an experienced general contractor manager in Denmark (Billman, 2015). So why does the unproductivity in the construction sector seem to be a continuous trial, a difficulty unable to be straightened out throughout the history of the industry?

1.1.2 Building construction productivity at the project level

The challenge that the construction industry faces is the fact that construction production differs noticeably from repetitive manufacturing mainly because of the nature of the product and the role of the customer (Ballard, 2012). The special attributes of the building production are valid reasons for the companies operating within the construction industry to adapt to survive in the market. First, the discontinuities of the projects force companies to adapt by shrinking and expanding rapidly according to the project requirements. Valuable experiences and hard-earned knowledge disappear from the organisations together with the construction team’s dissolution. Second, the supply chain must be organised in a flexible manner to support individual project needs. Last, the stakeholders of each project are different—e.g. client, designer, and consultant. Even if the same parties work on different projects there may be different people assigned to the projects. Moreover, different parties come together under different contract types, thus redistributing the roles and responsibilities.

So there are a number of valid reasons that make the construction industry particularly prone to obstacles, delays, interferences, and inefficient work flows. This does not, however, change the fact that the construction sector is a locomotive for other industries and, therefore, important for the economy. It does highlight the urgency of looking into how the particular challenges can be overcome or mastered by new and alternative approaches to the field.

Before moving on to the context and structure of this research, I wish to present a concrete story from my own working life, which illustrates the complexity and inefficiency of the construction industry at the project level.

On the day designated for slab concrete pouring, the architect sends a change order. There is a new drawing with a big cloud around the slab being produced and a ‘HOLD’ sign. The reason for the sign is unknown and the duration of the hold is uncertain. Most probably the current site situation and the urgency of the slab completion for the rest of the building construction are also unknown to the architect and other parties responsible for that change order.

The days pass and no clarification comes. The contractor gets more and more worried as production has been interrupted. The production cannot be finalised by pouring the concrete, which causes steel-bars to rust. The formwork under the slab is not able to continue the planned weekly cycles. The scaffolding under the slab is not contributing to the production. Furthermore, the next production module is pending because the slab concrete pouring is a pre-request for them to start.

The client is too busy with other issues and the architect has not been informed about the actual situation at the site. The consultant points out the other tens of square metres of the project to be built in order to prevent any claim of the contractor for a work schedule extension. Later we will find out the reason for the ‘HOLD’ sign is an embedded plate with undetermined dimensions. However, that does not require the interruption of the entire slab production, but only a small part of it.

This problem could have been avoided by identifying dependencies of the related activities, such as formwork placement, rebar assembly, assembly of embedded plates, and concrete pouring. In this way, one could cluster all related design activities into design modules making the whole process more manageable. Therefore, modularity is the approach that will be investigated and advocated throughout the thesis.

Modularity, as a strategy, is dominant in the computer and automobile industries and may not be 100% applicable to building projects due to the previously mentioned attributes of the building construction. However, it can be applied to minimise and eradicate such pitfalls as the missing design causing the ‘HOLD’ sign because it has the capacity to break down not only products, but also processes and organisations into smaller units with a structured logic to follow (Campagnolo & Camuffo, 2009; Sako, 2003). Modularity makes it easier to spot the pitfalls and take action before resources are wasted. The definition below inspired by Simon (1962) will be the guiding definition of modularity in this thesis.

Modularity is a perspective used in order to find the optimum unit decomposition having the dependencies within the modules high and the dependencies between the modules low.

1.2 Research Scope and Limitations

The scope of this thesis is to study, both practically and theoretically, the usage of modularisation of the products, processes, and organisations in construction to improve productivity in the industry. There is plenty of room for improving efficiency because studies in the US, Scandinavia, and the UK suggest that up to 30% of construction is rework and at least 10 % of materials are wasted (Egan, 1998). However, such a broad goal would be too ambitious for a Ph.D. study. Therefore, the scope of this thesis is limited to building construction only and not the large spectrum of the construction industry.

The following objectives are approved by the Danish Educational Minister, Innovation Agency as the research framework:

- Consideration of the product, process and organisational modularity together
- Deeper understanding of the challenges related to the knowledge and learning processes in a project based organisation
- Discovering the possibilities to create learning, project-based environments based on product, process, and organisational modularity
- A study of the “repetitions effect” on MTH projects

Furthermore, the research project is planned and executed as a single project. Therefore, it is not part of a greater research project or of a series of research projects with their roots in the same platform. The research project is designed as an industrial Ph.D. project and is limited to three years. Similar to other Ph.D. projects, research dissemination in academia and industry are compulsory to complete the industrial Ph.D. programme in Denmark. The main difference between an industrial and an ordinary Ph.D. project is that the former lacks an academic participation requirement in terms of preparing lectures or supporting teaching activities. Instead, an industrial Ph.D. project requires full employment in the host company and contribution to the company tasks related to the scope of the Ph.D. project.

The hosting company—i.e. industrial partner of the Ph.D. project—presents the Ph.D. candidate a research environment rich in data and in return the company profits from the Ph.D. candidate’s research on the first hand. Moreover, the research is designed in a way to serve as competency building for the host company rather than acquiring a ready-made solution through consultancy. In that sense, it is very similar to fieldwork. However, it is one step further than traditional fieldwork applying only an observer’s role, as the researcher interacts with the subject of the research and intends to change it.

1.3 Research Questions

The following research questions (RQ) have been formulated in order to propose a solution to the productivity problem in building construction. The objective is to explore the application of modularisation in the building industry elaborated in Section 1.1.

1. *What are the relevant theories to base the research upon in order to address the productivity problem of building construction?*

What is productivity? How is it measured? These questions are general and wide reaching. The theory section of this thesis attempts to narrow down the relevant contributions to the field of productivity in building construction. First, complexity theory is visited in the wider domain to diagnose the problem in the project-based build environment. How complex is the building construction really? Throughout the thesis, modularity theory, in particular, appears as a forceful tool to grasp and handle the main purpose. Defining and describing the relevant theories pertaining to the problem allows us to look at the problem from abstract and theoretical angles: product, process, and organisation. In this way, it reveals connections that the details of case studies and single project descriptions do not let us see.

2. *How does the complexity of the way in which building construction is organised, cause unproductivity?*

A description of the organisation of the building projects is illustrated with multiple case studies from Denmark. Hospital projects are under the same legislation and launched almost simultaneously between 2007 and 2009. Building projects are in different building phases today. Projects spread across the country are investigated to determine the way building construction is organised and how it causes unproductivity. A higher level of awareness of the actual organisation of building projects today allows for a more precise understanding of the concrete pitfalls and risks.

3. *What are the current understanding and applications of modularity in building construction?*

Modularity represents a wider theoretical approach developed in different domains. What are the different applications of modularity in building construction to handle the productivity problem? How are they developed in different contexts? What are the common drives for those applications? What are the common barriers and benefits? Multiple case studies are conducted with multiple unit analyses to identify matching patterns across the different cases.

4. *How can repetitions across the unique projects be traced?*

According to the findings of the exploratory study section and the descriptive study I section in Chapter 4, the modularity approach appears promising but limited. How can we reach modularity in building construction across the projects? How can the gained managerial knowledge and the valuable experiences from completed projects be transferred to future building projects? How do we identify the combination of factors that lead to successful project outcomes? Identifying repetitions in processes and organisations will provide solutions to improved productivity in construction.

5. *How do we operationalise modularity in building construction?*

Considering the previous RQs to be thoroughly investigated, the question remains how to operationalise the concept of modularity. Repetitions in products, processes, and organisations are milestones to reach standards that can further be modularised. In order find out how to operationalise modularity in building construction, there is a need for case studies with deeper case study investigations, which will provide examples for future projects.

Together, the research questions will, firstly; investigate the problematic background and current conceptualisation of modularity, and, secondly, look forward and exemplify how to hunt down patterns and suggest how to operationalise these patterns into viable modular tools.

2 METHODOLOGY

This chapter presents the research methodology and the research methods used in this study to answer the research questions presented in the previous chapter.

Silverman (2009, p.13) defines methodology as ‘a general approach to studying research topics’ and method as ‘a specific research technique for attaining some objective’. In light of the distinction between methodology and method, this chapter first describes the overall research methodology of this study. Then it elaborates on data collection and data analysis methods. Finally, it presents the tools applied to operationalise modularity in the building industry. These tools are network analysis, case study analysis, Qualitative Comparative Analysis (QCA), Design Structure Matrix (DSM), and Value Stream Mapping (VSM).

2.1 Research Methodology

The research object is a sociotechnical phenomenon. As a starting point, the organisations work with processes to create products in a sociotechnical world constructed through language and discourse (Hatch & Cunliffe, 2006). Therefore, DRM is a relevant strategy not only because it tries to provide solutions to problems onsite but also because it helps to deconstruct the current ways of working in the building industry through the multiple studies applied in different stages and presented in Figure 4. In that way, the common understanding of every building project as being unique, and therefore having unique conditions and unique challenges, can be questioned reflexively.

Epistemologically, in order to understand this social world constructed through generations of work practices passing from master to apprentice, we need a constructivist approach rather than a positivist perspective (Hatch & Cunliffe, 2006) Much of the observations and narratives are context dependent and, as opposed to positivist experiments in the natural sciences, different views points of the different stakeholders, such as designer and contractor, will be elaborated through a constructivist approach. However, even though data is context dependent and the problems identified vary according to different sites, the tendencies observed and solutions suggested in this thesis have a general character. To illustrate, the same solutions suggested as a result of the descriptive II studies can be applied universally although contexts can be different.

2.2 Research Design

As a general approach, the Ph.D. research follows the Design Research Methodology (DRM). Design Science was first articulated in Simon’s (1969) book, *The Sciences of the Artificial.* Design science was adopted as a research methodology to add new knowledge to the accounting theory by combining practice and already existing theory primarily by accounting purposes (Kasanen et al., 1993) and later by information technology (March & Smith, 1995). Van Aken (2005) first introduced design science research in management science.

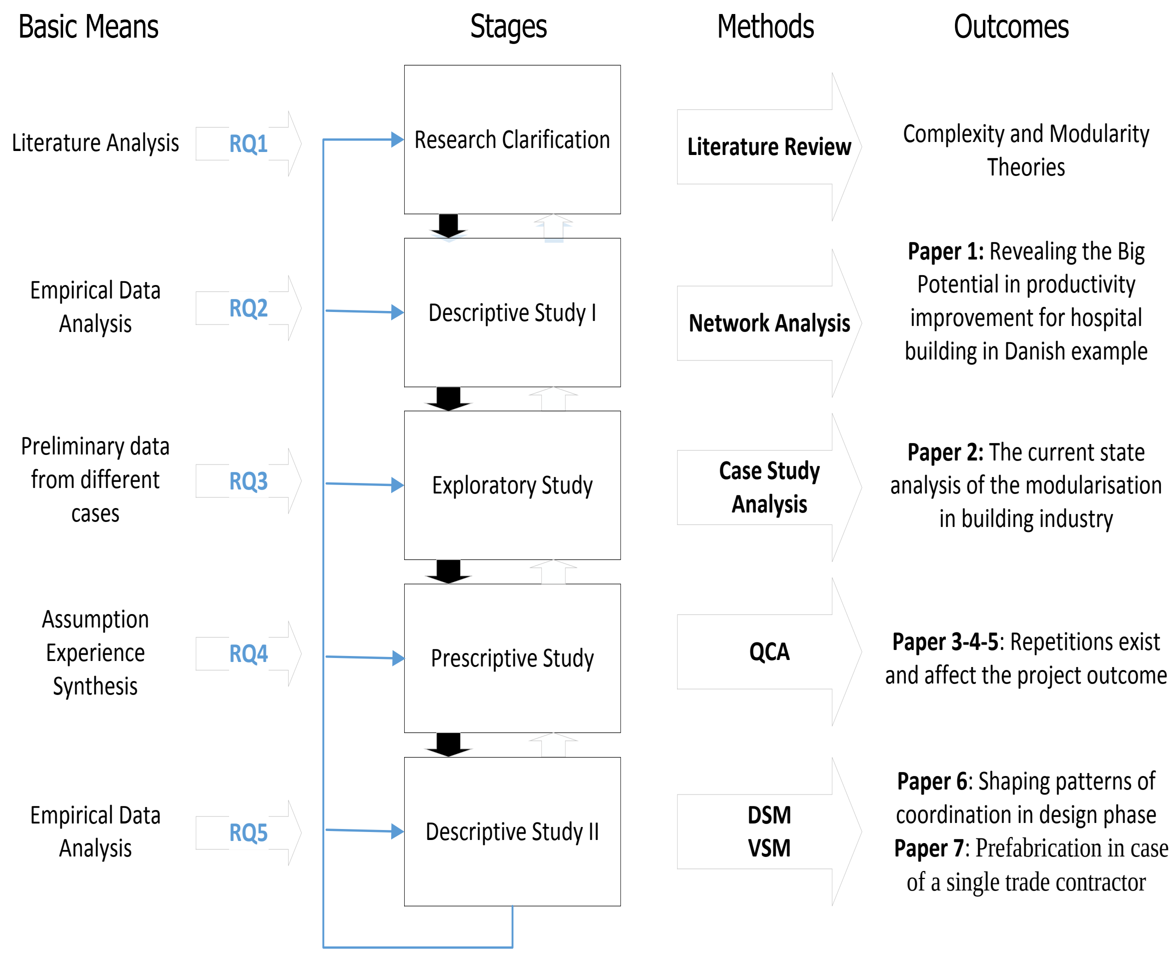


Figure 4. Detailed representation of followed DRM adapted from Blessing and Chakrabarti (2009)

In his article about design science research management, Van Aken (2005, p.20) states that 'the mission of a design science is to develop knowledge that the professionals of the discipline in question can use to design solutions for their field problems'. As the main purpose of the research is to get insights that will lead to solutions to be operationalised in the fields of building construction, DRM is found to be a very relevant research strategy. Moreover, the iterative nature of DRM (Figure 4) is adapted in general terms to investigate the industry problem of low productivity described in Chapter 1.

As illustrated in detail in Figure 4, the DRM is performed in five different stages in this thesis contrary to the original form having 4 stages (Blessing & Chakrabarti, 2009). The additional stage is the exploratory study added to the research because an extra stage was needed in order to understand the current level of understanding and application of modularity in practice.

In the research clarification stage, the research problem is defined together with the research scope and goals. Research questions, literature review, and literature analysis comprise this stage presented in Chapters 1 and 3 of this thesis. The research clarification stage has been revisited along the way as following stages and finding of the different case studies required further literature reading and adjustments of the research questions.

In the descriptive I study, there is a multiple case study analysis of hospital construction in Denmark to gain an understanding of the industry problem. The case is very useful to visualise how the current way of organising in building industry effects the product outcome. However, a broader picture of the industry is needed in order explore the current understanding of modularity in practice. A set of exploratory studies is conducted to reveal the current state analysis of the modularisation in the industry in different contexts and geographies. This exploratory stage can be treated as the extension of the descriptive study I because they both focus on the identification of core challenges and root cause analysis of those challenges. I preferred to differentiate the two stages in order to emphasize the take a ways.

In the prescriptive study stage, repetitions across projects with an effect on the project outcomes are identified. The case company's very extensive project portfolio which is not necessarily contributing to the current projects is utilised in order to identify the existing patterns. By doing so, the implementation of the modularity theory to the large project portfolio not creating any value is attempted in order operationalise the learnings from previous projects.

Finally, in the descriptive II stage, the implications of solution alternatives are evaluated in two case studies focusing on different aspects of the projects. The first case study in the final descriptive II stage focuses on the design phase and the second case study provides an overall picture of the execution phase in building construction.

Different than DRM originally targets the final descriptive II stage in this thesis suggests only solution alternatives for the organisations and processes. The way study is designed and applied in the host company is one of the reasons for the deviation from original DRM. The long lifecycle of the building projects compared to the limited research period of the Ph.D. study is another reason for the separation of research and implementation. Therefore, the implementation results of the alternative solutions are not presented as it might be expected according to the DRM. Instead of measurement of results as suggested by DRM, the thesis will attempt a contribution to the theory as it will be elaborated in the discussion and conclusion chapters.

2.3 Research Methods

An abductive approach is undertaken in order to research the questions presented in the introduction chapter. The iterative nature of DRM is very suitable for an abductive method, placed as it is between inductive theory building, based on the generalisations of the observations, and deductive theory testing, leading to guaranteed conclusions (Holmström et al., 2009). Both deductive and inductive approaches are representatives of hypothetical world descriptions and it is therefore difficult to apply just one of them in management sciences. A hybrid approach is necessary to use both deductive and inductive strategies as applied in this research.

First, a deductive approach is applied. The deductive approach to theory implies going from generals to particulars to identify a gap in the literature and to propose a solution by suggesting a hypothesis to fill that gap (Shepherd & Sutcliffe, 2011). All research sub-questions are structured to reflect a systematic presentation of the accumulated findings presented in Figure 3 (the structure of the thesis). Another reason for choosing an abductive approach is that the research required revisiting theory and adjusting the research questions as they evolved along the Ph.D. project's lifespan (Figure 4). The literature covering complexity and modularity theory is elaborated in-depth in the theoretical background section. This theory underlies the overall research.

The identified problems are then investigated through case studies of different depths and focuses. So doing operationalises a bottom-up inductive approach. Yin (2009) defines the use of case studies in research as an experimental investigation of a contemporary phenomenon in-depth and within its real-life context. The choices of different case studies having different focuses and purposes follows the DRM presented in Figure 4.

The data collection and analysis use mixed methods (Figure 5). The research objectives are qualitative. However, the collection and data analysis methods show quantitative characteristics as well as purely qualitative ones. By doing so, the qualitative data is supported by quantitative data originating from the factual project data. In order to use both data types in data collection and data analysis, tools such as QCA, lying in between the qualitative and quantitative techniques, have been used.

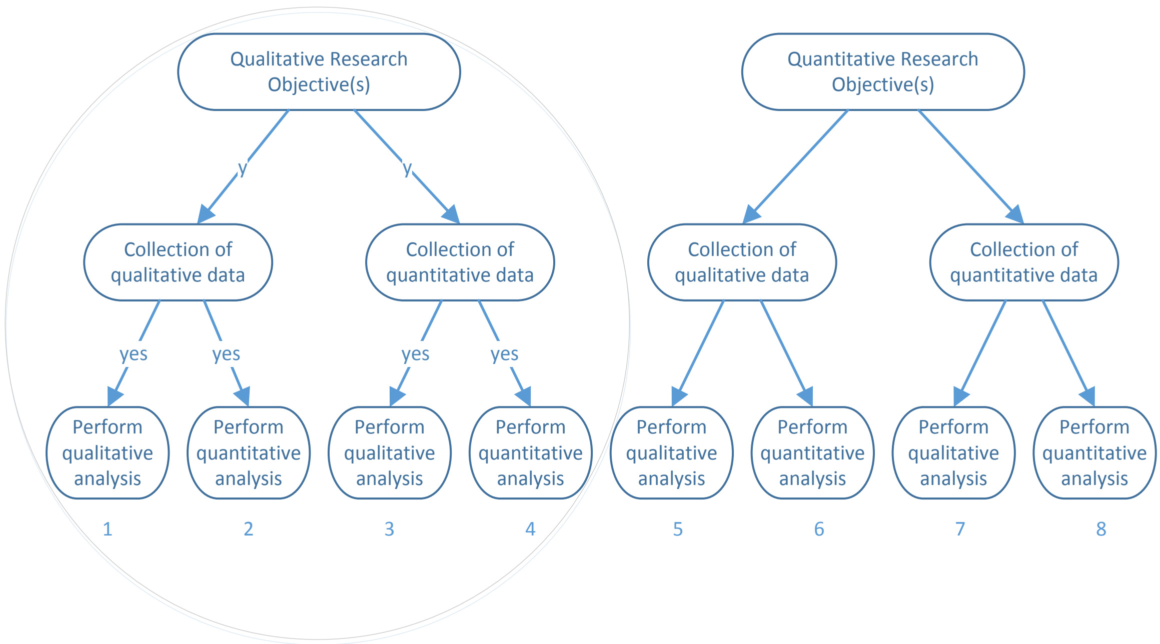


Figure 5. Mixed method research paths followed for the study (Johnson & Onwuegbuzie, 2004).

Philosophically, mixed methods research is the third pragmatic wave combining the strengths of both quantitative and qualitative research methodologies (Tashakkori & Teddlie, 2003). Multiple data collection and analysis methods selection is likely to result in complementary strengths of the research (Tashakkori & Teddlie, 2003).

Moreover, a mixed methods approach fits nicely to the abductive character of the overall DRM applied during the Ph.D. project. Parallel to combining research philosophies in an abductive way, qualitative and quantitative methods are mixed to reach the best set of explanations for understanding the results (Johnson & Onwuegbuzie, 2004).

As previously mentioned, although the research objectives are qualitative, the data collection and analysis methods are both qualitative and quantitative as represented by paths 1-4 tagged with “yes” in the circle in Figure 5. Different stages of the study follow combinations of paths 1-4. This means quantitative data is supported by qualitatively collected data and qualitative data is transformed into a quantitative form for further analysis, as in the case of the prescriptive study.

Table 1 provides an overall picture of the data collection and analysis methods applied at different stages of the research. In this table, the variety of cases can be seen in case descriptions and locations. Together with the data collection methods, Table 1 provides different amounts of hours used for data collection. The last column notes where more detailed information can be obtained.

Table 1. Overall picture of the case studies at different stages of the research.

Stage	# of Cases ∑:133 cases	Case Name	Case Description	Country	Data Collection Method	Total hours of data collection Σ:192 hours	Data Analysis Method	Detailed in
Descriptive Study I	27	Danish Hospitals	Building new hospitals in green fields and building extensions to the existing health care facilities	Denmark	Project documents such as Size, scope, technical drawings, contract types. Internet sources, Regions Denmark, Kvalitetsfonden, newspapers, technical reports and workshop at DTU.	30 Hours	Network Analysis	Analysis Section & (Appendix A)
Exploratory Study	7	Perception of modularity from GC	Various MTH projects	Denmark	Interviews	7 hours	Pattern Matching & Explanation Building	Analysis Section & (Appendix B)
	1	Scandibyg	Modular buildings producer	Denmark, Løgstør	Visit of prodution facility and interviews	8 hours		
	1	Ballast Nedam	Modular buildings producer	Nederland, Weert	Visit of prodution facility and interviews	8 hours		
	1	BSkyB London	Steel structure to be served as Sky tv London studios	England, London	Visit of prodution facility and interviews	4 hours		
	1	Broad Company	7 storey building being built in 15 days with modular	China, Hunan,	Visit of prodution facility and interviews	8 hours		
	1	Zorlu Center	Multi purpose building consisting of 4 high rise	Turkey, Istanbul	Visit of prodution facility and interviews	8 hours		
	1	ConXtech	Structural steel producer and contractor company	USA, Bay Area,	Visit of prodution facility	6 hours		
	1	Finilite	Modular lightning systemts producer	USA, Bay Area,	Visit of prodution facility	6 hours		
	1	Nautilus	Modular buildings producer	USA, Bay Area,	Company presentation and Interview	2 hours		
	1	HGA	Architect Company	USA, San Francisco,	Conpany presentation and Interviews	4 hours		
	1	Ancient Greek	Ancient archeological site	Turkey, Egean	Archeological site visit and interview	2 hours		
	1	Børneby en	Integrated Children's institution for 600 kids	Denmark, Copenhagen	Visit of construction site, interviews	4 hours		
Prescriptive Study	39	QCA Tendering Practices Analysis	Building projects of various functions such as office buildings, housing projects, hospital.	Denmark	Project Data about Size, scope, contract type, client type. Seniority data of the project managers and tender responsible. Interviews and verification phonecalls.	30 hours	QCA	Analysis Section & (Appendix C, D and E)
	46	QCA Dispute Cases Analysis				25 hours		
Descriptive Study II	1	Facade Projects in MTH	Building projects using different facade solutions	Denmark	15 Hours of Interviews with Architects, Facade Producers and GC Project Managers and 2 Hours Cross-functional Workshop with Two process consultants, two project managers, two design managers, and one BIM manager participated in the workshop.	17 Hours	DSM	Analysis Section & (Appendix F)
	2	VNGH and STL Hospitals	Two large-scale new hospitals for Sutter Health located in San Francisco, California. St. Luke's Replacement Hospital is a 20,900 m2 (215,000 square foot), 120 bed project and Van Ness and Geary Hospital is a 68,750 m2 (740,000 square foot), 274-bed project (CPMC 2020).	USA, San Francisco, California	Recorded interviews at the construction site with architects and owner representatives and interviews with production manager and forman at the temporary workshop. Filming of the jig module production and analysing.	40 Hours	VSM	Analysis Section & (Appendix G)

2.4 Data Collection Methods

A wide range of data is collected for the study to suggest a solution for the defined problem. The following subsections describe the different data collection methods. First, there is discussion of the data collected qualitatively through observations, participation, exploratory visits, interviews, and workshops. Then there is a description of the quantitative data collection originating from project metadata. Detailed information concerning data collection process for each individual study is presented under the relevant cases or in the methodology section of the papers presented in the appendices.

2.4.1 Observant and participant

During the whole study, I was officially employed by the industry in a major Danish general contractor company. As researcher, I have been working in the construction industry. I have been able to observe and experience the problems in place first-hand. I have had the opportunity to interact with professionals in formal and informal settings.

Eating lunch with other construction professionals working for the general contractor and attending informal events (such as Christmas dinner and a company run arranged by DHL(http://www.dhlstafetten.dk/)) provided opportunities to build trust, which is vital for obtaining the personal opinions of different actors with respect to the research topics (Saunders et al., 2012). Moreover, the general contractor's perspective is centrally reflected because the host company continuously criticised and evaluated the research findings and results.

2.4.2 Exploratory visits

Exploratory visits are short-term planned visits to different work environments. All exploratory visits were planned, which allowed the host to know my identity in advance, the research topic, and the purpose of visit. I did not take any role in the production during my visits. Therefore, I only had the observer role (Saunders et al., 2012).

The exploratory visits varied in duration, from only two hours to a full day. The limited duration of visits may be criticised for being insufficient to collect consistent data as the researcher runs the risk of misunderstanding parts (Justesen & Mik-Meyer, 2012) However, these visits are used for exploratory purposes only with the intention to understand current practices and problems rather than drawing general conclusion.

The second descriptive II study, however, is different. In that study, multiple visits were made to get in-depth knowledge about the case studied. Time recordings of the production, interviews, and feedback from trade professionals to study reports support the proposed solution.

In general, the visits took place at different workplaces, such as construction sites, production facilities, and design offices located in different countries and contexts to provide variance and therefore increase representability (Flyvbjerg, 2006)

2.4.3 Interviews, semi structured interviews

Kvale (1996) defines the purpose of interviews as obtaining "descriptions of the life world of the interviewee with respect to interpreting the meaning of the described phenomenon."

Moreover, interviewing someone in his own context gives the chance to both observe the context and get deeper understanding of the topic.

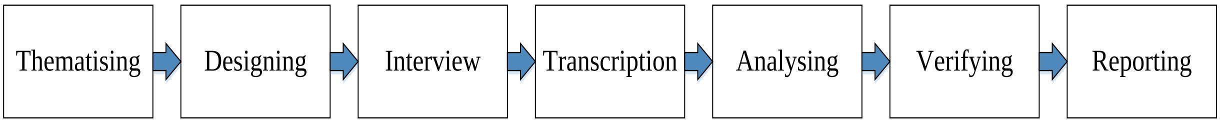


Figure 6. Kvale's (1996) 7 stages of interview study followed.

In preparing, conducting, and analysing the interviews, Kvale's guideline presented in Figure 6 was followed. All interviews were conducted in face-to-face manner at the workplace of the interviewee at the offices or at the construction sites. Individual semi-structured interviews (Kvale & Brinkmann, 2008) were recorded and transcribed, lasting approximately one hour each. The interviewees were selected based on their expertise in different phases of the construction process, such as tendering, designing, planning, and construction.

As the scope of the research was limited to the buildings and modularity in building construction only, this research excluded professionals coming from different trades working in other areas, such as infrastructure, bridges and offshore platforms. The interviewees had experience in all decision-making processes, both with external parties such as clients, architects, and consultants, and internal project organisation from early contact with the client to the final delivery of the project. On average, the interviewees had more than 20 years of experience in the field. In selecting interviewees, I tried to maintain a variation in origin of trade, position in the organisational hierarchy, and educational background (Flyvbjerg, 2006). The variation is evident in the exploratory study. However, in the prescriptive and descriptive II studies, MTH's perspective was dominant due to the research scope and context. Therefore, the employees of the general contractor were given priority.

Although, the interview guide consisted of an outline of questions, the order of going through these was improvised according to the respondent's narrative. The deviation from the prepared guideline both enabled the conversation to be natural and created space for unexpected out-of-the-box reflections. The semi-structured interviews were again very relevant for exploratory studies and initial data collection phases of other studies (Justesen & Mik-Meyer, 2012).

Only a few verification phone calls were made to clarify and double-check unclear points. These are not classified as interviews. All interviews were audio recorded and transcribed. Moreover, the interviews conducted in Denmark were translated into English during the transcription phase. Interviews were the main data source for the exploratory, prescriptive, and descriptive II studies.

2.4.4 Workshops

Workshops are great opportunities to bring people from different trades together to create an intensive dialogue platform for various discussion topics. The data creation process is intensive compared to interviewing the participants individually. Furthermore, due to the higher amount of participants, some valuable individual insights are likely to be missed. Therefore, cross-functional workshops were supported by one-to-one interviews. Two independent workshops were arranged for different studies in different settings.

The first workshop was carried out at DTU for the descriptive study I to find an answer to RQ2. The workshop involved 5 academicians representing different research perspectives. However, all participants were affiliated to DTU Management Engineering department. The workshop gave the opportunity to identify the problem from different systems' perspectives and gave valuable ideas about how to analyse and report the data. Moreover, further research ideas appeared during the workshop and were utilised at later stages of the Ph.D. research.

The second workshop was organised at MTH headquarters in Copenhagen for descriptive study II. Although all participants were MTH employees, they were from different trades and working in different departments of the company. The different perspectives of the project managers, design managers, and site managers on project level were reflected together with the perspective of the BIM managers and process engineers on business level making the workshop a cross-functional one. The results of the workshop provided data for the DSM that is presented in the first descriptive study II answering RQ5.

2.4.5 Data mining

The project metadata is quantitative information about individual projects such as project type, scope, size, contract type, location, time schedule, tender process, purpose, stakeholders involved and technical drawings. Moreover, human resources use sensitive data concerning project managers and project responsible' seniority levels. The advantage of working with this type of metadata source is that data is created independently from the researcher (Justesen & Mik-Meyer, 2012). Therefore, the involvement of factual data adds objectivity to the research.

The data is very heterogeneous and it is obtained from different resources such as MTH company archive, MTH human resources department, project BIM coordinators, project managers, non-governmental and non-profit organisation data base (fx. Kvalitetsfonden). The quantitative data was collected in all four type of studies from descriptive I to exploratory and prescriptive and finally descriptive II presented in Figure 3 and needed to be combined with other types of data before being analysed.

2.5 Data Analysis Methods

Different data analysis methods have been utilised at different stages for different purposes. The research question leading the investigation and different type of data require different analysis methods. These methods are described in the section below. The results obtained by using different methods are presented under relevant stage in the analysis chapter.

2.5.1 Network analysis

In order to analyse the first descriptive study network analysis is applied. Manning (2005) defines project networks, as sets of intra- and inter organisational relationships between individuals and organisations that interact within the scope of one or several projects. The complexity of the temporary organisations and the way this complexity affects project productivity is studied. Inter-organisational relationships between the hospital construction stakeholders and final design output that is in common in all cases, are investigated comparatively in order to reveal the productivity improvement possibilities.

In general, a network is composed of a set of actors, who are connected via a set of relations, with a specified content (Wasserman & Faust, 1994). The structural complexity caused mainly by both the number of stakeholders (size of network) and the relationship variations between actors (connectivity) play an important role to shape the network structure. Network theory offers several explanations for the effects different structural properties can have on the actors.

The chosen hospital projects (Table 6) have all the complexity attributes making the way the construction organisation is designed is complex. In addition to the structural complexity, project organisations suffer from temporariness, uniqueness, fragmented organising due to heterogeneity of the work tasks, short-term orientation, and lacking organisational routines (Geraldi et al., 2011).

The single patient room design is chosen as the project outcome because single patient room is common in all cases providing a comparability aspect across the projects. The essence of the network lies in the assumption that the embeddedness of network members in social networks has an influence on the outcome of decisions (Granovetter, 2005).

In order to analyse and visualise the network structure, 0.82.beta version of the software called Gephi is chosen due to the simplicity of usage and data display. The software tool is useful not only for getting the general network overview but also for the detailed analysis of single network members and relationships within the network. The results of the network analysis impact on the final design outcome will be elaborated in Chapter 4. For detailed information about how the method is applied paper 1 shared in the appendix A can be addressed.

2.5.2 CASE STUDY ANALYSIS

For exploratory study stage data analysis, cross case pattern search described by Eisenhardt (1989) and later elaborated as pattern-matching strategy by Yin (2009) are used. According to Yin (2009), pattern-matching is one of the most desirable strategies, especially if the case study is an explanatory one. With the purpose of building an understanding of modularity and its applications in construction two multiple case study analysis with 7 and 11 different case studies respectively have been made (Table 7 and Table 8). The findings of one individual case study helped to gain familiarity with data and enabled preliminary theory comparison and then theory generation (Eisenhardt, 1989). Moreover, the finding of each case study created a basis for the next case study, although semi-structured interview guideline remained fixed.

For the pattern-matching analysis, a single dependent variable was chosen to be the final product (i.e. building to be commissioned to the customer) as the entire cases share in common at least one type of building as the final product. However, independent variables were different in different cases. Most of the cases shared the same or similar drivers for them to develop the way they deliver the building. However, materials used varied from context to context remarkably. The independent variables, such as market conditions, economic development level, average wages, climate, company background were presenting a large spectrum. This variety in independent variables of cases made difficult to apply a comparative or a cluster analysis. Furthermore, due to the amount and variety of independent variables, neither simpler patterns nor literal replication meaning identical results in pattern making could be achieved (Yin, 2009).

Instead, more theoretical replication based on the similar but not identical patterns were observed in the analysis of the explanatory cases. Coinciding cross-case patterns added to the internal validity whereas cases not following the general pattern needed further explanation (Yin, 2009). The rival patterns in other words the patterns not following the main identified pattern were than analysed in depth with multiple lenses in order to look beyond the initial impressions (Eisenhardt, 1989).

In that sense, an explanation building approach described again by Yin was visited. Most of the explanation building of the cases was in narrative form making precise measurement of causal links (Yin, 2009). Findings of the case study analysis can be found Chapter 4 under the exploratory cases subsection.

Finally, the patterns described in cross-case analysis are used as leverage for the next stage prescriptive and descriptive II studies. The explanations of the causal links creating particular outcomes provided a basis for the following prescriptive study QCA method is operationalised. The next data analysis method subsection presents a detailed description of QCA.

2.5.3 Qualitative Comparative Analysis-QCA

In order to explore repetitions across so-called unique construction projects, QCA was used in the prescriptive study. QCA allowed me to draw combinations of different factors of practices (conditions) leading to a dependent outcome. As illustrated in Figure 7 the research process was highly iterative. During this iterative process, the literature is revisited and additional empirical material was gathered to solve occurring contradictions.

Repetitions are important to track the patterns resulting with particular outcomes. Only in that way, from the chaotic disorder level, can more ordered structures be created enabling prediction of outcomes. Identifying repetitions is the way to achieve prescribed standards. Without repetitions leading to standardisation and predictable outcomes the application of modularity is simply not possible.

The QCA research process shown in Figure 7 is in total accordance with the mixed methods research described in section 2.2 Research Design. The steps of the research and how it is applied can be read in detailed in papers about tender practices presented in appendices C, and D and in the unpublished paper about dispute cases presented in appendix E. In this section only the QCA method and its relevancy with the research is described.

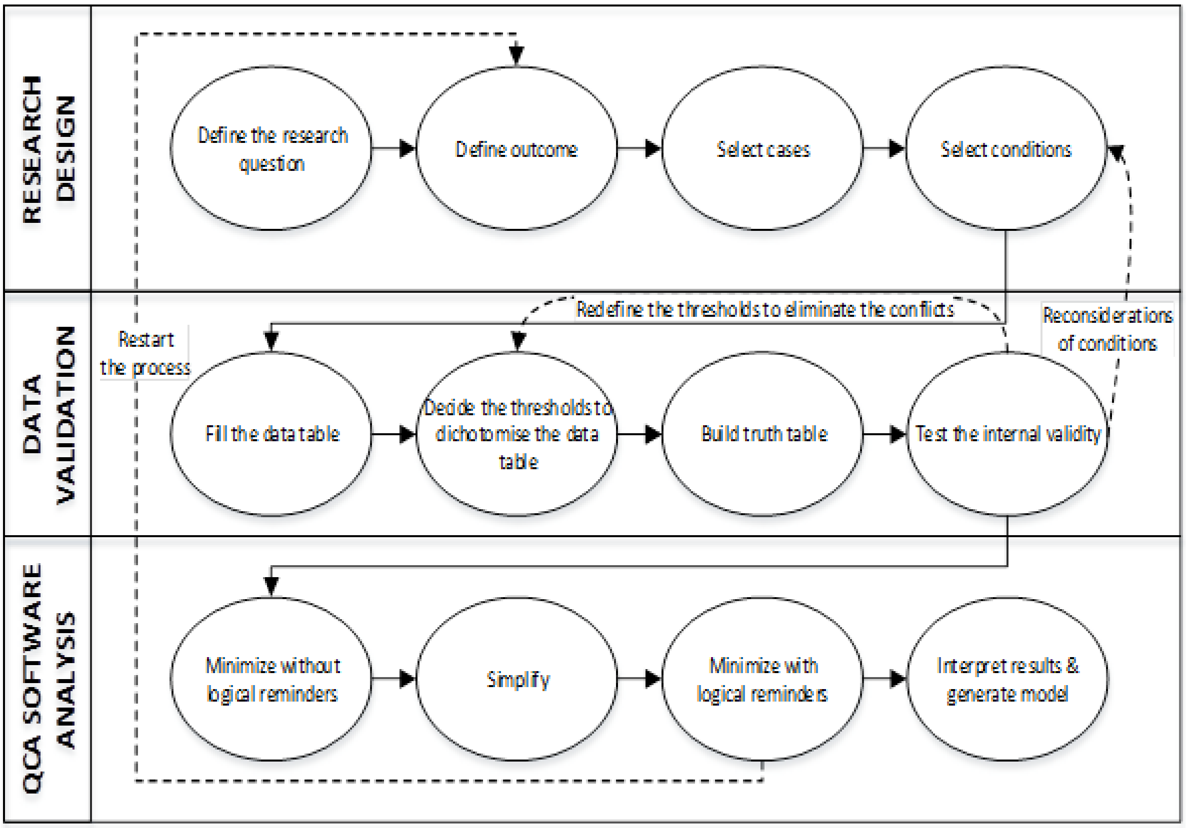


Figure 7. QCA Research Process adapted from Jordan et al. (2011)

First propounded by sociologist Charles Ragin in 1987, QCA is a relatively new approach but its principles have been applied extensively, primarily in the fields of sociology (Rihoux, 2006) and political science (Ragin, 1987), but also in management, economics, and engineering (e.g. Jordan et al., 2011) in the study of complex phenomena. Recently, it has been introduced in the study of various construction practices, like Public Private Partnerships (Gross, 2011) and a school sanitation project in Bangladesh (Chatterley et al., 2014).

There are two different approaches in the study of project organising and management. They are using either: (1) a large amount of quantitative data and well defined hypothesis testing or; (2) qualitative data and more explorative research questions. In contrast to working with quantitative data, focusing on numbers and statistical correlations without interfering with the individual project participants, a growing amount of research has focused on understanding project organising and management as situated and contextual practices. The QCA method appears to be the middle ground solution using the advantages of the quantitative and qualitative perspectives.

QCA lays in-between quantitative and qualitative research approaches for testing hypotheses in addition to allowing the researcher to work with small cases compared to statistical methods. The method, though, is closer to qualitative methods due to its sensitivity to individual cases (Rihoux & De Meur, 2009). This is also mirrored in the highly iterative processes, which to some degree are similar to the iterative interpretations within qualitative studies.

The tendering process is chosen for the case study as the uncertainty is highest in the early project phases, and differences between projects are already remarkable in the bidding phases. However, repeating patterns hypothetically exist even though projects have unique characters. The combinations of conditions repeating across the projects that lead to particular project outcomes are to be described.

To make best use of the data set available to describe a solution set with factors leading to particular project outcomes, the most used QCA method—a crisp set Qualitative Comparative Analysis (csQCA)—was chosen for this study (Rihoux & De Meur, 2009). Contrary to the fuzzy sets that use partial memberships such as 0.5, the crisp set is based on full membership and full non-membership, in other words absences as 0 and presences as 1 binary notation (Thomas et al., 2014). However, csQCA has certain advantages and limitations worth noting, identified by Jordan et al. (2011) in Table 2.

Moreover, QCA 3.0 software developed by Ragin was used to conduct the analysis. The software used for the analysis can be freely downloaded from Arizona University web page (http://www.u.arizona.edu/~cragin/fsQCA/software.shtml last visited on 03 October 2016).

Table 2. Crisp Set Qualitative Comparative Analysis advantages and limitations (Jordan et al., 2011)

Advantages	Limitations
• Ability to work with smaller set of data compared to quantitative approaches • Ability to work with large number of cases compared to qualitative approaches • Easy to understand for the reader • Transparent • Replicable	• Dichotomisation of data: Transformation of data into a binary notation • Difficulty in selecting conditions (independent variables) and cases • Lack of temporal dimension

The results of the QCA 3.0 software for two presciptive studies will be shared in the analysis section under prescriptive study. For the steps undertaken in different research steps, Papers presented in the appendices as C, D and E, can be addressed.

2.5.4 Design structure matrix

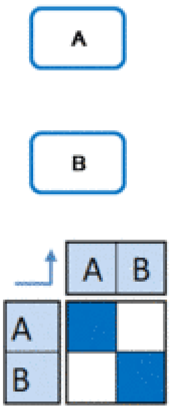
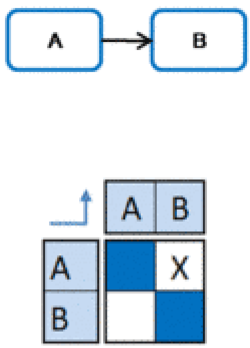
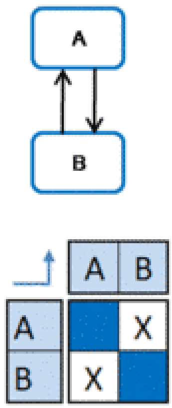
DSM is another method used in this research to operationalise modularity theory. DSM is described by its developer as a technique to plan the design process information flow by visualising the use of estimates, iterations, and design reviews (Steward, 1981).

The intensive information flow and interdisciplinary iterative nature of construction design projects makes design processes difficult to plan and schedule with traditional tools, resulting in inevitable rework and time wasted (Oloufa et al., 2004). Moreover, many important decisions, such as dimensions, size, material choice, and application of modular solutions are made in the design phase. Therefore, it is important that the design process be structured in a way that will allow the application of modularity at the product, process, and organisation level.

In parallel with Simon´s (1962) definition of modularity, I aim to cluster the design activities into groups to identify modules having high intra-component dependency and low inter-component dependency. For that purpose, Cambridge Advanced Modeller software, developed by the Engineering Design Centre at the University of Cambridge Department of Engineering and freely available online, is used (Wynn et al., 2010, http://www-edc.eng.cam.ac.uk/cam/ last visited on 15.05.2015)

Basically, a DSM is a square matrix with an equal number of rows and columns showing relationships between elements/tasks in a system. By using DSM, parallel, sequential, and coupled (iterative) activities are identified. Table 3 illustrates the graphical and matrix representation of these configurations.

Table 3. Reading and understanding a Design Structure Matrix

Configuration of Relationships	Parallel	Sequential	Coupled
Graph and DSM representation			

In Table 3, the dependency possibilities between Activities A and B are illustrated. In the first parallel case, Activities A and B are independent of each other. This allows them to be executed in parallel. In the second case, Activity B is dependent on the information resulting from Activity A. In this case, a cross is put in the matrix showing that Activity A supplies to the Activity B, thus showing the sequential relationship. In the last case, both activities are dependent on each other and therefore an iterative relationship between activities A and B exits.

Since iteration is an indispensable part of the design process, controlling the amount of iteration and making it manageable attracts the attention of many researchers. The DSM method has been applied in different research areas. Cho and Eppinger (2005) apply DSM to an aerospace company for scheduling the engineering design process. Some applications of DSM in the construction industry have been studied with different perspectives. Oloufa et al. (2004) take Critical Path Method (CPM) and its extensive usage in construction as a starting point, successfully combining DSM and CPM. Oloufa et al. (2004) use DSM to support the shortcomings of CPM, which occurs mainly in the design phase because activities there require continuous estimation and iteration to reach optimisation in design.

In comparison to other system modelling methods, DSM has two main advantages (Lindemann, 2009):

- It provides a simple and concise way to represent a complex process.
- It operationalises powerful analyses, such as clustering (to facilitate modularity) of iterative design activities and sequencing (to minimise cost and schedule risk in processes).

This method was operationalised to cluster the design process modules identified as a result of the cross disciplinary workshop that took place in MTH. The case chosen was design process of façades, because the façade design process is interpreted to be a representative case for general design activities with the amount of stakeholders and various dependencies between design activities.

The results of the case study will be presented in Chapter 4 under the descriptive II studies subsection. More detailed information about the case study can be read in the paper titled 'Design Process of Facades Through Application of Modularity: Divide and Conquer by use of Design Structure Matrix (DSM)' presented in the appendix F.

2.5.5 VALUE STREAM MAPPING

In order to operationalise modularity, a map visualising the flow of resource usage, including time, labour, and inventory, through implementation is used as a method. VSM, described as the blueprints for lean transformations, is applied in the final descriptive II case (Rother & Shook, 1998).

VSM helps to visualise an overall picture of the entire production process, describing both value and non-value-creating activities (Rother & Shook, 1998). Moreover, VSM makes information and material flow visualised; therefore, it is different than other process maps showing only activity sequencing or information flow (Rother & Shook, 1998). Finally, VSM helps to establish a direction for continuous improvement. In our case, this direction is the application of modularity in building construction.

In order to get rid of the waste in the process first step is the mapping the current state of the value stream. 'Current conditions are always based on facts derived from the gemba (Japanese word for the real place) - the place where the actual work takes place' (Shook, 2009, p.1). To do so, I made four visits to the final construction site where I had the chance to observe big room meetings, and interview the general contractor and trade contractor project managers, architects and owner representatives.

Furthermore, I had the privilege to observe the manufacturing work performed by the use of jig modules (Section 4.4.2 in Figure 47 on the left hand) in the temporary workshop. As suggested by Rother and Shook (1998), the professionals, such as production foremen and site responsible were involved in the VSM creation so that the VSM was not only an outsider's work but it was the co-creation of individuals involved in the work process.

VSM creation was undertaken in different steps. First, the overall process flow of the information and material was created. This process flow involves all the production locations, inventory placements, and work activities. Second, according to the project participants' narratives, stages such as the first run, supply chain, cutting and sub-assembly, testing, storage, delivery and final assembly stages were described. The detailed description can be found in paper presented in the appendix G. The current and suggested future state of VSM will be elaborated in Chapter 4.

2.6 Section Summary

DRM is the overall research strategy applied in this Ph.D. study. The iterative nature of the DRM helped me to shape the literature and to reformulate research questions along the way. Moreover, different case studies at different stages of the research supported and helped to shape the next stage study. In that sense, DRM helped to accumulate the findings from one stage of the study to the next one.

Figure 4 illustrates the DRM performed in the five different stages. The initial stage determines the research questions and literature underlying the overall study. Then, an initial descriptive I study was conducted to understand the defined industry problem in-depth. Next, a series of exploratory studies revealed the state-of-the-art analysis of the modularisation in the industry. As a fourth stage, a prescriptive study was made in the case company having a very extensive project portfolio, in order to trace the repetitions across projects. Finally, the descriptive study II stage evaluated the implications of solution alternatives.

‘The best management is a true science, resting upon clearly defined laws, rules, and principles, as a foundation’.

F.W. Taylor (1911)

RQ1: *What are the relevant theories to base the research upon in order to address the productivity problem of building construction?*

3 Theoretical Background

The following theory section presents the complexity and modularity theories. The deductive theorising strategy is applied as described in the previous section to identify the gap in modularity theory believed to be the cause of the problem.

The concept of modularity has long been successful to better manage structural–technical complexity (Oehmen et al., 2015). To elaborate the modularity theory and develop further its possible application in the building industry which hosts a typical example of the project-based production system, the complexity and modularity theories will be utilised. The theoretical contribution of the thesis and the fields the theory has been applied together with relevant fields are illustrated in the Figure 8 below.

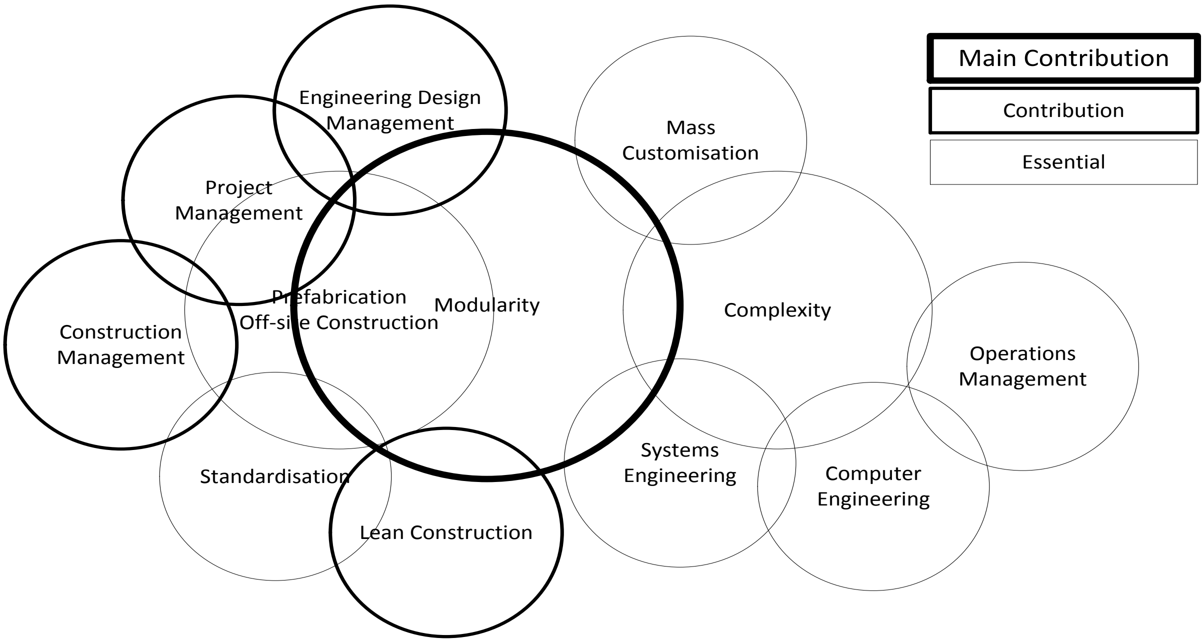


Figure 8. Fields of contribution and relevance

First, complexity theory and complexity in construction are described as a source of the problem. Then, modularity theory as a concept will be described in-depth together with applications in other industries. Furthermore, modularity in product, process, and organisation domains will be elaborated. The description of strategies to reach modularity and modularity in construction will be presented as a way to manage the complexity in building projects.

3.1 Complexity

The complexity is in the eye of the beholder as illustrated by the following example.

> Although all world agree that the brain is complex and a bicycle simple, one has also to remember that to a butcher the brain of a sheep is simple while a bicycle, if studied exhaustively (as the only clue to a crime) may present a very great quantity of significant detail (Klir, in UNU, 1985).

Similarly to the above-mentioned description, Casti (1986) argues that the observer and the interaction between the observer and the system play an important role to define the complexity level. He states that, 'system complexity is a contingent property arising out of the interaction I between a system S and an observer/decision maker O' (Casti, 1986, p.149) According to his perspective, the complexity of a system increases proportionally as the observer generates new descriptions of the system.

To define the level of complexity attracted the attention of the researchers Kurtz and Snowden (2003) as well. Kurtz and Snowden created a sense-making mechanism known as '*the cynefine framework*' describing the domains into which a given system will place itself, as shown in Figure 9. These are: chaos, complex, knowable, known, and finally disorder as shown with the dark area in between (Kurtz & Snowden, 2003).

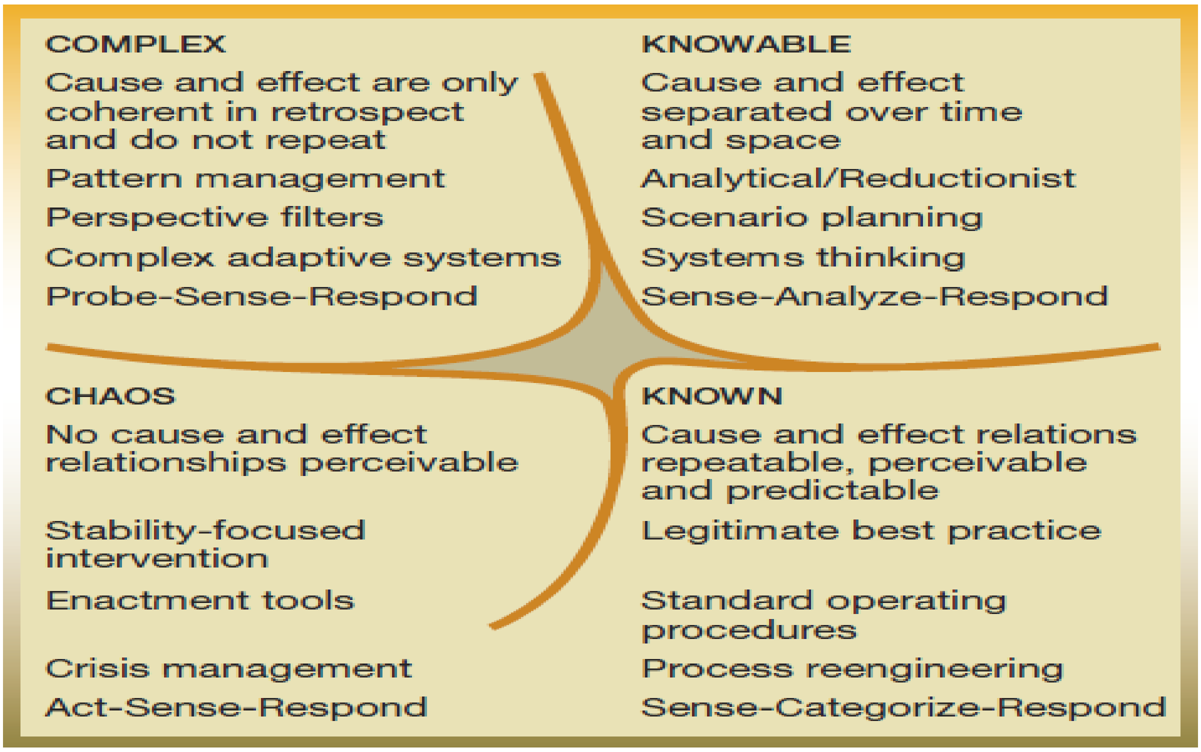


Figure 9. Cynefin framework (Kurtz & Snowden, 2003).

Complexity is not a new science but rather a new way of looking at systems. Ever since the 1970s, as Simon (1969) points out, multiple levels of hierarchy and a wide range of architectural choices in system specification characterize the architecture of complex systems. The product variety and multiple organisations will add significantly to the magnitude of complexity in a given system. Hofer and Halman (2005, p.56) support this argument through a negative description, 'We argue that the deliberate restriction of architectural choices (i.e., through a layout platform) is a powerful means to reducing engineering complexity and risk'. They further argue that efficiently reducing complexity will create a competitive advantage (Hofer & Halman, 2005).

3.1.1 Sources of Complexity

Geraldi et al. (2011) describe sources complexity in four different categories as a result of an extensive literature review: structural complexity, uncertainty & dynamics, pace, and socio-political complexity. As a typical project-based type of production, construction projects involve all four dimensions. As a result, managers must cope with challenges presented by each of these dimensions of complexity both at individual level and organisational level (Geraldi et al., 2011).

3.1.1.1Structural Complexity

Variety is a source of complexity (Sosa et al., 2007). However, as hinted in the above paragraphs, variety is not sufficient to explain a complex system. A system with large amount of components can yet still be fully analysed, making it complicated rather than complex (Cilliier, 1998). A machine would therefore be complicated as it is fully analysable but not complex.

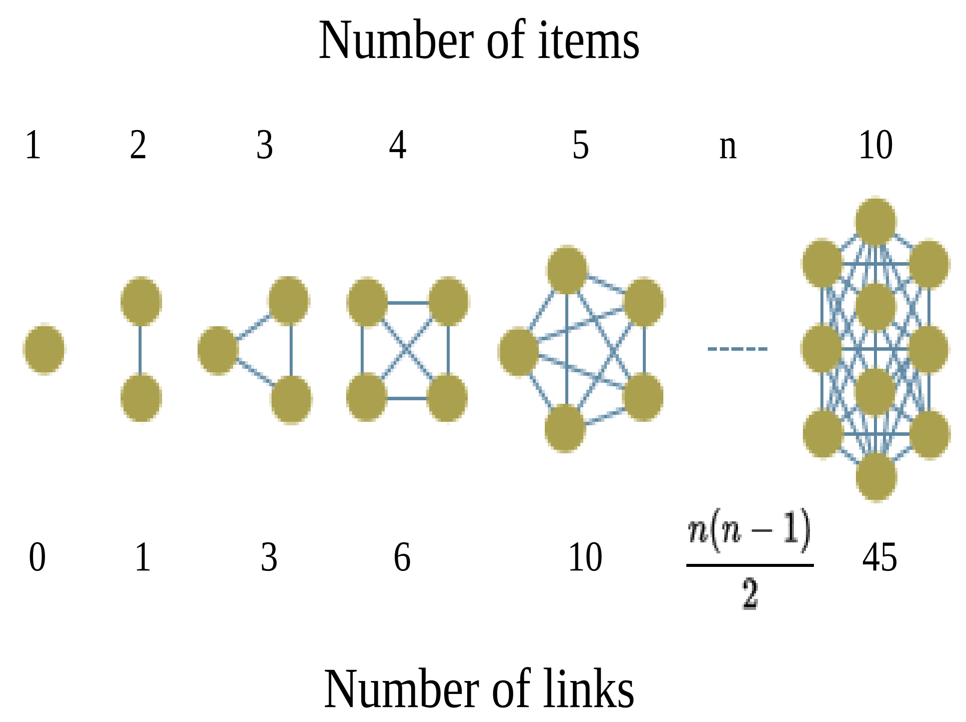


Figure 10. A measure of system complexity based on the number of stakeholders and interlinks adapted from Flood and Carson (1993).

The structural complexity will to a large degree follow Wilson and Perumal (2009), who argue that increased product variety likewise increases processes and organisational variety — this will again increase complexity costs exponentially. The end-product variety represents external complexity, visible for the customer, while internal complexity generated from sub-product, process and organisational variety is not visible, but adds cost (Wilson & Perumal, 2009).

'Many systems increase in complexity, primarily for two reasons: increase of interconnections and increase of customisation, (Fixson, 2006, p.28). The increase of complexity due to increase in interconnections can be visualised by viewing the number of items in relation to the number of links (interconnections) (Flood & Carson, 1993) as shown in Figure 10.

3.1.1.2 Uncertainty and dynamics

Sivadasan et al. (2002) define complexity as structural and operational. Structural complexity will increase with variety, while operational complexity will increase with the uncertainty created through the dependency between modules. Contrary, to the machine example having relatively large parts and components, 'complexity doesn't necessarily follow from large numbers' (Apello, 2011, p.4). Even 'the combination of just three atoms leads to unexpected behaviour of water molecules', this makes the water molecule unpredictable and complex as seen in Figure 11 (Apello, 2011, p.4). Building projects are a great example because activities in the design and execution phases depend on many others in terms of input or/and sequential order.

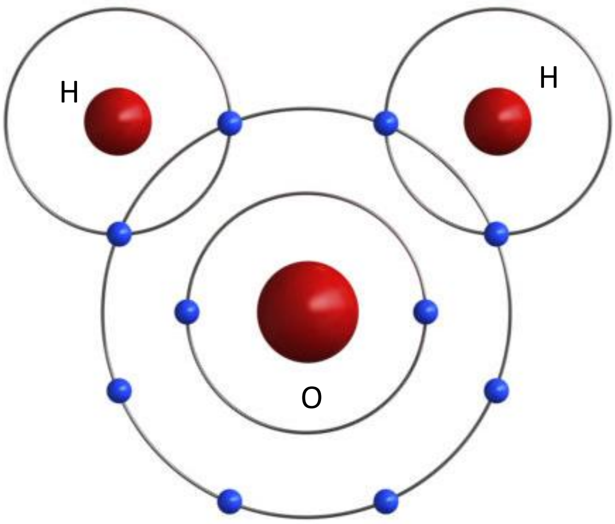


Figure 11. Water molecules (adapted from Bhunia et al., 2015)

Alter (2006) writes in his book *The Work System Method: Connecting People, Processes, and IT for Business Results* that, 'systems that are too simple does not address the variety of foreseeable situations that might occur', and that 'each additional function or feature shift the balance toward complexity' (p.140). Alter makes a very important point here. By simplifying too much and even just by standardising a degree too much, one risks becoming inflexible for changes and unpredictable circumstances. Alter (2006) states that, 'Systems that are too complex are difficult to understand, control and fix; especially when unanticipated situations emerge' (p.140), meaning, for example, that an overweight of bureaucracy in an organisation makes even simple changes difficult. Concerning change, Alter (2006) further argues that, 'as complexity increases, the ripple effects of changes in one part of the system become more difficult to trace' (p.140). From Alter's arguments, one draws the necessity of a certain balance in order to have an ideal efficacy. A system must have the right degree of complexity—neither too simple nor too complex.

3.1.1.3Pace

Pace is a critical dimension of complexity in project management as the clock continuously ticks against the projects. A tighter time frame in project management creates tighter interdependence between elements of the system and therefore intensifies the structural complexity (Williams, 1999). Moreover, tightness of time constraints makes project types of production more vulnerable to changes causing small problems to have unexpectedly large effects (Williams, 2005). One woman delivers a baby in nine months but nine women jeopardise the entire process and can never deliver a baby in one month. It is worth being aware of this, in order not to squeeze more than a compressible level.

3.1.1.4Socio-political complexity

Socio-political complexity emerges as a combination of political and emotional aspects involved in projects. This cause of 'complexity is expected to be high in situations such as mergers and acquisitions, organisational change, or where a project is required to unite different interests, agendas or opinions' (Geraldi et al., 2011, p.23). A lack of commitment of stakeholders and problematic relationships between stakeholders as well as those related to the team appear to increase with variety of project participants (Maylor et al., 2008).

Geraldi and Adlbrecht (2007) describes 'complexity of interaction' as the interaction between people and organisations, and involves aspects such as transparency, empathy, variety of languages, cultures, disciplines, etc. In addition to the root causes of complexity, a large literature exists aiming to locate the 'hiding places' of complexity. Many researchers (Aspinall & Gottfredson, 2006; Hansen et al., 2012) focus on the product complexity and defend that process and organisational dimensions are a direct result of product variety and, therefore, complexity. While some others (Sivadasan et al., 2002) trace organisations operating in supply chains exporting or acquiring complexity.

3.1.2 Dimensions of Complexity

Wilson and Perumal (2009) argue that analysing either process or product by itself does not address the problem of complexity. The organisational dimension as well needs to be included in the problem description. Moreover, the product, process, and organisation are integrated and have their own role of complexity (Wilson & Perumal, 2015). The improvement will be limited in case each subject is studied individually compared to a combined approach as illustrated in Figure 12 (Wilson & Perumal, 2015).

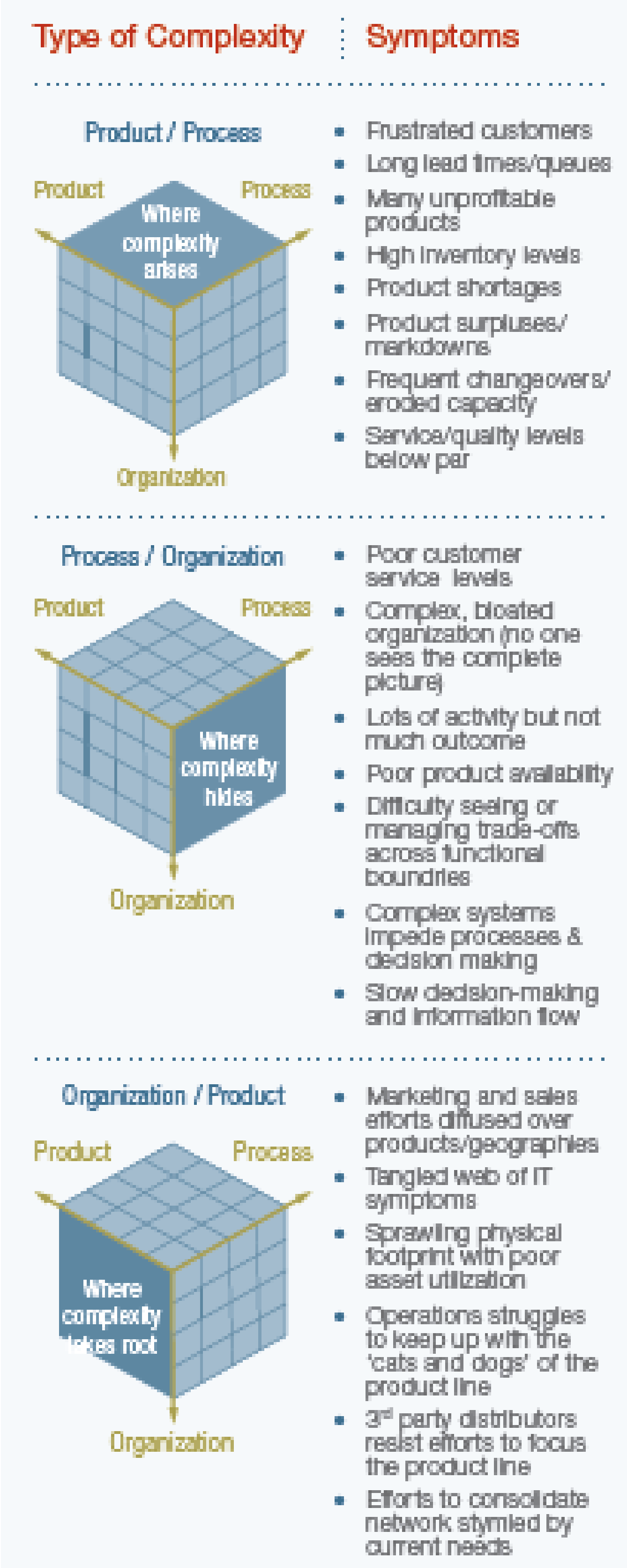


Figure 12. Complexity costs and how the Product, Process & Organisation affect one another (Wilson & Perumal, Complexity Cube, 2015).

In addition to the description of product, process, organisational complexity, Wilson and Perumal makes the distinction of the value-adding complexity and non-value adding complexity. According to Wilson and Perumal (2009) value adding complexity is the complexity that offers customers something they are willing to pay. Therefore, it is good complexity. Contrary to good complexity, complexity that the customers will not pay or will not pay enough for is bad complexity. The bad complexity not adding any value is difficult to distinguish in practice (Wilson & Perumal, 2009.

All variety adds costs to a business, but not all products add value to the customer. As Wilson & Perumal (2009) treat complexity costs and non-value adding costs equally, this also means that the degree of non-value adding will increase steadily with the company generating less revenue. Thus, to identify and eliminate the bad product complexity should be the obvious target for companies to pursue. The advantages of eliminating non-value adding product complexity are only visible when a company takes action in order to remove non-value adding complexity (Wilson & Perumal, 2009).

New products and product innovation adds significantly to the product complexity as well as the process complexity; as the variety of "items"/products increase through the whole value chain (Ashkenas, 2007). George (2003) writes in his book about Lean Six Sigma that; "The complexity of product and service offering generally adds more non-value-add cost and WIP (Work in Process) than either poor quality (low sigma) or slow speed (un-lean) process problems" (George, 2003). This statement supports the argument that the product variety has to add value to the customer otherwise a company wastes resources.

For companies there exists a trade-off between limiting the complexity and having the product variety addressing a bigger market. The complexity cube is a three dimensional diagram, where the centre of the cube have the least amount of complexity (Value add) and the further out you get the more complexity there is (Non-value add). The further from the centre the more complexity and this means that the complexity is multiplied rather than added for each dimension: product, process and organisation.

Illustration with a case from the thesis might be very useful for the reader. As it will be discovered later in descriptive study I the 27 hospital projects being built in Denmark do not share any identical patient room designs. The patient rooms are slightly or remarkably different from one another arguably does not create any value for the end users. Patients do not think about the design of the room in which they overnight being different from the ones in the neighbouring hospitals. Moreover, healthcare personal changing work place and again healthcare personal working in more than one hospital during a work week experience difficulties to adjust the new design every time they move from one place to another. As seen from the example the variation in product design creates a non-value adding complexity.

3.2 Complexity in construction

'Construction Projects are amongst the most complex of all undertakings' (Winch, 1987, p.970) Construction is a production. Koskela (2000) conceptualises that construction is not a transformation of inputs to outputs only but also a flow of work and a creation of value as well. Ballard (2008) focuses on lean project delivery system which takes the generating value as starting point and supports it with reducing waste principle (Ballard, 2008). Bertelsen (2003) describes construction production as a dynamic and complex system just like any other complex system (Bertelsen, 2003). Moreover, The one-of-a-kind character of building projects and the onsite production have arguably prevented the attainment of efficient flows as in stationary manufacturing production (Koskela. 1992).

It is well worth taking some time to look into the reasons separating the construction industry from other industries. There are relative attributes of the building industry separating it from other sectors, such as fragmented organisation, project based production, and the size of the individual projects. The product in the construction industry is the building itself. In the next subsections, the attributes of construction projects will be elaborated within product, process, and organisational domains with selected references from the construction literature.

3.2.1.1. Attributes pertaining to the construction product: Building

Immobility

The main attribute separating construction project output product from other projects is that the structure is attached to the ground. The variations of different locations, soil conditions, seismic activities, groundwater level, social, and environmental impact of the project (e.g. traffic and users shaping nature) all add to the complexity of the project because of the immobility of the final construction product (Turin, 1980; Nam & Tatum 1988; Ofori, 1990; Dubois & Gadde, 2002; Ballard, 2012).

The high cost

Construction projects are expensive. Even the cost of a single-family house is remarkable to the owner. To compare, consumers tend to buy a mobile phone every year and a car every five years, but, for many, a house often is a lifelong investment. The cost of the project is directly proportional to size and also substantially affected by the location, scope, choice of architecture, and materials used. Generally, construction projects are realised with a big amount of resources (Turin, 1980; Nam & Tatum, 1988; Ofori, 1990; Dubois & Gadde, 2002).

Longevity

Construction products are relative temporarily extensive compared to other types of products. A human lifespan is often referred for the building life after commissioning. Structures serve generations. The lifespans of construction products are so long that the function of the structure may change over time. In central London, for example, Tate Modern serves as a cultural institute although it was built originally as a power plant. In central San Francisco, the Ferry Building serves recreational purposes with restaurants and markets. Similarly, old military buildings and structures built for defence purposes add value to Copenhagen's every day and cultural life as recreational areas (Turin, 1980; Nam &Tatum, 1988).

Uniqueness

Every structure is unique. Even in the cases where previously applied design solutions are replicated the ground conditions and locations are different. Moreover, the product can be similar but organisation and processes might be slightly different from project to project because the product is produced for a specific customer (Turin, 1980; Ballard, 2012).

High level of impact

Due to their size, construction projects have an impact in almost every aspect of urban or rural life, depending on the location of the project. In many cases, the major projects become identifying makers of the places they are built. A big hospital is remembered with its location's name or a tower can change the landscape of the neighbourhood. With the generated traffic and number of users of the structure, the environment can be totally different before and after the project's completion (Nam & Tatum, 1988; Wood et al., 2013).

3.2.1.2. Attributes pertaining to the construction process

Time lag

Construction projects involve several stages and each takes a long time. The project duration, from the preliminary design phase to the project completion, can take several years. In many cases, changing conditions and demands mean design changes are almost inevitable. Moreover, time lag can occur between different stages because of various reasons, such as financial problems or change in political atmosphere. Such time lags between different construction stages create discontinuity, which affects projects negatively (Baccarini, 1996; Gidado, 2004).

Amount work tasks

A very large number of work tasks involving a large number of interfaces need to be put together during a project's duration, which increases the complexity. Moreover, many activities need to be executed simultaneously on a confined construction site, which increases complexity (Gidado, 1996; Dubois & Gadde, 2002; Gidado, 2004).

Subject to atmospheric conditions

Unlike other production industries, the building construction process is subject to weather conditions. Varying atmospheric circumstances makes long-term planning difficult and adds uncertainty to project schedules. Even in cases where the work can be completed as planned, the desired productivity often cannot be achieved due to cold or precipitation (Gidado, 1996; Wood et al., 2013; Ballard, 2012).

3.2.1.3. Attributes pertaining to the construction organisation

Stakeholders

Construction projects have numerous stakeholders if one includes material suppliers and sectors supporting the construction industry. The main stakeholders are: clients, investors, architects, consultants, contractors, speciality constructors, sub-contractors, public authorities, material suppliers, utility providers, and end-users. Due to the size and scope of the projects, government or public clients play a dominant role in most of the projects (Ofori, 1990; Baccarini, 1996; Dubois & Gadde, 2002; Gidado, 2004; Wood et al., 2013).

Project delivery systems

The above-mentioned stakeholders work together in different settings. Construction contracts define the project delivery system as well as the different roles and responsibilities. Contracts are needed that align the interests of project team members in order to deliver the project while generating value and reducing waste (Ballard, 2008). Organisations are shaped by contractual scope and duties. Some of the main project delivery systems in construction are as follows:

- Design-bid-build: The classical contract type used in construction industry known also as traditional or conventional project delivery. The design phases and building phases are separated contractually (The American Institute of Architects, 2009).

- Design-build: "Design-build is a process in which the owner contracts directly with one entity to provide both the design and construction of the project." (The American Institute of Architects-A141, 2014)

- Integrated Project Delivery (IPD): "A project delivery system that seeks to align all project team members' interests, objectives, and practices (even in a single business), through conceiving the organisation, operating system and commercial terms governing the project. Team members would include the architect, key technical consultants as well as a general contractor and key subcontractors." (Project Production Systems Laboratory, 2015)

Collaboration between different stakeholders depends on the project attributes—such as size, scope, time plan, maturity of the project data, stakeholder's competences and client's preference—and, therefore, it is difficult to apply the same contract type across all projects (Latham, 1994; Egan, 1998; Baccarini, 1996).

Labour intensive

Construction production is still dependent on hand workers compared to other industries. The workforce skill level affects how projects are organised. Working together with very low industry entrance barriers is causing fragmented company distribution in the sector. According to statistics, construction employs about 6.4% of the total UK labour force and represents around 50% of all registered companies (Bower, 2003). These figures show the dominance of SMEs in the sector. Typically, those companies do not have the resources to invest in long-term productivity improvement projects (Chan et al., 2002; Bower, 2003; Clarke & Winch, 2006).

Discontinuity across projects

The main challenge of working with project-based type of production is the discontinuity of the work. Project-based construction work implies that once the work is finished, the site team is dissolved and a new team is established on a new project (Bower, 2003). Moreover, companies have to assign personnel to execute simultaneously projects with different time schedules. These issues make maintaining organisational stability a big challenge for the companies operating in the industry (Bower, 2003; Wood et al., 2013).

This growing complexity has been highlighted by researchers as one of the primary challenges in the further development of construction practices. Gidado (1996) takes an ordered approach to assess complexity in construction projects. Williams (1999) describes complexity as structural uncertainty and uncertainty in goals and methods only.

Seen from the complexity theory perspective, building projects represent all the dimensions of the complexity outlined as outlined in this section. Working with numerous stakeholders of different trades and backgrounds adds to the complexity of the work (Structural complexity). Moreover, unpredictability of the production that cannot be executed as a linear sequential way also makes the building construction complex (Uncertainty and Dynamics) (Bertelsen & Koskela, 2003). Every trade contractor at macro-level or every craft at micro-level can execute the work in different ways, change the order of the tasks depending on logistics or machinery breakdowns or manpower availability or something as simple as weather changes may cause conflicts within the top-down imposed construction schedule (Pace). Finally, the increasing engineering and contractor specialisation combined with more tight construction schedules makes building construction more difficult to manage (Socio-political complexity) (Howell & Koskela, 2000). In light of the above-mentioned attributes, structural complexity, uncertainty, execution pace, and high level fragmentation of stakeholders, construction projects easily represent the complex systems that are described in the literature.

Besides a conceptualisation based on variety and unpredictability, another conceptualisation of construction production is possible by means of Cynefin framework shown in Figure 10 (Koskela & Kagioglu, 2005). The aim for project managers must be to identify which domain they are in (Tommelein, 2015). The boundaries of four domains are blurry as in real life things are described in a large spectrum and never absolute black or absolute white.

Once we identify where we are in the Cynefin framework, the improvement should be from un-order (Chaos-Complex) towards order (knowable-known) (Koskela & Kagioglu, 2005). The grey area in the centre represents the disorder zone where the domain of the actual stage is not identified. Therefore, the decisions made with the purpose to improve the actual towards best practice will be based on personal preference (Tommelein, 2015) Once the domain we operate is described, the improvements can be made from chaotic to complex, from complex to complicated knowable, and from knowable to know as illustrated in Figure 10.

In the journey to manage complexity, modularity appears as a crucial strategy enabling organisations to create products and services meeting individual customers' needs while still leveraging the benefits of similarity and standardisation (Oehmen et al., 2015)

3.3 Modularity

The working definition of modularity in this thesis derives from Simon's (1962) description of the focus of modularity as creating high intra-component dependency and low inter-component dependency. Modularity is becoming more and more popular as a concept in several disciplines including the building construction. However, there is no consensus about the meaning of modularity, its definition, and, more importantly, the value it represents. Since 'modularity is an attribute of a complex system' (Campagnolo & Camuffo, 2009, p.259) it is difficult to make a simple definition of it.

The definition of modularity taken as stand point in this thesis is 'a design of production systems or parts of a production system, that attempts to minimize interdependence between modules and maximize interdependence within them' (Campagnolo & Camuffo, 2009, p. 259). Modularity theory is treated as a tool to handle the complexity described in previous sections and it is introduced in the following order:

Firstly, modularity from different perspectives is discussed in the following subsection. Secondly, applications of modularity in different industries are exemplified. Thirdly, the chosen management perspective of modularity for this Ph.D. project within product, process, and organisational domains is elaborated. Strategies towards applying modularity are then outlined. Finally, modularity in construction is discussed.

3.3.1 Modularity as a perspective

Modularity as a perspective is gaining attention in research circles. As a way of looking at products and processes, modularity has been relevant in certain industries for a considerable time. For example in automotive manufacturing, producers seek to combine modules to optimise process, time consumption and costs. Outside production and manufacturing industry, however, the modular perspective may be difficult to reduce all the way down to a level of operationalisation. The literature on modularity is large, wide-ranging, and difficult to absorb (MacDuffie, 2013). However, studies in industrial and operations management suggest that the concept of modularity recurs as a relevant analytical tool in several research communities, such as computer engineering, production engineering, and automotive engineering (Ulrich & Tung, 1991; Baldwin & Clark, 1997; Fixson, 2006; Ericsson & Erixon, 1999; MacDuffie, 2013).

A review of the recent literature on modularity reveals a consistent focus on product. Fixson (2007) includes 168 references in the field of modularity and commonality. Campagnolo and Camuffo (2009) investigate 125 studies in the area of modularity. Both reviews agree on the lack of understanding of the interrelations between product, product system, and organisation modularity as seen in Figure 13 (Campagnolo & Camuffo, 2009). In general, the studies are biased towards the product, favouring the product as the decisive factor. Even researchers such as Ericsson and Erixon (1999), Sosa et al. (2004), and Campagnolo & Camuffo (2009) who take organisational and process modularity into consideration argue that these must follow the product architecture.

Figure 13. Distribution of articles about modularity in different domains based on the work of Campagnolo and Camuffo (2009).

To help understand the different perspectives of parties involved in the process, a particularly relevant classification of modularity is put forward by Baldwin and Clark (2000). They differentiate Modularity-in-Production (MIP) from Modularity-in-Design (MID) and Modularity-in-Use (MIU). A product designed and produced according to MIP may not satisfy the other approaches (Baldwin & Clark, 2000).

To illustrate, the modules designed for enabling parallel development in design may not be suitable for component economies of scale important at production stage A logical division of modules in production may not be preferred for users who prioritise upgradability. According to MacDuffie (2013), it may be possible that a given modular boundary and interface specification successfully satisfies both MID and MIP, but often these two objectives need different specifications, presenting trade-offs and requiring prioritisation. The classification of modularity into different parties' perspectives helps us understand the importance of a process view of modularity because the world we are living in is dynamic and in continuous change. The different requirements in different phases are elaborated in more depth in section 3.3.3.2 under process modularity. Moreover, as will be argued, the gaps in the application of modularity in construction may be due to an excess focus on the producer's perspective.

3.3.1.1 System perspective

Seen from a system perspective, modularity is a continuum describing the degree to which a system's components may be separated and recombined (Schilling, 2000). Langlois (2002) supplements Simon's (1962) descriptions by emphasising the ability of the product to decompose into modules. A module is an element of a complex system. To bring the definition to an extreme end, Langlois (2002) focuses on decomposing the complexity of a product into fully separable components, such that each component can be developed independently without necessary coordination with other components. This definition also helps us visualise modularity in construction as the bringing together of separate and independent modules into a complex final product, the building. Moreover, according to Langlois, a complex system composed of smaller subsystems can be managed independently yet function together as a whole by means of modularity.

3.3.1.2 Technical perspective

The system perspective is adapted to the production systems by Ulrich and Tung (1991) who present a standardised architecture consisting of modules in a hierarchy. Ulrich and Tung thereby adopt an engineering perspective that differentiates itself from the system perspective by focusing on the product modularity. From this technical perspective in order to attain modularity Ulrich and Tung (1991), focus on the similarities that should ideally exist in functional and physical design while having a minimum of interactions between components.

Ulrich and Tung (1991) take their starting point in the interchangeability of modular components and then move on to emphasise that the number of interactions between them must be minimised. This independency can be obtained by functional design. This definition is useful in understanding modularity in a building construction context. To illustrate with two examples, at product level building components are built separately in different locations, but these components are still compatible with each other in different building projects. Again, at process level-clusters of activities during the design phase deliver inputs to other design activity clusters.

3.3.1.3 Design perspective

From a design perspective, the modularity as a design principle is applied for production systems through the concepts of architecture, interfaces, and standards (Baldwin & Clark, 1997). The architecture provides the basic platform for how the hierarchy among modules is structured while the interfaces define relations between the modules and prescribed standards. According to Baldwin and Clark (1997, p.183), 'the act of splitting a complex engineering system into modules multiplies the valuable design options in the system'. By enabling parallel work, modularisation decisions can be made at the individual modules level rather than a central one. The newly decentralised system works through 'modular clusters' in the computer industry (Baldwin & Clark, 2006). Compatibility of the modules created by modular clusters is ensured by 'design rules' that define 'the architecture, that is what its modules are, the interfaces, i.e., how the modules interact and the specifying tests' which proves the modules follow the standards and work well as individual as well as with other modules in the architecture.

Finally, modularity is the starting point theory of some other concepts such as product configuration and mass customisation. According to Pine (1993), the writer of the book '*Mass Customization*', modularity is supposed to provide the customer with almost endless opportunities to customize his product. Mass customisation can be defined as producing goods and services to meet the customer's individual needs with near mass production efficiency (Tseng & Jiao, 2001) by 'effectively postponing the task of differentiating a product for a specific customer until the latest possible point in the supply network' (Chase et al., 2006, p.419).

The idea of mass customization is driven by the insight that a customer does not necessarily wants product variety per se but rather her or his own version of a product, and that the production of the individualized product at near-mass production costs can be achieved via product modularity Pine (1993).

3.3.2 Modularity in different industries

In many fields, modularity is a key principle to deal with the design and production of increasingly complex technology (Langlois, 2002). The meaning of the term modularity, its definition and, more importantly, the value it is ascribed differ from discipline to discipline. In this section, different examples will demonstrate the successful application of modularity in areas and industries other than construction. The documented benefits of modularity, such as harnessing unparalleled innovation rates (Baldwin and Clark, 2000), enabling large product variety production at low cost (O`Grady, 1999), and enabling faster product development (Thomke and Reinertsen, 1998), in other fields as various as biology, psychology, art and mathematics (Schilling, 2002) help us to get an idea about the potential benefits of applying modularity in the construction industry. In the following part, the application of modularity in some of the selected industries will be summarised.

3.3.2.1 Toy industry

Clearly, the perfect example to illustrate modularity in real life is Lego. Arguably, the most well-known Danish contribution to mankind, the word Lego originates from the Danish words 'leg godt' ('play good'). All Lego bricks are compatible with each other not only across different sets but also across generations and types. Although Lego bricks experienced changes over time, as can be seen in Figure 14, they can still be set together. According to Lego group all lego bricks made after 1985 are fully compatible regardless of the year and place of production (Lego, 2016). This feature exemplifies the full module swapping between models and generations of products introduced by Ericsson and Erixon (1999). Moreover, the constructs that can be created are endless.

Figure 14. Lego bricks (LEGO, 2016).

3.3.2.2Computer industry

The computer industry has dramatically increased its rate of innovation by adopting modular design (Baldwin & Clark, 1997). Different parts of the computer, designed to perform different functions, could be developed separately as shown in the Figure 15. Yet again, Baldwin and Clark (1997) studied modularity as a way to manage complexity, enable parallel work, and accommodate future uncertainty. They investigate the impact of design modularity in computer systems in companies, with figures showing the links between modular design applications and competitive advantages gained (Baldwin & Clark, 2006).

Figure 15. Computer parts separated into modules (IBM, 2016).

3.3.2.3Automotive industry

Similarly to the computer industry, modularity finds a great application area in the automotive industry. Starting with the mass production kick-off with 1915 Ford model T that ‘put America on wheels’ as shown in Figure 16 on the left hand side, automative industry has shown continuos productiviy improvement through decades. Volkswagen group adopted a modular strategy based on a platform strategy as presented in Figure 16. By implementing modular assembly kit synergies within all vehicle classes are maximised. Several car models within the Volkswagen group use common components such as Polo, Audi A3 and Golf bringing flexibility to all levels of production. MacDuffie investigates the implementation of modularity in the automotive industry not only in the production process but also in supply chains (MacDuffie, 2013). A long journey to use sub-producers starts with car seats and grows to a level of mega suppliers performing not only the production but also the design and development for world-known car brands such as VW, Mercedes-Benz, and GM (MacDuffie, 2013). Moreover, Zirpoli and Camuffo (2009) investigate organisational level vertical inter-company relationships in the dynamics of knowledge partitioning, coordination, and integration.

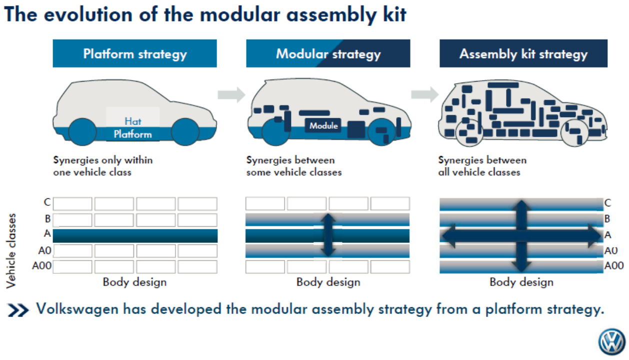


Figure 16. Ford 2015 T model (horseless carriage) Photo taken by the author Pedersen Automotive Museum, Los Angeles visited on 10 February 2016 on the left and Volkswagen evolution of the modular assembly kit (Volkswagen, 2016) on the right.

3.3.2.4Manufacturing Industry

As an umbrella industry covering many products and product platforms, manufacturing industry supply to several other industries, including the ones mentioned above. In their work on the drivers of modularisation in implementation of modular product platforms, Ericsson and Erixon (1999) developed a matrix to identify the degree of modularity in production systems, and describe their Modular Function Deployment method. This approach achieved the best rating result in a case study conducted by Bauer et al. (2014), which compared 12 methods of modular platform design. The degree of modularity in product platforms is a measure showing the success of modularity application in the study undertaken by Hölttä-Otto and de Weck (2007). They study a great variety of final products of different product platforms, such as cell phone, desk phone, jet engine, laptop, desktop, etc.

3.3.2.5Sub-summary

Together these studies in different industries show how modularity as a method is applied differently. Before moving on to modularity in construction and its possible ways of application there, I wish to direct attention to the different domains of modularity. There may be advantages in thinking about the levels of product, process and organisation domains in a more comprehensive manner. Modularity is a good tool for doing that. Fixson (2007, p.32) argues that, ‘the increasing interconnectedness of people, products, processes, and organizations, and the increasing degrees of product customization will continue to make the questions concerning modularity and commonality an interesting field of research that can be both rigorous and relevant’. Along the lines of these perspectives, I adopt the comprehensive management approach by Campagnolo and Camuffo (2009) in this study, taking up the challenge of analysing of how modularity may affect the simultaneous design of products, production systems, and organisations..

3.3.3 Modularity in different domains

Taking a managerial approach, product, process, and organisational elements should be treated as equal entities (Campagnolo & Camuffo, 2009). Fixson (2007, p.31) argues that modularity is mostly studied in static situations: 'In reality, however, no system is really static. Products change, processes evolve, organizations adapt, and innovations appear, and all of these changes are accelerating'. In order to incorporate the element of change and movement, one could paraphrase Fixon's dynamic approach to the elements of production as to:

- What is produced or delivered (product or service or experience)
- How is it produced or delivered (process or practice or tool)
- Who is producing or delivering it (organization or practice or institutional)

Baldwin and Clark (2000) remind us of the importance of including the considerations of all parties involved. In this study, I especially seek to demonstrate how including these parties will force aspects, such as process, and organisation rather than the product alone, to be considered.

3.3.3.1 Product modularity

In general, most of the studies about modularity are biased towards the product, favouring the product as the decisive factor and ignoring other dimensions of modularity, such as process and organisation. This tendency is clear because researchers like Ericsson and Erixon (1999), Sosa et al. (2004), and Campagnolo and Camuffo (2009) all claim that the organisational and process modularity should follow the product architecture.

The architecture of a product can be understood as the combination of subsystems and interfaces. The architecture of any product can therefore be more or less modular or integral (Meyer & Lehnerd, 1997). An integral product includes components that perform many functions, are in close proximity or close spatial relationship to each other, and are highly synchronised. Normally, a change made to one component requires a change to other components for a correct functioning of the total product. In contrast, in modular product architecture, components are interchangeable, autonomous, loosely coupled, individually upgradeable, and interfaces are standardised (Fine, 1998).

To enable an understanding on the range of product design possibilities Ulrich and Tung (1991) define the following product designs:

- Component-swapping modularity advocating swapping different components for the same basic product
- Component-sharing modularity meaning that the same components are shared between a series of basic products

The two points can be mixed endlessly. To obtain the component sharing is more difficult but obviously the gains are also great as many products will share the same already developed and proven component.

The extended research of modularity literature conducted by Campagnolo and Camuffo (2009) describe product modularity as a functional perspective based on Ulrich and Tung's writings. Campagnolo and Camuffo (2009) identify further two more perspectives: lifecycle perspective and mixed perspective. They claim that in order to apply a successful functional perspective, the other perspectives must be considered as well (Campagnolo & Camuffo, 2009). The three perspectives will be described in the following sections.

Functional perspective

The first category includes studies on product design modularity from the point of view of technical architecture: the functional perspective. Product architecture may be defined as follows (Ulrich, 1995):

1. The arrangement of functional elements
2. The mapping from functional elements to physical components
3. The specification of the interfaces interacting between physical components.

The three specifications enable a distinction between modular and integral product architectures. Ulrich (1995, p.121) states further that modular architectures imply 'a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components'. Whereas integral architectures are characterised by a different mapping (one-to-many or many-to-one) and/or by tight and complex coupling between physical parts.

The flexibility of a modular architecture stems from its ability to substitute different modules without having to redesign other components (Campagnolo & Camuffo, 2009). A functional perspective is technically oriented—it focuses on components, functions, and interactions. Fixson (2007) makes clear the ability to modularise the product in the early design phase for the required functionality. Fixson (2007) states that the functional structure can be applied in the beginning of the product design, where the design involves puzzling with modules to enable the required functionality of the product. This is a very useful perspective to consider when improving productivity at product level.

Lifecycle perspective

A second perspective to consider concerns on product design modularity from development to retirement is the lifecycle perspective. The lifecycle perspective consists of Design/Development, Production, Use/Operation, and Retirement (Campagnolo & Camuffo, 2009). Each of the phases entails a set of objectives, which can be seen exemplified in Table 4 (Campagnolo & Camuffo, 2009).

Table 4 shows the different life-cycle phases—the objective, methods and measures associated with modular design. The life-cycle perspective emphasises it is the company´s decision of objectives, which determines the products modularity and thus makes diverse modular design possible (Campagnolo & Camuffo, 2009). 'Consequently, product modularity must be guided by clearly stated goals, which in turn affect product modularity definition and how to modularise. Indeed, a modular design can vary according to a specific objective and timing of product development' (Campagnolo & Camuffo, 2009, p.266). This perspective does not like the previous functional perspective take into account the static functionality; instead it focuses on the entire lifespan of the product.

Table 4. Product design modularity and the life-cycle view (Campagnolo & Camuffo, 2009)

Life-cycle phase	Product design modularity objectives	Modularity methods (examples)	Modularity measures (examples)
Design Development	Design for Design	Increasing models reusability across subsequent product generation	No. of modules shared across subsequent generations
	Design for time-to-market	Increasing modules reusability within model range	No. of modules shared within model range
Production	Design for manufacturing	Reducing cycle time of manufacturing process	Reduction of cycle time
	Design for purchasing	Reducing purchasing costs	No. of outsourced modules
	Design for assembly	Reducing fixing points and using plug-and-play interfaces	No. of assembling operations
	Design for testability	Reducing test time and cost	No. of pre-tested modules used in the assembly line
	Design for logistics	Making physical transportation easier	Reduction of the storage space and costs
Use Operation	Design for usability	Making the product usable independently from each single module	No. of modules necessary for product to perform core functions
	Design for serviceability	Making subsequent versions of the same product compatible and upgradable	No. of powerful versions compatible with each other
	Design for reparability	Reducing recovery time	No. of operations for detecting failures
Retirement	Design for environment	Reducing variety of inputs used in the same module	No. of diverse input used in each module
	Design for disassembly	Increasing ease of disassembly	No. of operations for product dismantling
	Design for material recycling	Reducing recycling methods	No. of recycling methods for each module

The mixed perspective

The third category combines the two previous points of view, considering the product architecture, functionality and the lifespan perspective: the mixed perspective.

The mixed perspective described in Campagnolo and Camuffo's (2009) research is a methodology that mixes up the product architecture and the life-cycle. They relate it to Baldwin and Clark's (1997, p.86) modularity strategy and argue that modularity is 'a strategy for organising complex products and processes efficiently' achieved by dividing design parameters into three 'visible design rules' (Baldwin & Clark, 1997):

- Architecture: It specifies the structure of the system. This includes specifying modules included in the system and also what functionality these apply to the system.

- Interfaces: These are the interactions between modules. By defining these in detail, modules can interact physically and functionally, which includes physical joining, connections, and communication.

- Standards: These involve testing conformity of the modules to the system and associated design rules. Standards are also applied for testing modules according to equivalent modules (Baldwin & Clark, 1997, p.86).

Here the idea of interfaces deserves elaboration because the concept of modular design is to create interfaces that will work as fences between modules. Interfaces are hidden shortcomings of modularity (Smith, 2008).

> A well-defined module, in terms of simple interfaces, can ease project management due to decoupling of tasks and providing design freedom within a module. Modularity also makes complex product architecture appear simpler and therefore easier to manage (Hölttä-Otto & de Weck, 2007, p.115).

Independent modules communicate with each other through interfaces. Therefore, interfaces have vital importance when different modules come together to perform together. Moreover, the designed system interacts with the outside world again through interfaces. User interfaces in computers are good examples, which show how the user and the computer interact, for example, through keyboard, touchscreen, or even mouse.

Ericsson and Erixon (1999) help us by making tangible the positive effects of applying the modular product designs perspective (including the above-mentioned). A properly used modularisation has the following drivers (Ericsson & Erixon, 1999):

- higher flexibility-product changes, due to market or new technology, can be made more easily since they will only influence limited parts of the product
- reduction of product development lead time-parallel development activities are possible once the interfaces between the modules have been defined
- parallel development of the product and production development can be translated into production plans for each module
- reduction of production lead time-parallel manufacturing of modules instead of manufacturing an entire product in a single sequence
- less capital tied up in production-work-in-progress is reduced due to shortened lead times, less stock maintenance of ready-made products
- reduced material and purchase costs-the reduction of part numbers means less to purchase and less to administrate, and higher volumes per part number
- improved quality-modules tested before final assembly have shorter feedback links, allowing easier adjustments
- easier service and upgrading-standardised interfaces make adding or replacing a module easy

- easier administration-quoting, planning, and designing customised products can be done more efficiently

Furthermore, Ulrich (1995) investigates many advantages of modularity together with the disadvantages of technical constraints in the product design. He argues that there is a trade off between modular and integral designs with respect to local performance characteristics and global performance. In some cases where weight and size constraints exist, integral architecture might be a better solution (Ulrich, 1995).

The material on positive outcomes of applying modularity on product level is extensive and convincing. References become somewhat scarcer on the next level: Process Modularity.

3.3.3.2 Process modularity

In relation to the faces of the Complexity Cube in Figure 12, process modularity relates to the underlying processes for a given product. Campagnolo and Camuffo (2009) argue that a modular product must have an underlying predefined modular process. Similarly, the Swedish duo, Ericsson and Erixon (1999) describe the symmetry between product and process as having to be a predefined goal when designing the product architecture.

'Future work should try to understand better the dual-role of engineering products and processes as decision variables on one hand and constraints on the other' Fixson (2007, p.31) says.

Another approach to process modularity is outsourcing products and their underlying processes rather than doing everything in-house. In this way the organisation can focus on core activities creating more immediate value. Such an initiative requires cautious management of the output from the given organisation. Campagnolo and Camuffo (2009) explain how outsourcing can lead to modular product architecture, simultaneous with an outsourcing process. Sako (2003) outlines the three different paths towards module outsourcing—acd, abd, ad—illustrated in Figure 17.

In the first path (acd), the company defines modular product architecture before outsourcing one or more modules. In other words, by following the first path (acd), a firm competes as an 'architect', creating visible information and attracting module designers to its design rules (Sako, 2003)—equivalent with Baldwin and Clark's literature (design rules). In the second path (abd), the firm starts to outsource some product components before moving towards a modular design. For a firm operating in a mature industry, however, the second path (abd) appears more likely, because firms have probably already started to outsource some product components (or activities) to achieve efficiency in the manufacturing and assembly phases. In the third path (ad), the firm simultaneously implements product modularity and outsourcing (Campagnolo & Camuffo, 2009).

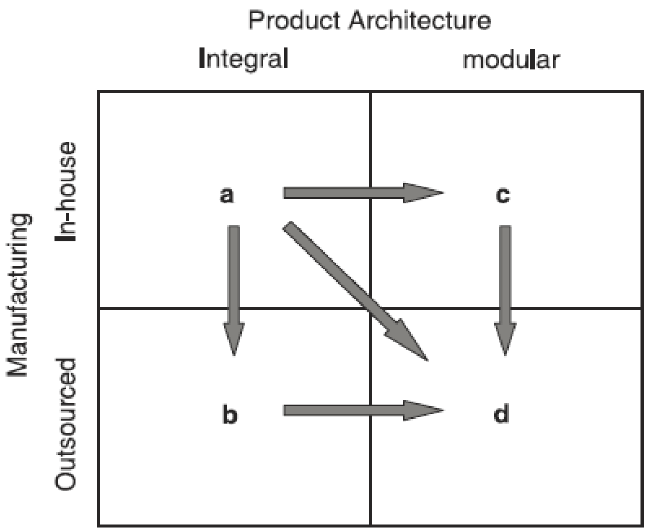


Figure 17. Paths towards module outsourcing (Sako, 2003).

The second and third path (abd and ad, respectively) appear to involve higher risks in terms of choosing in-house capabilities and control, because of the role played by suppliers who are both architect and module maker. Following this rationale and relying on external providers for design, engineering, and production, the outsourcing firm may be forced to base its competitive advantage in other complementary value chain activities. The outsourcing also is irreversible because the firm has lost its system integration capabilities (Campagnolo & Camuffo, 2009).

The research shows that the right path to follow the outsourcing strategy is highly dependent on various conditions, such as the specific attributes of the product, industry maturity, firm strategy, firm capabilities, and the task itself (Campagnolo & Camuffo, 2009). Therefore, there is no one-size-fits-all recipe.

Campagnolo and Camuffo (2009) believe that different trajectories can lead to different modular architectures, even for the same product, in terms of module boundaries and interfaces. This can be illustrated. For example, in case an in-house strategy is preferred for the production of a laptop the final product will look different than if the production had been outsourced.

In a multiple case study focusing on the construction industry, Voordijk et al. (2006) claim that, in addition to the above-mentioned architectures, modular boundaries, and interfaces, two more process dimensions need to be coupled: time and space. They state that the construction process and its possible modularisation are dependent on the geographical conditions and capabilities of the companies involved and, furthermore, on the changing requirements of the product according to the particular needs in different phases: production, transportation, and final usage alternatives (Voordijk et al., 2006).

3.3.3.3 Organisational modularity

Goffman (1961, p.176) defined a formal organisation as a ‘system of purposively coordinated activities designed to produce some overall explicit ends, products such as material artefacts, decisions, or information'. Organisations are abstract entities, but organising is a relational process of co-participants, and when these organising processes come into contact with the hierarchical aspects of organisations, there may be conflict. Those in command segments can create limits by setting rules and procedures (Manning, 2008).

In relation to the faces of the Complexity Cube presented in Figure 12, organisational modularity relates to the process modularity as organisation units perform the underlying process for a given product. For example, it matters for the process whether the organisation is top-down hierarchically managed or flatly structured. Also, and as mentioned in the section above, outsourcing is highly related to organisational modularity as the process and the product are outsourced to another organisation.

According to Campagnolo and Camuffo (2009) and their extended literature review, they distinguish between 'product architecture - organizational architecture' and 'organizational design architecture'. They explain that integral products should be supported by integral organisations (tightly connected to reduce risk of opportunism and increase communication) and modular products should have an underlying organisation that is loosely coupled, easily reconfigurable and autonomous (Campagnolo & Camuffo, 2009). They further state that product modularity reduces the need for communication of hidden information—as the knowledge within the module does not need to be shared. The modular organisation operates more as a network rather than hierarchy (Campagnolo & Camuffo, 2009). This is an advantage in terms of making fast decisions and producing with high speed—that is, increasing productivity.

Modularity in the supply chain is an important aspect to consider when investigating construction projects. The following section describes this attribute and the literature pertaining to it. Voordijk et al. (2006, p.601) elaborate on Fine (1998, 2000) who claims that the degree of modularity in the 'final output product has a one-to-one correspondence with the degree of modularity in the transformation processes and supply chains'. This claim is a direct consequence of the addition of a third perspective on modularity, namely, that of 'supply chain modularity'.

The supply chain concerns not only the internal organisational structure but also the positioning of all involved organisations in relation to each other. Therefore, the supply chain is considered not a separate section but it is treated under organisation or process, depending on the context.

Fine (1998) argues that product, process, and supply chain architectures tend to be aligned along the integral-modular spectrum. That is, integral products tend to be developed and built by integral processes and supply chains, whereas modular products tend to be designed and built by modular processes and supply chains (Fine, 1998). Product, process, and organisation are all modular or they are all integral.

However, there may be a risk of modular organisational units becoming too isolated and thereby alienated from one another. Russel and Taylor (2009) elaborate on some key activities to enable an effective supply chain management: information, communication, cooperation, and trust. They add that suppliers and customers must have the same goal (Russell & Taylor, 2009). It is important that organisations and their units keep in sync with each other.

A similar challenge is anticipated by Alter (2006) who explains how each major step in the value chain can be viewed as a system. Alter (2006) further describes the need for integration between participants in five different levels: common culture (ease communication), common standards (ease maintenance), information sharing (transparency), coordination (feasible plan), and collaboration (performance). Alter (2006) further explains that lack of integration causes extra work and delays because pertinent information or knowledge from another work system is not accessible.

Ericsson and Erixon (1999) identify one of the important modularity drivers as the availability of suppliers. Instead of producing in-house, some subsystems in the product may be suitable for purchase as standard modules from vendors. This black box engineering implies that the vendor takes the manufacture, development, and quality responsibility. For these modules, a traditional make-or-buy analysis must be carried out and should address these questions:

- Are there strategic reasons why the technology should be kept in-house?
- Have we enough resources to develop and produce this module today and in the future?
- Is there any vendor offering the subsystem as a standard module today? (Ericsson & Erixon, 1999)

Salvador et al. (2003) add that a modular supply chain consists of 'geographically dispersed actors, each one characterized by autonomous managerial and ownership structures, diverse cultures and low electronic connectivity' (Salvador et al., 2003, p.3).

3.3.4 Modularity in construction

The examples above suggest that many sectors could benefit from adopting modularisation. In the following section, the understanding of modularity in the building construction industry is outlined. Different classification systems and some examples of modularity applications are presented.

Fine (1998) describes the evolutionary development of product, process, and supply chain in the computer industry and claims the same lifecycle can be adopted in other industries. Despite successful applications in other sectors, and the growing interest in modularity, it has limited use in the construction industry and has mostly been associated with efforts of industrialised construction (Gibb, 1999; Pan, 2007; Jonsson & Rudberg, 2014).

A clarification of terms is necessary. The discussion of modularity in the literature so far has proceeded without much clarity of terms. In the construction industry, the implementation of modularity theory is unfortunately more or less reduced to product level only and regarded as synonymous with prefabrication, off-site fabrication, off-site production, and pre-assembly. In the literature covering off-site construction, the terms off-site construction, prefabrication, and Modern Methods of Construction often appear interchangeably. An effort has been made by Gibb (1999) to define the terms, such as off-site fabrication, off-site, prefabrication, pre-assembly and modularisation as part of a broad spectrum. I believe that spectrum can be understood and developed further by placing it within the right theoretical background.

In general, Gibb (1999) describes offsite technologies as moving work from the construction site to the factory. Here, though, modularity is seen as a much broader strategy to address the problems of productivity in the industry. Not only the physical location of products is concerned, but also elements of process and organisation.

When trying to understand and interpret the discourse concerning modularity in construction, two interrelated problems appear. First, there are the distinctions of the terms arising from different concepts and production approaches. For example, off-site construction and preassembly are two different terms based on the production location. Second, there is the issue of how far distinctions arise from variations in the eyes of the observers. The bad reputation of prefabricated buildings is the reason for using the terms interchangeably. Therefore, some researchers and industry players deliberately avoid using the term prefabrication or off-site building. One good example of that phenomenon is the UK government describing a number of innovations in house building as 'Modern Methods of Construction' (MMC) (Pan et al., 2007).

The Construction Industry Institute (CII) (CII, 2002), a joint academic-industrial institution based at The University of Texas, defines these terms as the following:

Prefabrication: a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of a final installation. Prefabricated components often involve the work of a single craft.

Preassembly: a process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a sub-unit; generally focused on a system.

Off-site fabrication: the practice of preassembly or fabrication of components both offsite and onsite at a location other than the final installation location.

Module: a major section of a plant resulting from a series of remote assembly operations and may include portions of many systems; usually the largest transportable unit or component of a facility.

As the above definitions are so close to each other, it is not surprising that prefabrication, offsite, and pre-assembly are used together and often mixed. The later definitions made by researchers do not differ radically from the definitions presented by CII (2002) but vary mainly in the importance given to the manufacturing process or the location of the production. For instance, Ballard and Arbullu (2004) focus on the location. They define prefabrication as the production that is performed outside of the construction area in a temporary or more permanent workshop (Ballard & Arbullu, 2004).

Figure 18. Top left: Component manufacture and sub-assembly Zorlu Center Project Istanbul, 2009; top right: Non-volumetric pre-assembly DTU Life Science Building 2014; bottom left: Volumetric pre-assembly, Mortenson Construction, Saint joseph Hospital in Denver, Colorado, bathroom pod, from Modular Building Institute, and bottom right: Modular building, Scandi Byg from Licitationen 3 August 2016.

In comparison to the above-mentioned definitions, the classification made by Gibb (2001) is more tangible as it identifies four degrees of off-site construction:

- Component manufacture and sub-assembly: The traditional approach in construction. Raw materials and components are used to build o site.

- Non-volumetric pre-assembly: In this concept, ‘two-dimensional’ elements are prefabricated offsite and assembled onsite.

- Volumetric pre-assembly: Volumes of specific parts in the building are produced offsite, and assembled onsite within an independent structural frame.
- Modular building: In this concept, much of the production is carried out offsite, with modules fabricated to a high level of completion. The only work performed onsite is the assembly of the modules and finishing operations.

Finally, Voordijk et al. (2006) specifically use the term ‘modular solutions’ and classify modular solutions in construction into three categories: (1) modular, (2) integral, and a combination of these two, (3) hybrid. Moreover, Voordijk et al. (2006) build on Fine's (1998) three-dimensional modularity concept of product, process, and supply chain modularity.

A construction project involves several players/organisation within the same project (Bertelsen, 2003). Defining and coordinating these and their activities is a complex task, which currently lacks supply chain management and a general overview (Pinho et al., 2008). Salvador et al. (2002) have the same point, as they state that research that combines modularity with concepts from supply chain management is an emerging area. Moreover, an increase in competition within construction projects and a growing demand for variety are major drivers for the construction industry to consider new supply chain design (Voordijk et al., 2006). They argue that the construction industry should try to benefit from mass production by adopting the concept of modularity. That is, there is increasing interest and focus on a more modular approach to the organisational level, as well.

Table 5. Effects of modularity in literature review

References in the Literature / Effects of Modularity	Gibb (2001)	Blismas et al. (2006)	Pan et al. (2007)	Jaillon and Poon (2008)	Jonsson and Rudberg (2014)	Ulrich and Tung (1991)	Ericsson and Erixon (1999)	Fixson (2006)
Cost	X	X	X	X	X			
Logistics					X			X
Health & Safety	X	X	X	X	X			
Quality	X	X		X	X	X		
Common Unit							X	
Carryover							X	X
Separate Testing						X	X	X
Service/ Maintenance						X	X	X
Recycling	X			X	X	X	X	X
Time		X	X	X	X	X		X
Productivity	X	X	X	X	X			
Customisation/ Styling						X	X	
Supplier Available							X	X
Design Flexibility	X	X	X	X	X	X	X	
High volumes			X	X	X	X		
Organisation		X	X	X	X		X	
Process							X	

Going through all these different theoretic approaches to modularity in construction one finds a considerable bias towards the product. Although studies of modularity in supply chain (Voordijk et al., 2006) and process (Thuesen & Hvam, 2011, Bonelli & Guerra, 2012) exist, disproportional attention is allocated to the product.

Ulrich and Tung (1991), Ericsson and Erixon, (1999) and Fixson (2006) have studied the drivers of and barriers of modularity, covering product platform development and design. Similarly, in the construction industry, Gibb (2001), Blismas et al. (2006), Pan (2007), Jaillon and Poon (2008), and Jonsson and Rudberg (2014) have treated the drivers and barriers in the context of offsite construction and production systems in construction. The effects of modularity reported by these authors can be seen in Table 5. Although they concentrate on different drivers and barriers of modularity in different industries, they all tend to see the application of modularity from the product or product's or producer's perspective.

So, as readily pointed out by Fixson (2007) and Campagnolo and Camuffo (2009), there is a gap in the literature when it comes to studying modularity, not only from product perspective. Also, in their extensive literature review, Campagnolo and Camuffo (2009) do not take modularity within construction into consideration. In this thesis, I attempt to fill in part of these gaps by focusing on repetition and standardisation at all levels in building construction. The next section pursues strategies towards modularity by investigating standardisation and repetition.

3.3.5 Strategies towards Modularity

3.3.5.1Degree of Modularity

The degree of modularity is an important concept for describing the correct placement of a product, process or organisation in the modular-integral spectrum. Compagnolo and Camuffo (2009) argue that every system is modular to some extent. They believe that in order to adopt strategies such as repetition, standardisation and interfaces between modules we need to describe where we are at each level.

According to Campagnolo and Camuffo (2009) the degree of modularity depends on:

The type of system under analysis
- The unit of analysis
- The point in the lifecycle, as modularity is also a design principle

Taking product architecture as a unit of analysis, Ericsson and Erixon (1999) describe how product architecture can be treated on three levels: the product range level, product level, and component level. According to the Swedish writers, measures to reduce complexity affect the three levels of modularity exponentially (Ericsson & Erixon, 1999). This means that if the right design decisions are made at the higher level affecting several product ranges the potential benefits of modularity are much greater (Ericsson & Erixon, 1999).

According to the Figure 19, the standardisation of components is the first step. The benefits of applying modularity grow exponentially by using standardised components in products and further in product ranges. Therefore, in the next subsection, standardisation will be elaborated as a primary strategy towards modularity.

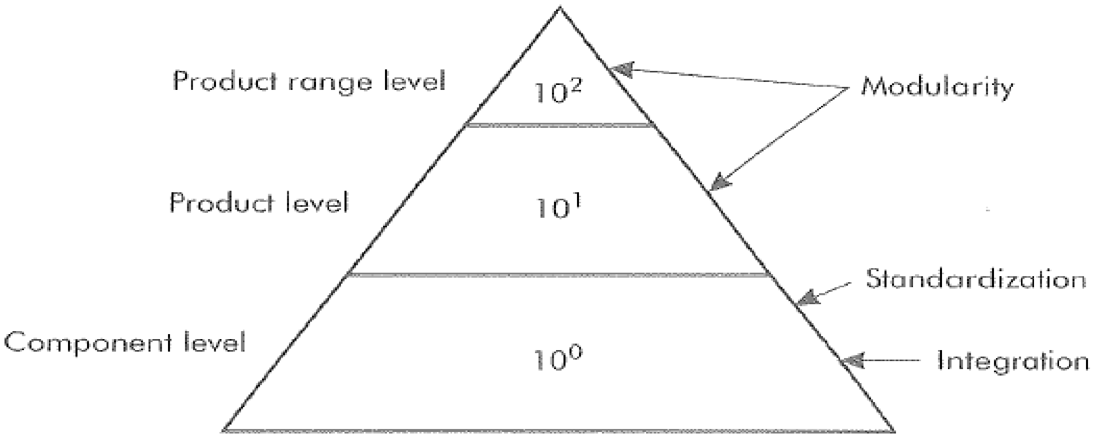


Figure 19. The three levels of product architecture and its exponential growth (Ericsson & Erixon, 1999).

3.3.5.2Standardisation

A clear way to deal with the complexity of construction is to make greater use of standardised components. The benefits of standardisation are listed by Egan as reductions in manufacturing costs; fewer interface and tolerance problems; shorter construction periods; and more efficient research and development of components (Egan, 1998).

Furthermore, standardising and modularising components can save costs and time. This also improves lifecycle costs, because spare parts can be used across assets. 'The use of standard designs should be considered on a case-by-case basis, taking into account local conditions or the latest technologies, to avoid using suboptimal design' (Changali et al., 2015, p.6)

Baldwin and Clark (2006) define standards as design rules fixed and communicated ahead of time, and not changed along the way. Standards are essential for the modules to be swapped and shared as they define rules for modules and interfaces. Lack of standard solutions for construction projects is identified as a reason preventing the construction industry from achieving higher productivity (Thuesen, 2012)

Product

In the construction industry, Gibb (2001) claims that the accuracy and interchangeability of components play a decisive role on the way to standardisation. Therefore, the interfaces between the components, more than the components themselves, are the most important point to be considered to achieve standardisation.

The final customer may prioritise the value associated with the uniqueness of a facility, but using unique materials increases system complexity, making it more challenging to manage (Tommelein, 2006). The use of standard products or components shortens lead times, improves quality and eases operations at the construction stage (Pasquire & Gibb, 2002). However, the use of standard products must match the production system design; otherwise, the incorporation of standard products may harm the flexibility of the production process (Jonsson & Rudberg, 2015).

In a recent case study conducted in Denmark, Kudsk (2013) shows that substantial benefits can be gained through implementing modularised construction. It is especially interesting to note that these benefits are achieved through the development of a module with a focus on the interfaces in the examples of configured balconies and standardised shaft (Kudsk, 2013).

Similarly, in construction industry, standardisation stands for the use of components, methods or processes enabling regularity, repetition, and background of best practices and predictability (Gibb, 2001). Standardisation can be illustrated by an example from the building industry. The use of standard formwork has the following advantages (Oberlender & Peurifoy, 2011) over custom-built formwork:

- Simple installation that can be performed even by low-skilled workers
- Reduced erection time
- Higher number of reuses that leads to reduced overall costs of equipment
- Improved safety for the labour force
- Better quality concrete surfaces which reduces further finishing work
- Automation of formwork operations and improved productivity

Process

According to Toyota's description 'a standard is how a process should operate. It is pre-specified, intended normal pattern' (Rother, 2010, p.113). The creation of standardised processes is based on defining, clarifying (making visual), and consistently utilising methods that will ensure the best possible results.

Focussing on especially on process, Bonelli and Guerra (2012) create a design structure matrix for the construction process to help visualise the interrelations and dependencies of activities both in the case of traditional and modular construction methods. They conclude that the success off the methods depends to a great extent on the early definition of the project design; early integration of the client and external parties and the coordination and integrated project delivery methods where all parties work for the same purpose and do not simply provide separate services.

In yet another study, by Thusen and Hvam the focus is taken away from just the product and instead directed towards the coupling between process and product. In their study the two researchers emphasise that the productivity increase comes from a platform focusing on repetition and standardisation and not necessarily from the location of the production such as moving the work to off-site (Thuesen & Hvam, 2011).

Organisation

Standardisation is driven by people, not done to people (Liker & Meier, 2006). From an organisational theory perspective, Adler (1999) undertakes an 'enabling' standardisation of bureaucracy by empowering the employees in order to avoid unintended consequences of bureaucracy.

According to Toyota outermost standardisation is actually the starting point for achieving a continuous improvement. There can be no 'kaizen' (Japanese term for improvement, changing towards better) without standardisation (Imai, 1986).

Finally, according to Liker and Meier (2006) a certain degree of stability is needed in the following areas in order to move on to standardised work.

- The work task must be repeatable.
- The line and equipment must be reliable minimising interruptions.
- Quality issues must be minimal

Therefore, repetitions will be further elaborated in the next subsection as a way to reach to the standardisation and modularisation.

3.3.5.3Repetitions

Already in the Ancient Greece 2.500 years ago the temples were built with identical columns. Moreover, 'the columns also appear to be spaced regularly, but the three at each corner are closer together than the rest and the six in the centre of the front and back are wider apart than those down the sides' (Honour & Fleming, 2009, p.130). The Parthenon shown in Figure 20 may be the most well-known structure applying optical refinements technique. However, they were used in all structures in the Ancient Greek with variations making each temple different than others (Honour & Fleming, 2009, p.130). This is wonderful example of the differentiation and personalization by still using repetitions extensively both within and across the buildings.

Figure 20. Partheon, Athens, from the north west 447-438 B.C. (Honour & Fleming, 2009, p.127.)

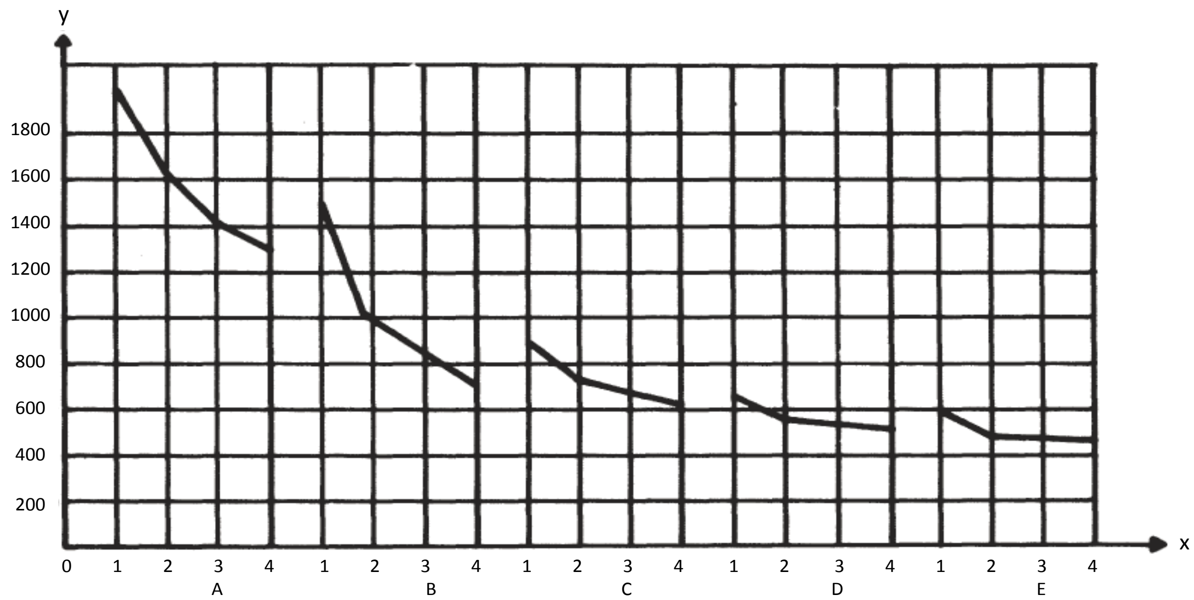
In the 18th century, Adam Smith (1776) takes repetitions as a point of departure in his book commonly known as *The Wealth of Nations* in order to master a work task. Smith highlights the division of labour, and repetition of work in order to reach a dexterity level. He states that by making this operation the sole employment of his life, necessarily increases very much the dexterity of the workman (Smith, 1776).

Back in 1965, it has been shown that substantial improvements in labour productivity and reduction of building cost can be achieved through the repetition effect in building construction (UN Committee on Housing and Planning, 1965). The cross-national study included countries from different geographical locations and different political and economic systems. The participant countries were Austria, Belgium, Bulgaria, Czechoslovakia, Denmark, Finland, Federal Republic of Germany, France, Hungary, Israel, Italy, Luxembourg, Netherlands, Poland, Spain, Sweden, Switzerland, Ukrainian Soviet Socialist Republic, Union of Soviet Socialist Republics, and the UK.

The studies vary from country to country and involve all sorts of building construction tasks, such as formwork, panel assembly, and concrete pouring. Moreover, the repetitions effect has been studied in case of identical multiple dwellings construction in the Netherlands, Czechoslovakia, Sweden, the UK, and France. In all examples, noticeably reduced man-hours could be observed varying 40-55% (UN Committee on Housing and Planning, 1965).

Furthermore, multi-story building construction has been studied to investigate the identical floors effect of a thirteen-storey building in Poland. It has been found that despite the increasing height, up to 38% reductions in total man-hours per cubic metre of concrete on each repeating storey could be measured up until 10th floor up. Similarly, studies have been made in Israel and Federal Republic of Germany with 10-storey and eight-storey buildings. The results vary in exact savings. However, they all point out the reduction of man-hour obtained through repeating floors. In another multi storey building erection in France, prefabricated slab panels assembly were recorded. It was noticed that already in the first floor a time reduction was achieved due to the large floor area from first floor panel to the last floor panel. Overall reduction in accumulated man-hours to complete one floor was drastic from 32,000 after the first floor to 5,500 when the last floor was completed.

Finally, in Finland identical multi-storey buildings have been studies with repetitions effect within and across the projects. As seen in Figure 21 it has been recorded dramatic man-hour savings up to 65% from the first storey erection of the first building to the last floor of the fifth building (UN Committee on Housing and Planning, 1965).



X: Story number
Y: Manhours
A, B, C, D, and E: First, second, third, fourth and fifth houses.
Source: Information received from the Government of Finland

Figure 21. Time consumption per storey in the erection of five identical four-storey building (Finland) (UN Committee on Housing and Planning, 1965).

In a study made in Denmark, Gottlieb and Haugbølle (2010) summarise the factors influencing the possibilities of achieving benefits of repetition:

- High complexity is conducive to learning effects.
- High work/task continuity is conducive to learning effects.
- High degree of mechanisation is detrimental for learning effects.
- Higher quantities are conducive to learning effects.

It is important to make the distinction between repetitions adding value and repetitions not adding value. The repetitions not adding value, i.e. repetitive errors, has to be identified, the reasons causing them have to be studied and thereafter avoided best as possible. Likewise, repetitions adding value should be identified and where possible transformed into best practice.

Every operation has a period of learning during which participants acquire necessary knowledge and gain the practice to perform the activity. The learning rate can depend on factors such as number of operations in one unit, activity complexity, and management (Arditi et al., 2001). Based on the statement of Arditi et al. (2001) and the examples shown above it is clear that the more operations repeat themselves the more the productivity is improved. By vitalising the effect of repetitions across the projects the learning phases causing unproductivity and time losses can be avoided or minimised. The longer the (continuous) project duration, the higher the learning effect (Gottlieb & Haugbølle 2010). So, the challenge is to think the building construction in a continuum in order to apply repetitions that will lead to modularity.

To conclude a small glossary is made in order to provide the basic understanding of the important terms as used in this thesis. The definitions presented at the end of the theory chapter are the results of the literature study covered in this literature section revisited during the different stages of DRM as a part of the iterative research process. In that way the definitions can be seen as the contribution of the overall Ph.D. study.

Glossary

Component is a smallest decomposable unit that constitutes modules. A component alone can function like a module when put together with other modules.

Interface is a set of dimensional or hierarchical rules and protocols, which define how a module communicates and interacts with other modules as well as the outside world.

Module is an optimum unit when keeping the intra-component dependencies high and inter-component dependencies low. Although the size and dimensions may vary according to the functionality and context a module must have predefined interfaces to other modules so that a module would always fit to its place and work in accordance with the other modules when put together.

Modularity is a perspective in order to find the optimum unit decomposition having the dependencies within the modules high and inter-component dependencies low between the modules.

Repetition is a product, process or organisation form that repeats with small or no variation again and again.

Standard is a pre-agreed reference point defining interfaces and tolerances in order to assure the modules to be put together, or swapped.

Standardisation is a continuum of set of rules and measures predefining interfaces and tolerance levels.

“Take a boring design and repeat it a hundred times then it becomes beautiful”

Arne Jacobsen

Danish Architect (1902-1971)

4 ANALYSIS

This chapter summarises the studies conducted in different stages, such as descriptive I, exploratory, prescriptive, and descriptive II. The relevance of each study is discussed with respect to the main research question. Then, the findings of each study are presented.

The results of the studies will be presented in the same order as presented in Chapter 2, Section 2.1. Figure 22 illustrates the overall view of the stages and amount of cases investigated under each study.

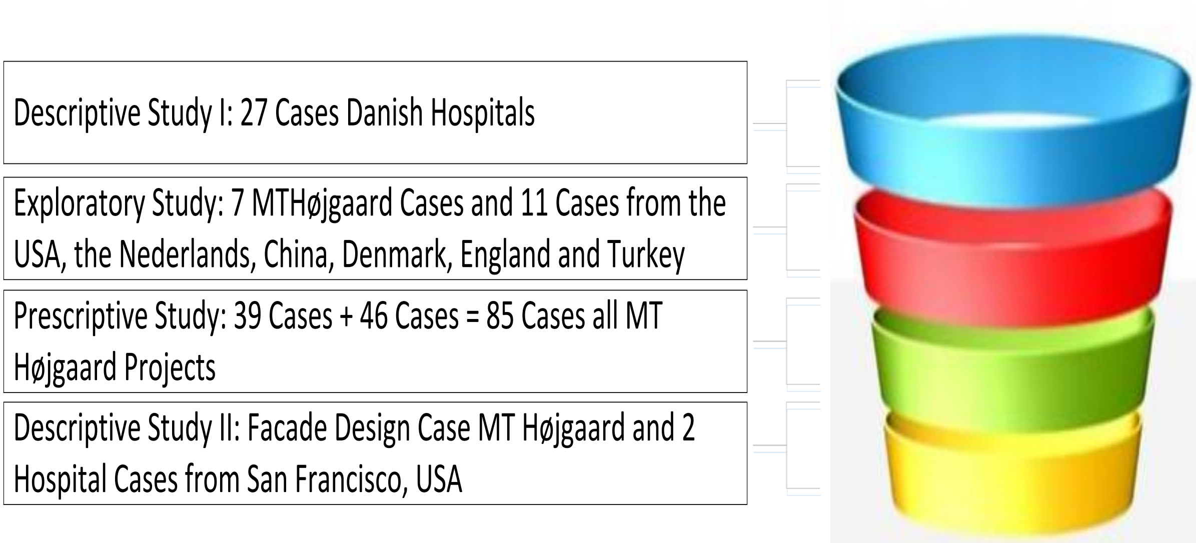


Figure 22. Stages of cases studies illustrated in order of presentation in this thesis.

The types of cases collected and analysed for this thesis may seem many and varied in depth and character. This variation, however, is intended in accordance with Flyvbjerg’s (2006) suggestions about the necessity for variation. In Figure 23, the different studies elaborated in this chapter are placed according to the case designs and unit of analysis in Yin’s (2009) two-by-two matrices. The figure serves to show how the studies used in this PhD cover the unit of analysis and number of cases. I treated the unit analysis and cases design axes as a continuous spectrum rather than presenting boxes. Therefore, different case studies are placed in the matrix with respect to each other, depending on the number of cases in each study and the type of unit analysis conducted.

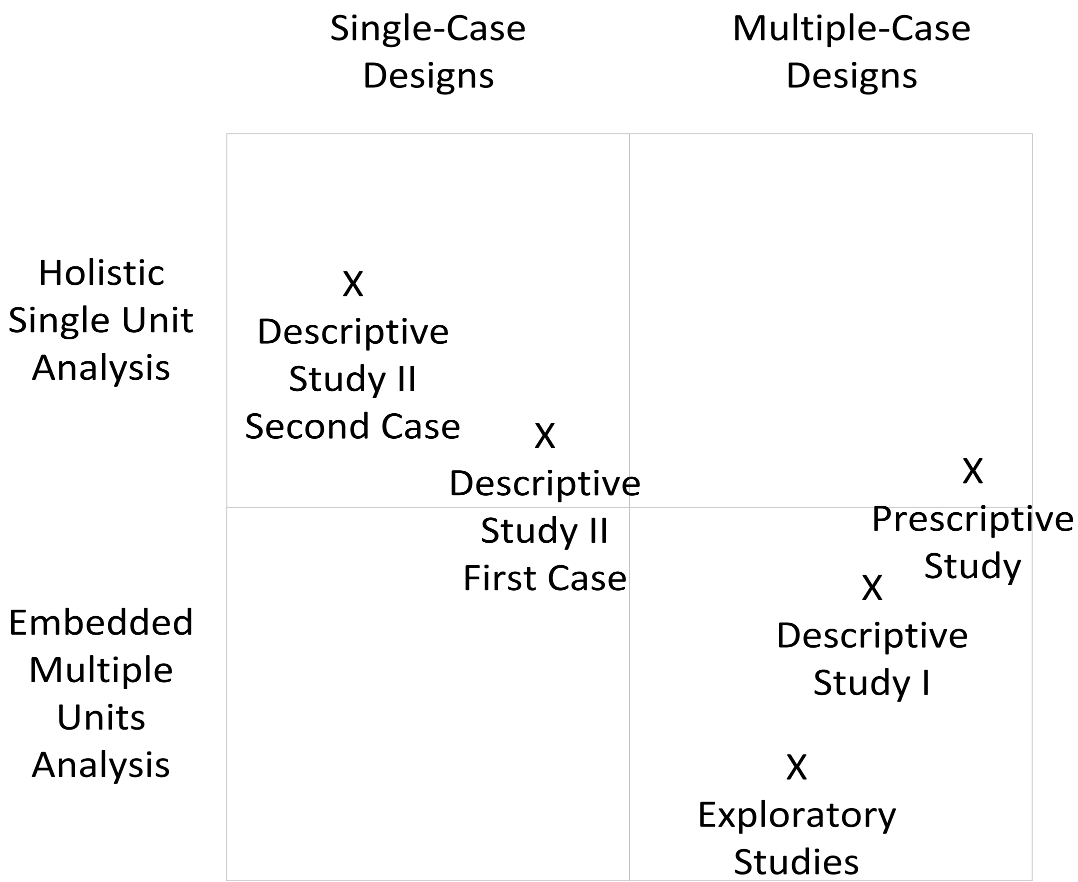


Figure 23. Placement of different stage studies according to the types (based on Yin, 2009).

The descriptive I study is based on the 27 hospital cases in Denmark. In terms of numbers, this one is in-between the exploratory study and the descriptive study. Furthermore, the descriptive I study has more than one unit analysis. There is focus on the network of the project participants and the single patient room design in different cases. The two fields of focus are then combined to find the effect of the network on the final design of patient rooms. This study serves to illustrate the current state of organisation and the low level of productivity this leads to.

In the exploratory study, there is multiple unit analysis because the purpose is to know the current perception of modularity in construction and the current state in application of modularity in the building construction industry. The case aims to present the reader with the rare view on modularity as seen from the contractor's perspective.

The prescriptive study involves the most number of cases, which makes the study located in the outer most right of the spectrum. The prescriptive study actually consists of two main studies totalling 85 cases. These were analysed to find patterns as a part of a holistic analysis. In the first prescriptive study, 39 cases were used to analyse the patterns leading to project wins and losses in the tender phase. In the second prescriptive study, 46 cases were analysed to determine the combination of factors leading to disputes in the execution of a building project. It is important to note that although the same QCA method was used to analyse the cases originating from the same company (MTH), the two studies have completely different cases in their samples. The prescriptive study takes the level of modularity from the commonplace product level to the levels of process and organisation.

In the descriptive study II, the first case is a DSM application, taking façade design as unit analysis involving multiple parties and activities. I classify it as holistic single unit analysis, because the perspective embraces the different competencies and activities under one umbrella (Yin, 2009). Moreover, although the experiences from many façade projects executed under different delivery systems were considered, the DSM created as a final result of the study is representative of a general design case. Therefore, I place it in the ‘single case design’ category as seen in Figure 23. The DSM study is an example of how modular principles can be applied to the design process of a construction project.

Finally, in the descriptive study II the second case is a VSM application; therefore, per definition it was a holistic description of the entire process and not a separate description of separate elements. The two hospital cases are considered one big project, both in practice by the sub-contractors and in the study itself. This study shows the benefits of applying modular principles to all levels of building construction and simultaneously points to the concrete, potential uses of modularity in future projects.

First, we must begin locally, in Denmark, with the current state of construction. Through Research Question 2, as restated in the following blue box, the problem with the way things are done today is investigated in detail through a concrete case.

RQ2: *How does the complexity of the way in which building construction is organised, cause unproductivity?*

4.1 Descriptive Study I

This case comprises 27 hospital projects in Denmark, which includes new buildings and extensions of existing ones (see Paper 1 presented in Appendix A). The clients are six different regions that are administrative units in Denmark and responsible mainly for delivering health care to citizens. The full list of 27 hospitals, together with region responsibilities, appears in Table 6.

Politicians have a decisive position in terms of budget and major organisation: The budget for all included hospitals starts at 80-90 billion DKK, but is later cut down to 60 billion DKK and later again to 41.4 billion DKK (uncertainty and dynamics described in Chapter 3, Section 3.1.2). There are several unfortunate characteristics in the set-up, which cause serious impediment to the process and create higher costs.

First, although the different projects are in different construction phases, they all run simultaneously, which makes knowledge or resource transfer impossible from one completed project to the next (pace described in Chapter 3, Section 3.1.3). Second, they are all run independently. Even the hospitals under the same administrative region have their own project organisations and specific design solutions (socio-political complexity described in Chapter 3, Section 3.1.4).

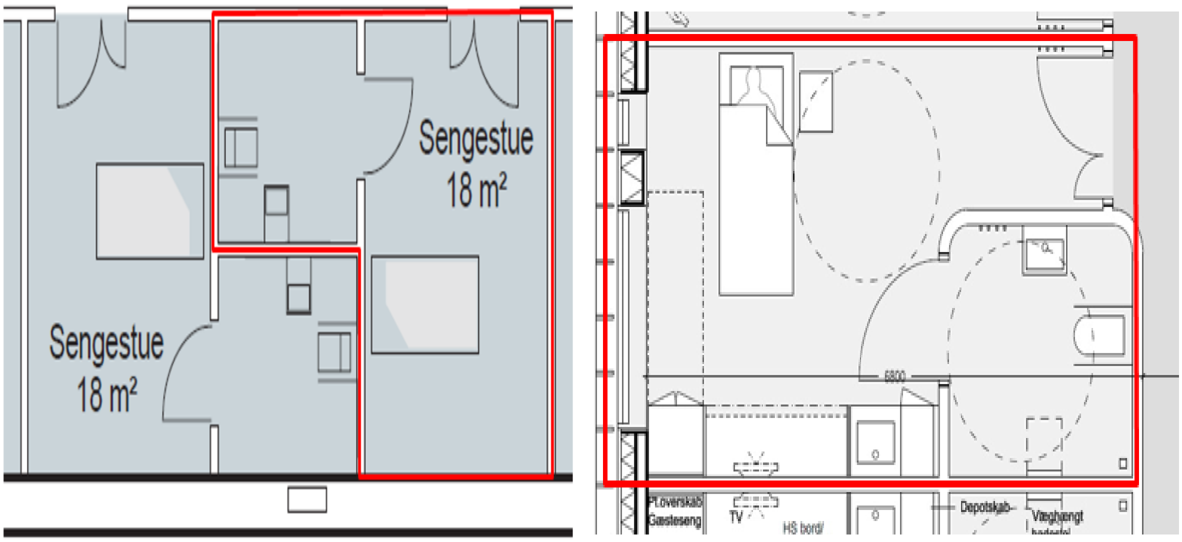


Figure 24. The two patient room types: L-Type on the left example is from NAU and box Type (C-Type) example is from NHH.

For example, the popularity of the L-Type is found across all projects. 70% of the projects use the L-Type and only 30 % use the C-Type (Box Type). The existence of the two types of patient rooms would make one expect that is was based on one common standard solution. The analysis reveals, however, that each of the 27 hospital projects has its own specific design, with different dimensions, m2, and interior. Consequently, the patient rooms have been reinvented 27 times—once for each project.

Table 6. The Danish hospital projects studied as cases at descriptive I stage

#	Case Project Name	Administration	Single Patient Room Design Archetype
1	Glostrup (OPP)	Region Hovestaden	L-Type variation
2	Herlev Delprojekt A	Region Hovestaden	L-Type
3	Herlev Delprojekt B	Region Hovestaden	L-Type variation
4	Hvidovre Nyt byggeri	Region Hovestaden	C-Type (Box Type) variation
5	Hvidovre sengeafsnit	Region Hovestaden	C-Type (Box Type) variation
6	NHN	Region Hovestaden	L-Type variation
7	Rigshospitalet DNR	Region Hovestaden	C-Type (Box Type) variation
8	Ny Retspsykiatri Sct. Hans	Region Hovestaden	L-Type variation
9	DNU	Region Midtjylland	L-Type variation
10	DNV etape 1	Region Midtjylland	L-Type
11	DNV etape 2	Region Midtjylland	L-Type
12	Viborg	Region Midtjylland	L-Type
13	Hjørring	Region Nordjylland	L-Type variation
14	NAU	Region Nordjylland	L-Type
15	Thisted	Region Nordjylland	C-Type variation
16	Brønderslev Pskiatrisk Sygehus	Region Nordjylland	L-Type
17	Himmerland (Hobro)	Region Nordjylland	C-Type (Box Type) variation
18	Vordinborg	Region Sjælland	L-Type
19	Slagelse	Region Sjælland	L-Type
20	Slagelse fase2	Region Sjælland	C-Type (Box Type) variation
21	Køge USK	Region Sjælland	TYPE B
22	Esbjerg	Region Syddanmark	L-Type variation
23	Kolding	Region Syddanmark	C-Type (Box Type) variation
24	Middelfart psykiatri	Region Syddanmark	L-Type variation
25	OUH	Region Syddanmark	L-Type
26	Vejle	Region Syddanmark	L-Type
27	Aabenraa fase 1	Region Syddanmark	L-Type variation

This type of project delivery and lack of synergy between projects exemplifies clearly the product/process symptoms described in Figure 12 in Chapter 3 of this thesis. Long lead times, delayed projects, unprofitable products (in construction terms), running over budget, and frustrated customers. Each project contains an unnecessary level of complexity (as described in Chapter 3) (Wilson & Perumal, Complexity Cube, 2015). Furthermore, the network between projects itself represents a complex organisation.

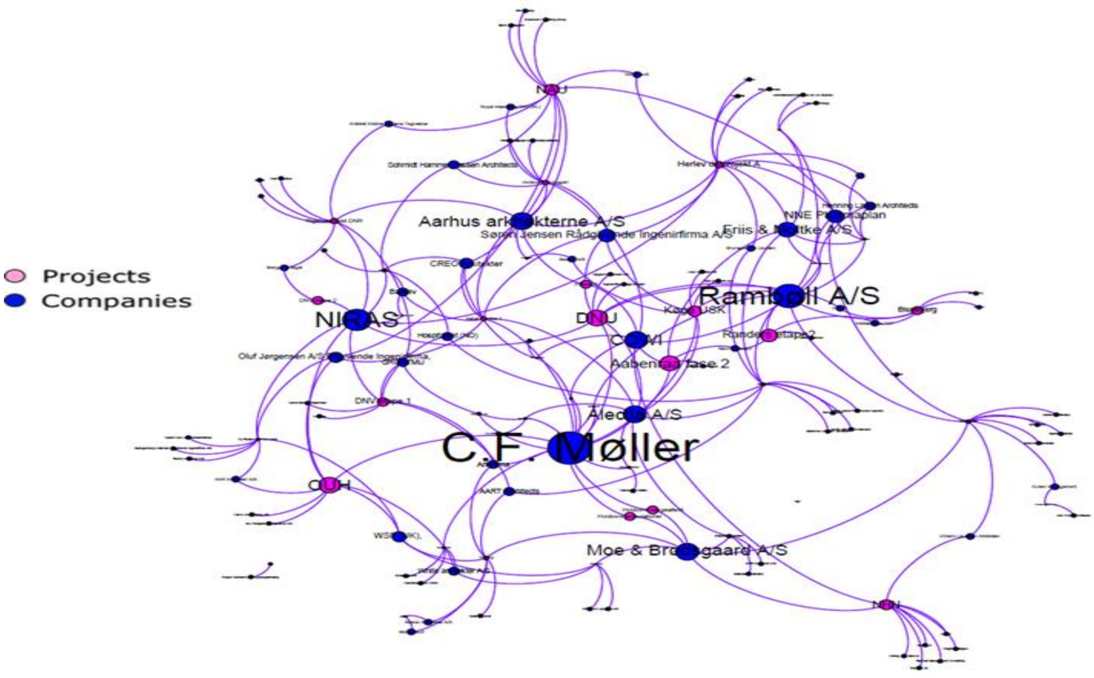


Figure 25: Network map of dependencies between the project and companies.

To illustrate the complexity: A network map showing the relations between the projects and participating companies was developed as seen in Figure 25. In total, 98 companies are participating in the projects; out of which 12 represent foreign countries. The numbers exemplify structural complexity described in Chapter 3, Section 3.1.1. Moreover, these figures are only at company level. The real structural complexity is much bigger when the subcontractors and individual professionals are considered.

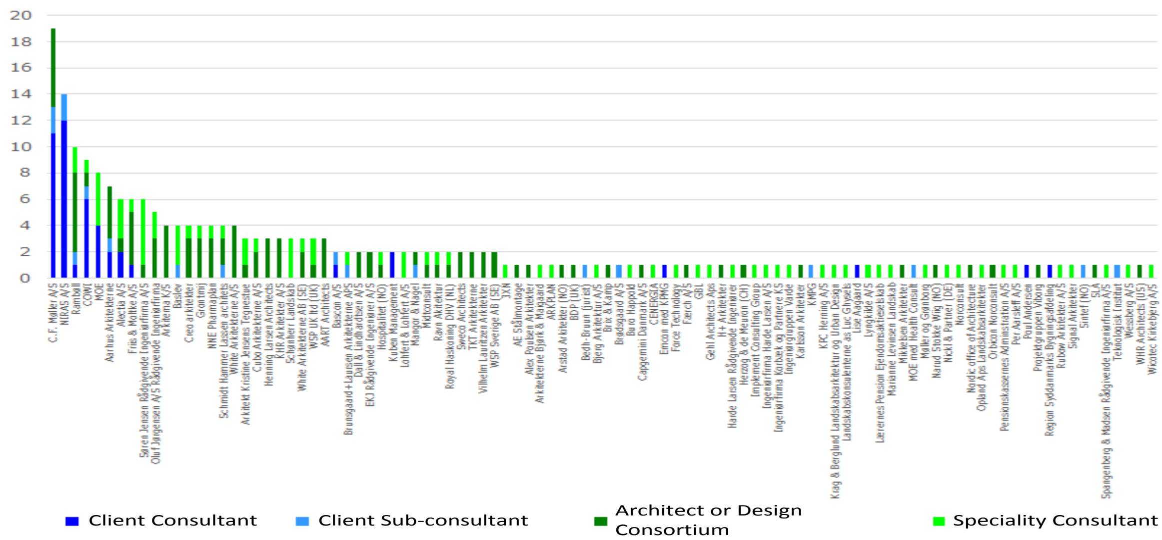


Figure 26. Frequency diagram of the companies taking roles in all hospital construction projects.

As seen in Figure 26, most of the companies taking roles in the 27-hospital construction projects in Denmark are only getting involved in these projects once or twice (seen as small dots in Figure 25). Moreover, most companies involved in projects more than twice have different roles, such as consultant and architect, in different projects. This long tail is arguably one of the reasons why projects lack standard solutions. It is a good illustration of the complexity cube organisational/product interface presented in the literature section.

Similarities exist in an unsystematic way. The analysis shows that all the green field projects use the room archetype L or a variation thereof. Almost 70% of all centrally-funded projects use the L-Type of patient rooms. Again, some unsystematic associations of some companies and design outcomes are observed. For example, C.F. Møller consistently uses the L shape patient room design in all of its projects. However, there exists no general organisation-product (design outcome) pattern as illustrated in Figure 27. Referring to the theory about product design outlined in Chapter 3, Section 3.3.3.1, there is no component-sharing modularity across the selected hospital projects..

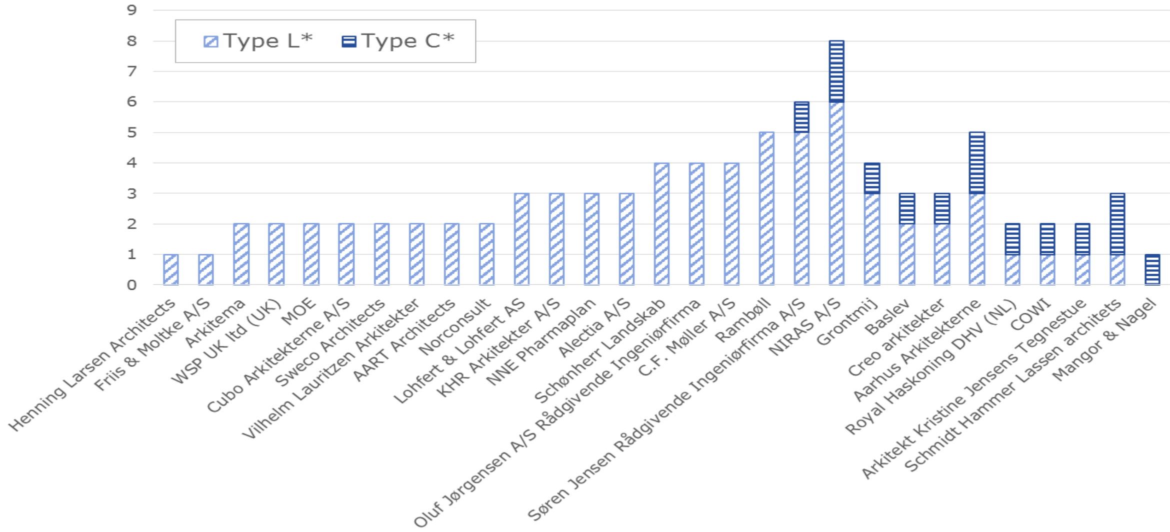


Figure 27. Companies vs room types.

The research question prompting the above-described study was to what extent the complexity of the way construction is organised cause unproductivity. As a result, one has to say that unproductivity is very much a consequence of complexity outlined in Chapter 3 by Geraldi et al. (2011). All the dimensions of complexity can be observed to an extensive degree in the above-mentioned study. As will be raised in the discussion section of this thesis, a high level of user involvement may be an asset at the outset of a project; however, it loses its benefits when it leads to an unnecessary level of complexity.

The descriptive study I makes it clear how the opportunities for boosting repetitions' effect across projects is wasted in a project portfolio like this

RQ3: *What are the current understandings and applications of modularity in building construction?*

4.2 Exploratory Study

Research Question 3 will be investigated in two parts. In the first part, the current understanding of the modularity concept in the building industry will be researched through a case study conducted in the MTH. In the second part, the application of modularity in building construction will be explored in a broader context.

4.2.1 DK MTH CASE STUDY

The purpose of this study is to identify the understanding of modularity in building construction (see Paper 2 presented in Appendix B). To do so, the perceived effects of modular solutions as seen from a contractor's perspective are studied. As mentioned in Chapter 3, Section 3.1, complexity increases with the parties involved, such as owner, architects, consultant, contractors, etc. and every observer generates new perspectives of it. The empirical material is collected from site visits and interviews of seven MTH Project Managers (PMs), procurement, and law specialists, which is detailed in Table 7. This is combined with the results of a review of modular solutions in Chapter 3, specifically the literature dealing with the advantages and disadvantages of modular solutions in systems engineering, product platforms, and off-site construction. The results are presented in the same order as presented in the Table 5 given in Chapter 3, Section 3.3.4. More detailed analysis can be read in Appendix B together with the full paper.

Table 7. List of MTH case participants

Participant's Position	Department	Seniority
Section Director	New Building / Carpenting	+20 years
Senior Project Manager	Nordatlantic / Island	+30 years
Senior Project Manager	New Building	+30 years
Senior Project Manager	New Building	+25 years
Design Director	New Building / Project Development	+20 years
Attorney at Law	Law / Insurance	+10 years
Department Chief	Strategic Purchaising	+10 years

Seen from the contractor's perspective and contrary to the literature, not only do the disadvantages outnumber the advantages but also negative effects, such as delivery lead times and interface problems, put question marks to the positive effects that the literature suggests. Contractors generally question the positive effects of modular solutions reported in the literature, as their perceptions of the benefits contrast considerably with those of producer companies, such as house builders.

4.2.1.1 Positive Effects

Lower *cost* is mentioned by the majority of interviewees as the main driver making modular solutions interesting for any contractor. According to the interviewed PMs, given that quality and deliverability are assured, a modular solution mainly proves attractive for the contractor because it is likely to reduce project costs significantly. When choosing between a modular and a non-modular solution, reduced square meter costs tend to be the decisive factor for the PM.

PMs also agree that modularity facilitates *logistics*. In cases where everything runs smoothly, modular-built elements simplify logistics at the construction site: they arrive together, quickly, and intact; and they are packed and arranged in the most systematised way possible, thereby improving both security and space utilisation. 'It is a great advantage to work with modular solutions when they are delivered in ready-made packages. They occupy less space at site as they are already pre-assembled compared to the other methods. Due to fast installation, the modules use less time between arrival to site and installation,' says one of the interviewed PMs.

Another advantage repeatedly mentioned is the facilitation of site *organisation*. 'Fewer elements mean fewer people to handle them and that simplifies the logistics of not only materials, but also of employees,' comments one respondent.

Fewer employees on-site is also an advantage so far as *health and safety measures* are concerned. 'Fewer people on site means less risk for accidents,' say the project manager. One interviewee observes that most accidents happen in the shell construction phase and, therefore, the application of any modular solution that would require less work on-site in that phase reduces the risk of accidents.

Similarly, instead of working with five to 10 suppliers and subcontractors, working with modular solutions brings advantages at the level of site organisation as just one single producer is needed and just one single team is necessary for installation. As a PM emphasised, 'absence of workers, weather conditions, strikes and work accidents will be less of an issue where the contractor's site organisation are shaped by the applications of modular solutions'.

PMs also acknowledge *quality of products* is an advantage. With standardised modular solutions and off-site production, more consistent quality can be expected as a result of the working conditions and production teams not being subject to changes as is the case with on-site production.

4.2.1.2 Negative Effects

All interviewees perceive *limitations to free design and creativity* to be a major problem with modular solutions. They also mention the discrepancy between the typical dreams, thoughts, and ideas of the architect and owner to create an outstanding, unique final product on the one hand and the mass-produced anonymity of modular solutions on the other hand. The PMs spell out how, from their experience, mainly in projects such as company headquarters, residential buildings, and publicly-owned building projects, both the owner and the architect are driven by the will to have each project remembered in their names and therefore wish for as individual an expression as possible. From their experience, clients also tend to prefer houses with a degree of personalisation. One PM mentioned the buildings built in Denmark during the 1960s and 1970s as examples of modern period style and points to their low market value partly as a consequence of their anonymous mass-produced appearance. Therefore, according to the PMs, modularity in construction is a drawback on an individualised-oriented market, since it produces standardisation in composition and looks of the final product.

Also according to the PMs, the *risk of design changes* is another major drawback. The inability to change design along the way makes it necessary to freeze a design at a very early stage. As one PM said, 'the earlier the modular solutions are considered in a construction project, the greater the possibilities are to apply them. As a consequence the design is completed in the early phases of construction projects using modular solutions.' From the interviews, it was clear that it might be difficult to have all parties agree on the design completion, especially the designers themselves who perceive e design to be a flexible and living process. Moreover, it is very likely that unforeseen elements could occur during the building process, requiring design changes. Modular solutions do not accommodate this need—or they do so only at high cost.

Another recurring disadvantage is the *high volume deliveries of products* when the contractor wishes to purchase only a small amount. The producer of modular solutions needs high volumes to reach an economy of scale. However, when only a few units are needed, it can be more efficient and more economical for the contractor to produce on-site. As one project manager explained: 'In the case of renovation projects where, for example, 200 houses are going to be renovated, the modular solutions are the most convenient solutions - but how often do you have 200 houses to deal with?' In order to reduce costs significantly, high volumes are needed to apply modular solutions.

Reuse of technical specifications is an aspect of modularity, which at the outset appears to be an advantage. However, it is rarely the case in practice because standardised technical specifications actually tend to prove a challenge to the constantly changing interests of client, architect, and consultant from project to project. In the hypothetical case that parties agree on the binding issues from project to project, there would be much to gain by reusing technical specifications: design and quality assurance documents are provided by the supplier, facilitating not only the contractor's job but the entire construction process; and the approval process is shorter and requires less energy because the previous project can be shown as a reference, and so on. However, even if the method and modular solution applied in the previous project remain the same, the project parties, such as the client, architect, and consultant, can change, bringing the same challenges back to the surface.

The interviewees also identified *country-specific standards* of buildings as a potential disadvantage. Despite the existence of Eurocode and free market regulations within the EU, an experienced PM raised the issue, stating, 'To work with foreign suppliers who have no experience in the Danish market can cause problems. In many cases Denmark has higher standards, for example in sound insulation and fire resistance, than neighbouring countries.' That may mean that a well-known modular method commonly used in Germany, for example, may not be approved for use in Denmark.

Although the PMs admit the importance and advantages of working with stable organisations and crews, the interviewed PMs think that it as unrealistic. Typically, they are used to the dissolution of project teams after every project. 'For every project a new team with relevant competencies in a new organisation is created in order fulfil the specific project requirements', says one PM. In general, PMs rely on the ability to find the people with the required skills for the particular constellation of a particular project.

Furthermore, *time* is an aspect of the construction process where modular solutions can easily become disadvantageous. Time is one the most attractive promises of modularity as it reduces the time required for on-site production to only a matter of installation. However, this time saving is only realised if the process is described clearly, agreed upon in advance, and well coordinated by all parties. Otherwise, it adds more complexity, chaos, and inflexibility to the construction process. By using modular solutions, traditional work activities are clustered into modules that are more independent of each other. As a result, the buffer times between activities disappear and the construction process becomes more sensitive to changes, such as failure to design, produce, or deliver on time. A modular solution therefore makes the project design and project planning phases even more critical for the success of the overall construction project. This is a clear example of the dilemma mentioned in Chapter 3, Section 3.1.1, to prioritise MID or MIP. Unfortunately, in construction it appears like modularisation in one works against the other.

Finally, similar to time, *productivity* is another clear advantage of modularity, but which can easily turn into unproductivity if the construction process is not planned and managed properly. Productivity highly depends on early planning. However, 'the challenge in the company and in the construction industry is that we often end up planning while we are executing. As a natural consequence of that there is not enough space left in our time schedules for using modular solutions,' states a PM.

As can be seen, PMs perceive modularity as having certain advantages and disadvantages. The theory visited in Chapter 3 makes a clear case for the benefits of modularity. It is also clear from descriptive study I that much is left to wish for in the present-day utilisation of standards and repetitions effect. However, from a contractor's point of view, modular solutions represent a questionable approach as they pose vital risks to for example delivery lead times and interface structures. In other words, the contractor sees different constraining aspects of modularity in practice than does the product-oriented industries.

Yet, when discussing modularity, it is rarely considered that modular solutions also affect processes and organisations. This will be fold out more so in the discussion together with the results of the other studies.

4.2.2 Multiple case study

The second part of Research Question 3 concerns the application of modularity in building construction rather than the perception, which thus far only has been investigated. To achieve a diverse, heterogeneous, and illustrative sample of modularity applications, 11 cases from six different countries in developed and developing parts of world are selected (as shown in Table 8). A select amount of different perspectives mentioned in Chapter 3 (Casti, 1986) is covered. Moreover, cases represent different categories according to the classification made by Gibb (2001) as detailed in Chapter 3 modularity in construction.

Table 8. Multiple case study overview

Case Name	Case Description	Country	Data Collection Method	Project Delivery System	Modular Classification
Scandi Byg	Modular buildings producer	Denmark, Løgstør	Visit of prodution facility interview with production leader and facility manager	Design Build	Modular Building
IQ Homes Ballast Nedam	Modular buildings producer	The Netherlands , Weert	Visit of prodution facility interview with production leader, facility manager and R&D Director	Design Build and developer	Modular Building
BSkyB London	Steel structure to be served as Sky TV London studios	England, London	Visit of the construction site and interviews with GC site chief, architect and consultant representatives	Design Build	Volumetric Pre-assembly
Broad Company	7 storey building being built in 15 days with modular structural steel	China, Hunan, Changsha	Visit of the construction site and interviews with GC site chief, Vice Ceo, investment manager and structural engineers	Design Build and developer	Non-volumetric Pre-assembly
Zorlu Center	Multi purpose building consisting of 4 high rise buildings, a total area of 750.000 m²	Turkey, Istanbul	Visit of the construction site and interviews with GC project manager, structural works project manager and structural works general formen	Design Bid Build	Component Manufacture and Sub-assembly
ConXtech	Structural steel producer and contractor company	USA, Bay Area, California	Visit of prodution facility	Structural Works contractor	Non-volumetric Pre-assembly
Finelite	Modular lightning systemts producer	USA, Bay Area, California	Visit of prodution facility	Electrical Contractor	Non-volumetric Pre-assembly
Nautilus	Modular buildings producer	USA, Bay Area, California	Conpany presentation and Interview with company owner	Developer	Modular Building
HGA	Architect Company	USA, San Francisco, California	Conpany presentation and Interview with the chief architect and the owner (architect)	Different	Non-volumetric Pre-assembly
Ancient Greek	Ancient archaeological site	Turkey, Egean region, Izmir.	Archeological site visit and interview with an archeolog	Unknown	Non-volumetric Pre-assembly
Børneby	Integrated Children's institution for 600 kids between 0-5 ages	Denmark, Copenhagen	Visit of construction site, interview with the architect and institution leader	Design Bid Build	Volumetric Pre-assembly

The multiple case studies presented in the following section are placed within the ‘embedded multiple unit analysis’ as seen in Figure 23 (Yin, 2009). The ‘embedded units’ in this case are the product, process, and organisation domains of the different company studies.

The cases show great variance in terms of location, context, background, and even time (Flyvbjerg, 2006). *Broad Company* is a conglomerate from rapidly industrialising China producing high-rise solutions, whereas *IQ Homes* is from the Netherlands providing max. four-storey buildings. *Scandi Byg* from northern Denmark can be compared to *Nautilus* from California, USA, in terms of final product and modular volumetric units—but the way the two companies arrive at that final product differs noticeably. *ConXtech* from Bay Area, USA produces load bearing steel columns with a similar end purpose to two millennia ancient *Greek temple* pillars, albeit with totally different materials and motivations. There is also variance in market placements and services provided across the cases: from architects (*BSkyB London, HGA Architects and Børnebyen*), over contractors (*Scandi Byg. BSkyB, IQ Homes, Zorlu Center, and ConXtech*), developers (*IQ Homes, Broad Company, and Nautilus*), and all the way to producers (*Finelite)*. It is important to note that some of the cases take more than one role, depending on the market conditions.

Pattern making (Eisenhardt, 1989) and explanation building approaches (Yin, 2009) are followed as elaborated in Chapter 2, Section 2.4.2 case study analysis to highlight the repeating patterns across the cases. As will be seen, although standing points, geographies, and expertise areas vary widely across cases, the similarities in main drivers, end products, and main challenges are remarkable.

At all company visits, the interviews were conducted with questions pertaining to modularity of product, process, and organisation. The findings are presented in the order accordingly.

4.2.2.1Product orientated questions:

What are the main areas in which modularity/repetition is used?

Modularity as a term is unclear to almost all interviewees. The application of modularity as a strategy was instead studied by looking at the application of repetition in different work areas. Out of the companies visited, *HGA Architects* is the only company working consciously with modular design on a larger scale than the isolated product itself. HGA Architects aim to increase the utility of a hospital room during a workday as illustrated in Figure 28 with different colours by assigning multi-functions to each room. This is a good example of MIU described in Chapter 3, Section 3.3.1 on page 36.

HGA Architects’ slogan is ‘the more is actually less’. By this, the company means that even though the design of larger rooms makes the area/per room bigger, it adds extra functionality and, therefore, less rooms in total are required to serve the overall needs of the hospital. Moreover, the new larger rooms serving multi-purposes are identical (MID as described in Chapter 3, Section 3.3.1) and thus different room typologies disappear. By implementing this basic strategy, *HGA Architects* could lower the amount of rooms by 15% representing a 7% reduction in the overall area. This was achieved by increasing the room space by 10% on average and by making the rooms universal and more occupied during a day.

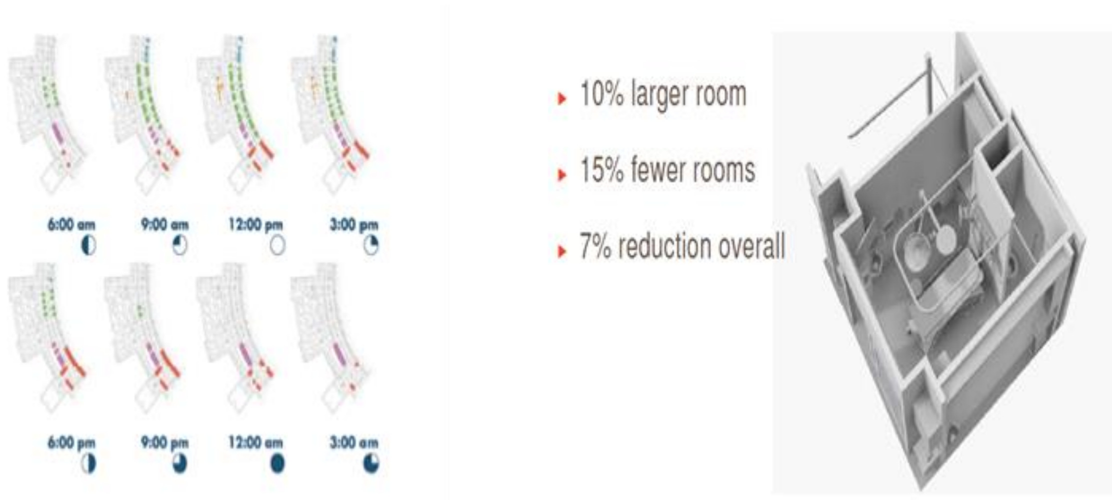


Figure 28. HGA Architects ‘the more is actually less’ concept, 2015.

Furthermore, the repetitions are well acknowledged in all cases instead of modularity. All case participants admit the positive effect of work repetitions and they all try to implement it in their business even though the ultimate goal is not modularity. Here, I shared only *HGA Architects* as the only studied case practising modularity consciously. How these repetitions are realised by different cases is unfolded below.

What is the main drive for the modularity applied?

Cost appears to be the most important drive in the decisions about different building alternatives. All producers or developers aim to provide a more competitive price for their customers. In one case, the developer *ConXtech* mentions that ‘we must at least attain the same price level as other competitors so that we can talk about our other competencies such as delivery time and quality’ (ConXtech, site visit on 30 October 2015).

Figure 29. Zorlu Center, Istanbul, Turkey, from west on the left and from north on the right (Mak-in, 2012).

Furthermore, time savings is the second factor again with the purpose of reducing the overall project cost. PM Soner Coban from *Zorlu Center Project* in Istanbul (Figure 29) stated that:

> We are constantly fighting against time. Repetition enables us to build faster. When the tasks are identical we don't even need to check the drawings. We simply follow the process again and again. We just repeat. Moreover, with similar tasks everyone can foresee the plan so that I can give bonuses and make the teams compete against each other. Once there is an agreed method all parties stick to it and building raises fast (PM Soner Coban, Zorlu Center, 2013).

This exemplifies the importance of repetitions in order to achieve pace mentioned in Chapter 3, Section 3.1.3. It is very important that all the involved parties in the process can adjust their pace with respect to each other.

This last sentence of PM Soner Coban actually summarises the connectivity of product, process, and organisation: an agreed method (*process*) leads to all parties sticking to it (*organisation*), leading to the building rising fast (*product*).

Speed is again mentioned as most the important factor in the *Broad Company* case. *Broad* breaks the speed records of the world when it comes to building construction. I had the chance to visit the company's site where they constructed a 15-storey building in seven days, including the architectural finishes. From completion of the earth works and fundament to the building was in function only seven days passed. *Broad* also built a high rise building consisting of 30 storeys (as shown in Figure 30 on the right-hand side) in just 15 days (again, excluding earthworks and fundament).

Figure 30. Broad Company Changsha, People's Republic of China, site visit on 5 May 2014.

Building site constraints appear as another drive prompting the application of modularity. In case of the '*Børnebyen*' day care institutions in central Copenhagen, the sports hall, was assembled on the parking lot 200 m from the actual site because of space limitation at the site to set up a crane for the assembly. After the assembly, the steel structure was transported to its final location with a single day operation as seen in Figure 31.

Figure 31. Børnebyen, Sports Hall Assembly in Copenhagen, 12 August 2016.

Similar to the *Børnebyen* project, all cases prioritise the logistics in their design solutions as mentioned in Chapter 3, Section 3.3.3.1 (see Table 4). Making physical transportation easier is decisive in the building construction especially when working modular solutions.

What is the main structural material? Concrete, steel, wood, or a combination of them?

The material used in structural solution is very much context and market dependent. In ancient Greece, the material preferred for major buildings was stone. Stone blocks (see Figure 32) were shaped in the mines outside of the urban area and then transferred to the final building location for assembly. According to the archaeologist interviewed at site 'in the ancient Greece they prioritized to limit the slaves to be in the urban area' pushing the labour intensive, dusty work to the outside of the town. Interestingly, the same stone blocks were used over and over again simply following the same original assembly technique putting modules together according to the codes (similar to the IKEA furniture assembly) given at mines by different civilisations with hundreds of years' intervals for different buildings having different functions. It is a remarkable example of usage repetition even though it was never the intention.

Figure 32. Magnesia ancient Greek town archaeological site Aydin, Turkey, 5 June 1016.

With similar drivers, building off-site steel is preferred in examples from USA China and UK (*ConXtech* steel column as seen in Figure 33, *Nautilus, Broad Company* and *BSkyB London Project* respectively).

Figure 33. ConXTech Column Manufacturing workshop visited on 16 November 2016 (Photo courtesy of Prof. Iris Tommelein).

In the examples from Turkey and the Netherlands, concrete is the material chosen for structural system. *IQ Homes* from the Netherlands uses steel formwork with fixed dimensions to pour exactly the same amount of concrete for every batch (see Figure 34). The standardisation of the final product boosts the repetitions effect achieved by doing exactly the same every day (*Ballast Nedam/IQ Homes*).

Figure 34. Ballast Nedam/IQ Homes, workshop visited in the Netherlands, 15 January 2014.

In Denmark, a similar repetitions effect is obtained by using the wood as the main material as it is illustrated in Figure 35 by *Scandi Byg* which is an MTH subsidiary. According to the production manager of *Scandi Byg*, ‘working with wood not only fulfils a strong market demand but also it gives flexibility to both our daily work and design’ (*Scandi Byg*). The trade-off between working with fully standardised products and flexibility in design is a very hot topic in this example. The main argument to maintain the flexibility in design is the ability to provide solutions to a greater market—in this case, design-build projects, such as day care institutions, schools, and dormitories. However, this limits the usage of standardised production. Repetitions are still present in limited production because it does not lead to standardisation.

Although different materials are used fort the structural system in order to address different markets, the drivers of applying modularity are remarkably similar in all cases.

Figure 35. Wood is the primary construction material used, Scandi Byg, Denmark, workshop visited on 4 February 2014.

4.2.2.2 Process orientated questions

Are there any repeating works?

The Zorlu Center Project is chosen as an example of a repetition work because it consists of four high-rise buildings; thus, it requires a highly repetitive production of floors. The high amount of repetitions and the existence of identical floor plans means that industrial scaffolding systems, such as German Peri table platforms, were used and hydraulic elevated formworks were preferred for the core walls.

'The repetitions effect was clear in our building performance. To prepare the first floor for the concrete pouring we have spent 10 days. However, the cycle time was reduced after only building four floors gradually first to six days/floor and by the seventh floor three days/floor cycle time was reached. After that we could not squeeze the cycle time any further but we started to decrease the amount of workers. When we got to the top floor, in other words the 30^{th} floor, 70% of the workforce that was used to build the 10^{th} floor could easily maintain the three days/floor cycle' (PM, *Zorlu Center*).

Similarly, in *IQ Homes* the same described work activities are repeated continuously. Even the working days are similar as the suppliers know well in advance when to bring what sometimes without waiting for the official orders. As the production manager states 'we pour exactly 20 m^3 concrete every day at the same time so that our concrete supplier knows well in advance our need. Moreover, the concrete supplier prioritizes us as being a reliable costumer and they do not take any other orders that would disturb our production'.

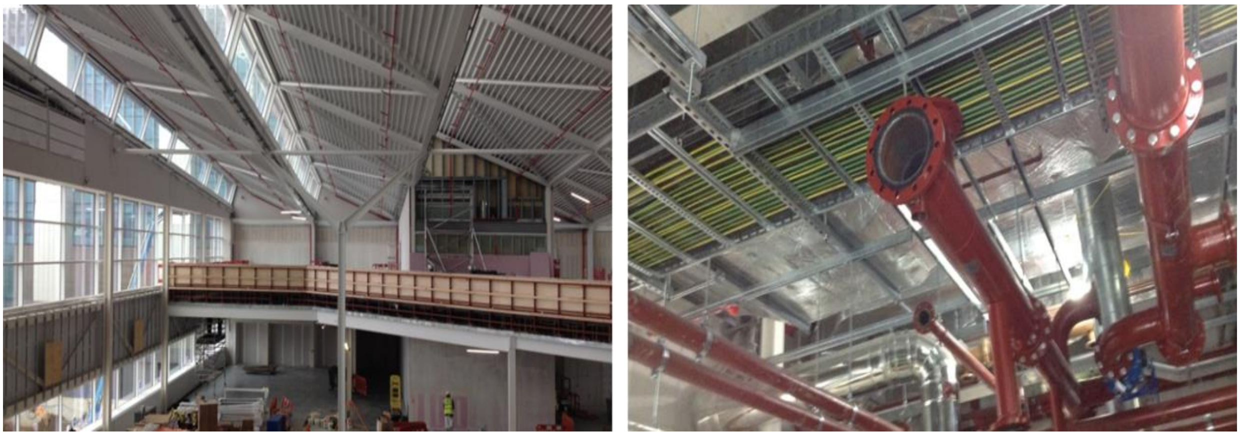


Figure 36. BSkyB Studios building project in London, England, 12 February 2014.

Repetitions are also mentioned at the site production level. For the *BSkyB London Project,* they use the repeating design to divide the work tasks into manageable sizes as illustrated by the structural and mechanical works in Figure 36. Moreover, the on-site PM states that 'only through with repeating works they can forecast their work plan and anticipate the required man hours'.

The Zorlu Center Project and other examples support the well-documented, continuous productivity improvement obtained through the repetitions effect outlined in Chapter 3, Section 3.3.5.

Is there any band system for the production?

In all the cases visited, there existed a certain band production system. In the case of *ancient Greece*, according to the archaeologist 'they had developed sort of band production systems at the mines to shape the stone at different levels.' As mentioned also in Chapter 3, 'standardized modules were produced repetitively'. 'The same production technique implies to all sorts of stone products such as building blocks but also statues.' This can easily be noticed as all the stones at archaeological site are like pieces of a big puzzle; however, there are many identical ones waiting to be put together and re-erected. Reducing the cycle time of the manufacturing process is the core gain of applying design modularity mention in Chapter 3, Section 3.3.3.1 (see Table 4).

Some companies have fixed workstations where they perform the exact same work activities (*ConXtech, IQ Homes*). However, some companies (*Scandi Byg* Figure 37) prefer to have flexible layout in their production to be redesigned according to the project requirements.

Figure 37. Different work stations at Scandi Byg factory, 4 February 2014.

Expectedly, *Finelite*, a producer of lightning systems, represents the most established production line as can be seen in the top-right picture in Figure 38. The factory is divided into work departments. The flow from one workstation to another is provided with wheel carriers as seen in Figure 38 on the bottom pictures.

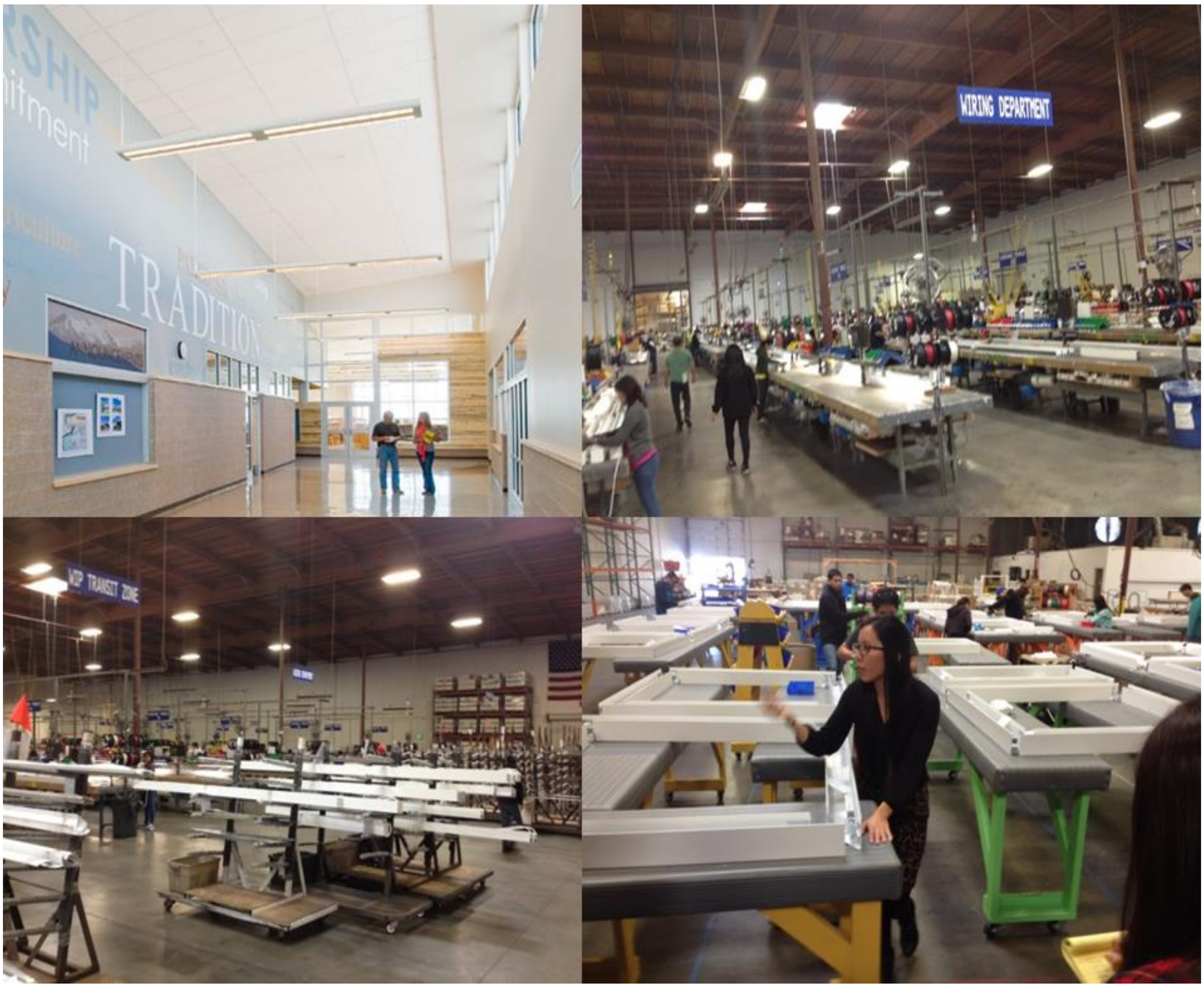


Figure 38. Finelite lightning systems, Bay Area, California, USA, 16 October 2015.

4.2.2.3 Organisation orientated questions

What is the contract type/project delivery system chosen?

The cases are all different in project delivery types. However, they share one thing in common: the necessity of early involvement in the project before the design phase is over. Therefore, none of the studied cases applying volumetric modular solutions bid for the projects design is completed. The only design-bid-build cases are the *Børnebyen* day care institution, applying only partial modular approach in the sports hall part of the building, and *Zorlu Center*, applying no volumetric modular solution.

Early involvement in the design phase is crucial for the contractor in order to apply the modular solution. Vice President and Business Development Director at *ConXTech* stated that: ‘as ConXtech, sometimes we deliberately didn’t take projects, because they were too advanced and the benefits of the modular solution would not be vitalised anyway’ (*ConXtech*). In some cases, the proposed modular solution is not flexible at all. The design is locked, such as in the cases of *Ballast Nedam / IQ Homes* and *Nautilus*. In these cases, the companies have the developer role targeting a market to sell their products rather than the contractor role bidding to build for a designed project.

Are any subcontractors used and, if so, for what purposes?

Subcontractor usage varies case-by-case, including the specific needs and conditions of a case project or company; therefore, no generalised answer could be obtained. Willingness and preference to work with fixed teams or previously known subcontractors, however, is an obvious tendency in the way the companies work no matter if the service is outsourced or performed by in-house teams. In many cases, the transport and assembly works are performed by the same teams across the projects. Cases: *Scandi Byg, IQ Homes, ConXtech,* and *Nautilus* (see Figure 39).

Figure 39. Nautilus, Bay Area, California, USA, (2016).

How does it contribute working with same organization to the work?

Similar to the study by Russel and Taylor (2009) described in Chapter 3, Section 3.3.3.3, ‘trust’ is mentioned as the key word in all non-Danish cases. In Danish cases, ‘we know each other’(‘vi kender hinanden’) is used instead of the word ‘trust’. The difference in putting things into words might be a language or cultural difference. However, the universal thing in all cases is that we tend to prefer the people we already know when working together. The same is valid on organisational and personal levels.

> Whenever there is a change in the organization so to speak a new consultant joins the team the process is reconsidered. It is frustrating and time consuming to update the process while the production is ongoing. The same problem occurs when a new PM joins the team. Unfortunately it is almost inevitable to avoid personal changes in long term projects. Every individual comes with his own experience and methods. It takes time for the individual to adopt the way we do things at site and the organization. When I hire a new worker, a week goes before he finds his way to the toilet (General Forman Aydin, *Zorlu Center*).

In *Scandi Byg*, all working teams are local. They are loyal to the company. If there is no work, they go home and wait for a call. The availability of workmanship when it is required provides flexibility for the production.

4.2.3 Advantages and disadvantages

The disadvantages or limitations of the applied modular solution have been asked as an open-ended question in all exploratory case studies. None of the parties would name any disadvantages. Instead, they carefully made clear that some limitations could be mentioned in order to get the best out of their solution. The common named limitation was to be involved in the process before the main design decisions are made. After fixing the design, the modular solution would lose its meaning and applicability. The previously completed projects are the best way to address the scepticism. The success obtained in previous projects makes the modular solution attractive.

This multiple case study shows us many different types of applications of modularity. Even when the application is not 100% intentional, it is clear that the advantages of modularity, which theory describes to us, such as reduced project durations and improved productivity and more competitive costs are aimed at through the modular kinds of approaches practised by these companies. So while the MTH case study preceding this one reveals a rather negative attitude towards modularity among PMs when asked in an interview, these examples serve to show that contractors around the world are nevertheless trying to work out standards and codes for themselves to optimise their processes. In some cases, the practitioners name their approaches *standards*, *standard processes*, *repetitions*, and *working procedures*. They are clearly not relating their practice to the theory or the academic articles written about the subject. Rather, they go about their business in an intuitive way, sensing the big advantages to be won by the modular, but advancing at it in a rather unsystematic way.

Through the next research question: 'How can repetition patterns across unique projects be traced and what are their effect on the outcome?', I wish to present a method to make projects modular, which targets a very broad spectre of projects and organisations. I suggest that not only can construction industry be more systematic in its utilisation of the advantages of modular building techniques; it can also bring modularity to another level by applying modular approaches to process and organisations as well.

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RQ4: *How can repetitions across the unique projects be traced?*

4.3 Prescriptive Studies

Repetitions exist not only within the projects but also across projects. Although projects are independently executed, there are traceable organisational and processual patterns across them. The patterns, involving combinations of certain organisation and process factors, have substantial effect on project outcomes (see Papers 3, 4 and 5 presented in Appendices C, D and E).

Table 9. Final conditions used in the analysis.

Condition	Description and the threshold	Source
Client & GC	The previous collaboration between the general contractor and client within the last 10 years: if there exists take (1); if not take (0)	Literature (Becker, 2004; Bygballe *et al*., 2015; Egan, 1998; Dewulf & Kadefors, 2012; Gersick & Hackman, 1990; Langlois, 1992; Marshall, 2014; Nelson, 1994; Tyre & Orlikowski, 1996 and Case Knowledge
Architect & GC	The previous collaboration between the general contractor and architect within the last 10 years: if there exists take (1); if not take (0)	Case Knowledge
Consultant & GC	The previous collaboration between the general contractor and consultant within the last 10 years: if there exists take (1); if not take (0)	Case Knowledge
Client Type	Client type as private or public: for public clients take (1); for private take (0)	Case Knowledge
Project Delivery System	Construction project delivery system: design & build projects (1), others (0)	Case Knowledge
Project Type	Project type if residential (1), others (office, hospital, hotel vs) (0)	Case Knowledge
Tender Responsible Seniority	Contractor's tender responsible seniority in the sector: for years 15 and more than 15 take (1); for less take (0)	Literature (Kog & Loh, 2012; Muller & Turner, 2007) and Case Knowledge
Project Manager Seniority	Contractor's project manager seniority in the sector: for years 15 and more than 15 take (1); for less take (0)	Literature (Kog & Loh, 2012; Muller & Turner, 2007) and Case Knowledge

In this section, two examples of predictable patterns are presented. First, a study investigating the practice of tendering and the factors leading to a successful bid is displayed. Second, the elements and patterns likely to lead to disputes during a project's lifecycle are explored. Both use qualitative and quantitative material from the general contractor MTH and both make use of the QCA method (described in detail in Chapter 2, Section 2.4.3), which proves a useful tool in tracing repetitions.

Although conditions investigated (see Table 9) are in common in the two studies, the cases selected for the analysis are completely different. In the first study, the projects are either lost or under construction while in the second study all projects are completed with or without disputes. Furthermore, there are a total number of 85 building projects in the two studies and this makes the prescriptive study the richest part of the analysis.

4.3.1 Repetitions in the tendering phase

It is a well-known fact among academics and practitioners alike that decisions made in the beginning of a project have the most significant consequences for the success or failure of the project (Winch *et al.*, 1998). One of the main decisions affecting the overall project is how to bring the right companies together. Given this importance, tender practices have been subject to a considerable amount research primary taking a client perspective covering topics as contractor prequalification (Nieto-Morote & Ruz-Vila, 2012) and decision-making in the project tender phase (e.g. Hatush & Skitmore, 1997; Diekmann, 1981).

The purpose of this case analysis is to deliver a mechanism for enabling successful tenders by general contractors. In this case study taking tendering practices of MTH into focus, the patterns leading to successful bids is studied from the contractor's perspective (see Papers 3 and 4 presented in Appendices C and D).

As a result of the QCA software analysis, two different mechanisms in the form of two solution sets presented in Figure 40 obtained. These are previous work experience between architect and general contractor in the last 10 years for projects that are not planned to be delivered as design-and-build; or the contractor's PM having more than 15 years of experience in the cases of design-and-build projects. Each of the solutions has 0.40 coverage with total 80% of coverage together making a satisfactory solution coverage according to the csQCA expectations that are above 0.750 (Jordan et al., 2011; Thomas et al., 2014). To reduce the complexity further, the two pathways were simplified into one single solution set in Figure 40 given below.

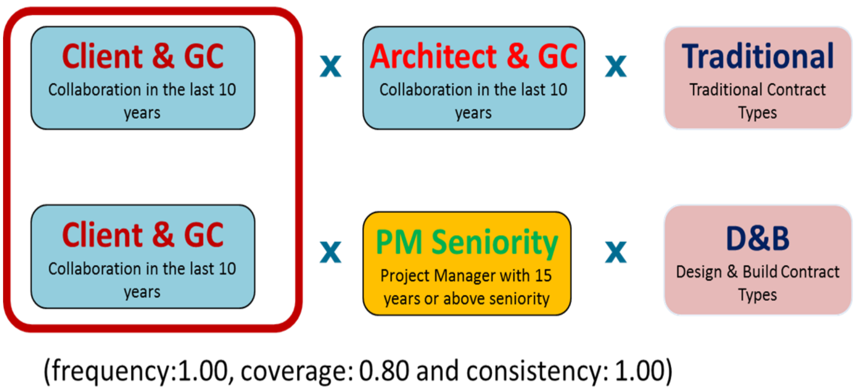


Figure 40. Simplified pathways leading to successful bidding using Boolean algebra.

In order to interpret the solution sets obtained and to get in-depth understanding of the research results, case knowledge and experiences in the field are revisited. To extract the solution sets in Figure 40, previous work experience between client and general contractor was a necessary, but not sufficient, factor as it existed in both solutions together with other factors. One can conclude that it is the most important factor as it is present in both solution sets. It makes full sense that parties that have worked together previously on a project will decrease the socio-political complexity mentioned in Chapter 3, Section 3.1.3. Moreover, in the first solution path, the previous work experience between architect and general contractor is decisive in the cases that another project delivery system is chosen different from the design-build system, such as the traditional design-bid-build. In the projects where the design-build delivery system is applied, the seniority level of the general contractor's PM assigned for the project plays a decisive role. As in the design-build delivery system, the design task is expected to be delivered or coordinated by the general contractor alongside the construction execution. Therefore, the experience of the PM plays a more important role.

It makes sense to have previous work experience with the architect in non-design-and-build cases, in other words in traditional delivery systems where tasks are separated, meaning simply that the architect designs and the contractor builds. Whereas, for design-and-build projects, the general contractor's PM plays an important role as the design works are expected to be performed by the contractor as well together with the construction project execution. The performance of both design-and-build tasks under the same roof means more responsibility and risk for the general contractor. This special condition is therefore, expected to be handled by the more senior PM.

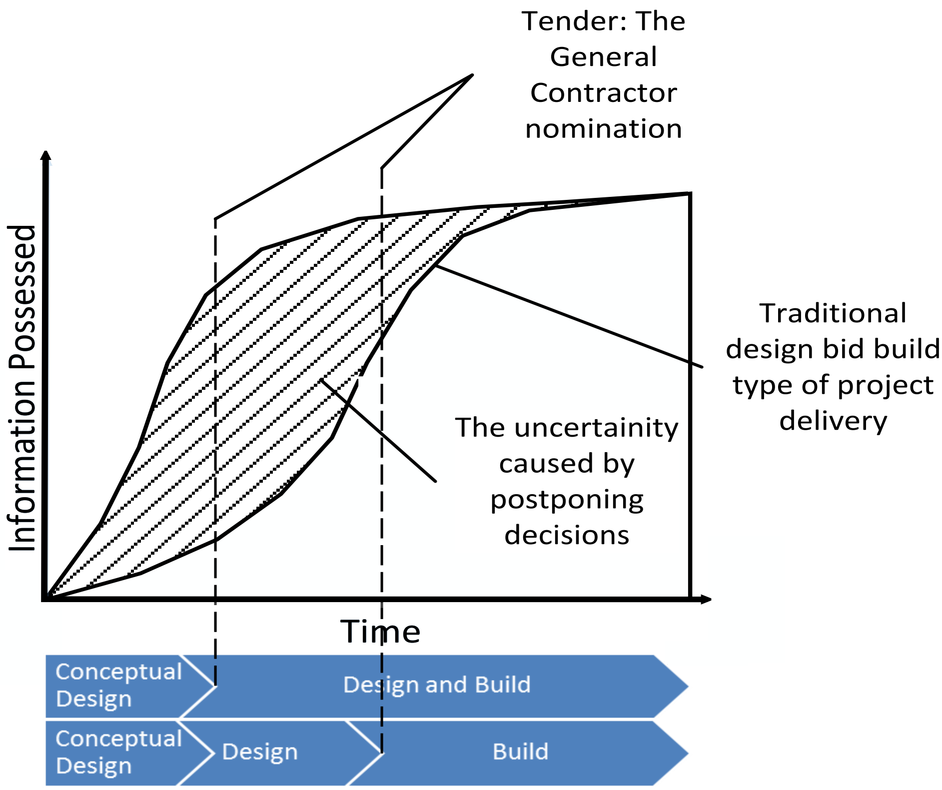


Figure 41. The uncertainty related to the project lifecycle in different project delivery systems (inspired by Winch et al., 1998).

Furthermore, in the design-and-build cases, the decisions must be made at earlier project phases whereas in the traditional type of design-bid-build contracts many important decisions, such as contractor, can be postponed. As seen in Figure 41, postponing decisions allows for more time for important decisions but it adds to the uncertainty. According to the solution paths, the challenge to overcome uncertainty in the design-and-build type of project delivery system has to be handled by experienced PMs.

The results don’t necessarily impose one project type against others as there might be project requirement forcing some decision to be taken in later stages to maintain the flexibility; however, mechanisms leading to successful tendering should be known when PMs are allocated to the different type of projects.

Although the projects that contractors bid on depend on the current project portfolio, technical and financial ability to execute the project and the risk acceptance level, it might be beneficial for the bidder to be aware of the combinations of different factors that are more likely to result in particular outcomes.

Finally, factors affecting the project outcomes are various and it is debatable to highlight particular ones, since projects are arguably unique. However, 39 projects with similar size and scope along a five year time frame give an opportunity to describe a pathway of factors working together to lead to a particular tender result.

4.3.2 Repetitions in dispute cases

Projects are unpredictable and non-linear and cannot be followed through specific linear phases (Koskela & Howell, 2002). Contractors’ operating in project-based industries work in many projects simultaneously, all fighting against time with limited resources to remain within the agreed budget and provide the requested quality. When a conflict occurs, it causes loss of valuable working hours, delay, frustration in the project team, unsatisfied clients, and, finally, financial losses. Moreover, future collaboration opportunities of parties and the reputation of the involved contractor are severally damaged (Li et al., 2013). Therefore, it is important to resolve conflicts in early stages before they turn out to be disputes.

In the conducted interviews, the general contractor’s advocates argue that ‘a project is classified as dispute case when claims by the parties are not discussed anymore one to one directly by conflicting parties’ (see Paper 5 presented in Appendix E). At that point, lawyers get involved and only they conduct communication. Most of conflicts are settled without a case becoming a dispute, thus avoiding the involvement of lawyers. The company managers interviewed underline that there is benefit for all parties to come up with a solution before a case becomes a dispute case requiring a resolution. An interviewed project manager states, ‘Disputes are time, energy and money consuming for the parties being involved’.

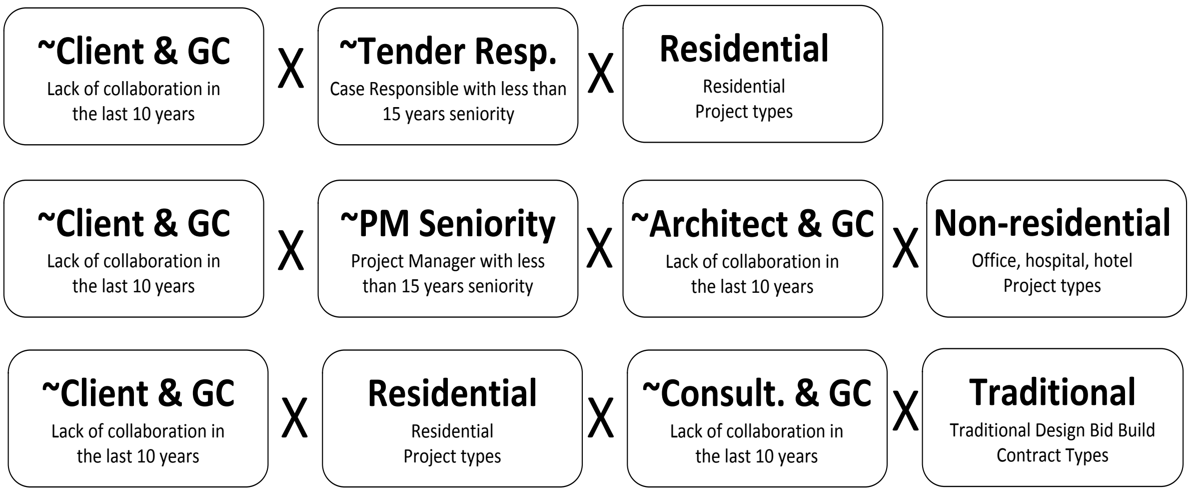
A list of projects with disputes was obtained from the judicial department. Dispute projects having a total amount of disputed money more than 2 million DKK were chosen as the threshold because the data available for those projects was more detailed to conduct the analysis. To maintain comparability, only building projects realised in Denmark were considered. As a result, 23 case projects with ongoing disputes were obtained. The 23 projects selected for the analysis had tender prices varying between about 19 million and 700 million DKK and the average tender price of the projects was about 155 million DKK.

A control group of 23 completed projects during the last five years without any dispute from the completed projects archive of the company were chosen to drive the analysis. To maintain comparability, these were projects of similar type (all building projects) and similar size. The average tender price of the control group projects is 138 million DKK. Again, similar to the disputed projects, control group projects vary between 19 million and 432 million in tender prices.

The following solution space was found as a result of the standard analysis for parsimonious solution. For the parsimonious solution, there was observed with full (100%) solution coverage. The solution consistency is also fully covered as all contradictory cases were eliminated. The frequency cut-off is 1.0000, meaning that all cases were taken into consideration even though the sample size is relatively large—46 cases—to conduct QCA analysis.

In some QCA analyses, the investigating researcher choses to include in the analysis only cases observed more than once and in some analyses even more. For this analysis, as there exists no importance or significance difference between cases, all observed cases were taken into consideration, resulting with frequency cut-off: 1.000000. Consistency cut-off: 1.000000 implies that contradictory cases have been resolved. There exist no two cases with identical conditions leading to two different outcomes. This is the result of an iterative process by involving different conditions with trial and error method.

Because of working with seven conditions describing a solution space = 128 solutions (2^n with n being number of conditions), the final function is a complex one. In Figure 42, three combinations of conditions obtained from intermediate solution are presented. As a result of Boolean algebra, they represent a more broad solution set compared to the parsimonious solution, and therefore they are more complex.



Sign: ~ represents absence of the condition in the solution set.

Figure 42. Three solution sets leading to dispute in building projects execution.

Obviously, this is still a parsimonious recipe; however, it is highly reliable as it explains 0.695652 solution coverage and it has a consistency of 1.0000. We can also minimise the formula by using Boolean algebra simplification shown in Figure 43 and we can conclude that lack of previous work experience between the client and general contractor is a necessary condition for the dispute to occur.

Nevertheless, lack of previous work experience is not a sufficient condition alone. It should be followed by other conditions. In the case of housing projects, the tender responsible of the general contractor with less than 15 years' experience in the field or lack of previous work experience between the clients' consultant in non-design-and-build projects lead to dispute. Another possible path leading to dispute is a combination of lack of previous work experience between the architect and the general contractor and the project manager having less than 15 years' experience in projects other than housing projects. All the above-mentioned three solution paths lead to dispute when combined with lack of previous work experience between the client and the general contractor.

At last, a final interview is conducted with the department chief of the judicial department in order to get a final approval concerning the confidentiality of the data and his feedback about the findings. His acknowledgement of the conditions and solution paths is considered as a validation of the study.

Although the final product the building projects are independently executed, the prescriptive study shows that there are organisational and processual repetitions traceable as patterns. These patterns involving combinations of certain organisation and process factors have substantial effect on project outcomes.

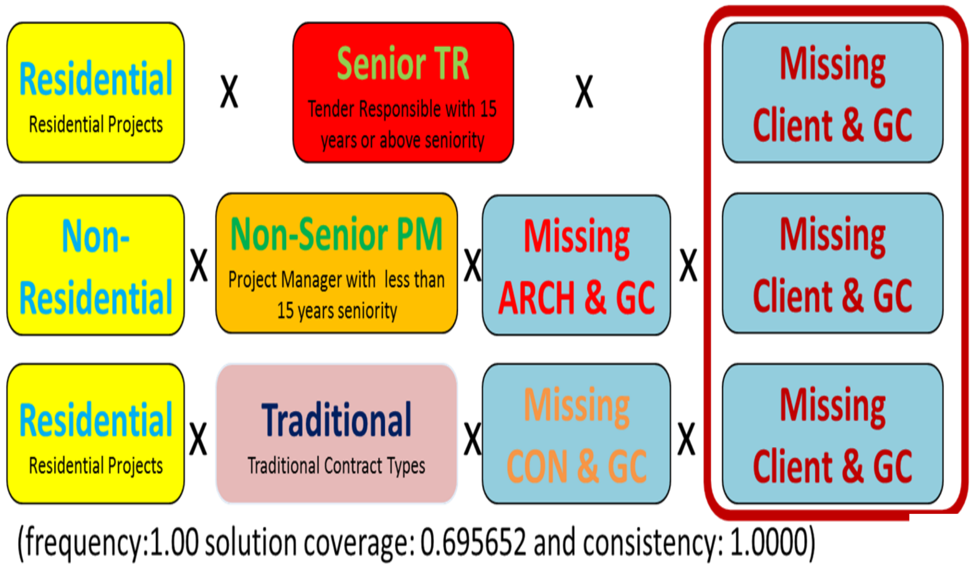


Figure 43. Three minimised solution sets leading to dispute in building projects execution.

In this prescriptive study, the vital role of repetitive patterns is investigated in two different studies: first tender phase (papers presented in the appendices C and D) leading to a project win or lose and then dispute cases in building projects (paper presented in the appendix E). Factors such as previous work experience between organisational entities, seniority of managers, and project delivery system tell us a lot based on the past project histories (organisation and process). To achieve the desired project outcomes, already proven patterns must be replicated in forms of standard applications.

The QCA presented in this prescriptive study has aimed to show the potential of drawing patterns within and across projects. Using a prescriptive filter like QCA highlights the systematic in a process that could otherwise look chaotic. As will be elaborated in the discussion, it is vital that this systematic is embraced according to its own nature instead of trying to force it into a certain direction. Only in that way, it is argued, can the benefits of modularity be reached. Simultaneously, QCA brings modularity up to the level of process and organisation.

The next study seeks to give a more concrete example of how to modularise the design process, but through a different method. As will be seen, the DSM can work as supplement to QCA in speeding up the construction process by a method of clustering.

RQ5: *How do we operationalise modularity in building construction?*

4.4 Descriptive Studies II

This study final stage study investigates the above-mentioned RQ how to operationalise modularity in building construction in two sections. The different ways to operationalise modularity taking process and organisation as well into consideration alongside with product are illustrated in two examples. First, a study investigating the dependencies of activities in the design phase is displayed by using DSM in the example of MTH. Second, the overall process map is drawn in order to give an overview of the material and product flow (VSM) in the case of a trade contractor.

4.4.1 Design Structure Matrix

This study investigates the software DSM as a tool for planning and designing the construction process. The software was originally designed to plan the design process information flow by visualising the iteration and design reviews. Moreover, the different parties, such as designers, general contractor, trade contractors, engineers, consultants, and municipality officials, represent the structural uncertainty and uncertainty in goals and methods described in Chapter 3, Section 3.2 (Williams, 1999). The DSM tool elaborated in Chapter 2, Section 2.5.4 was tested in MTH façade design process. Furthermore, the detailed process of data collection (interviews and cross-functional workshop) and analysis can be found in Paper 6 presented in Appendix F.

The study suggests that DSM is a valid tool for converting the similarities within the design process to manageable modules and clusters as described in Chapter 3, Section 3.3 about modularity. Doing so, the study concludes, the design phase can considerably be accelerated and make it much easier to re-apply the same design form in subsequent projects instead of embarking on a unique journey for every new process.

Initially, the manual approach of clustering the DSM posed a challenge because of the strong interconnections within the work activities. Cambridge Advance Modeller was used with a cluster algorithm to group elements and to create modules within the façade design process. The goal was to find subsets of the DSM elements (i.e. clusters or modules) that were mutually exclusive and have a minimal interaction with other subsets. This implied that the activities in the module were significantly interconnected while the connection to the rest of the system was as little as possible (Chapter 3, Simon, 1962; Lindemann, 2009).

To run the software required iterative process as well because in each step the clusters defined by the computer was analysed and further processed with other activities in order to get the optimal solution. After running the software, it was found that the activity elements containing the acoustic and the static analysis of the façade were not integrated in the clusters, because of their low in-degree values. Moreover, the activity elements that cause the most iterative processes were found to be the design and geometry, cost calculation, and the selection of the façade elements. These three activities were then defined as parallel running activities due to their fundamental nature and excluded from the second cluster iteration. The result of this final DSM run can be seen in Figure 44.

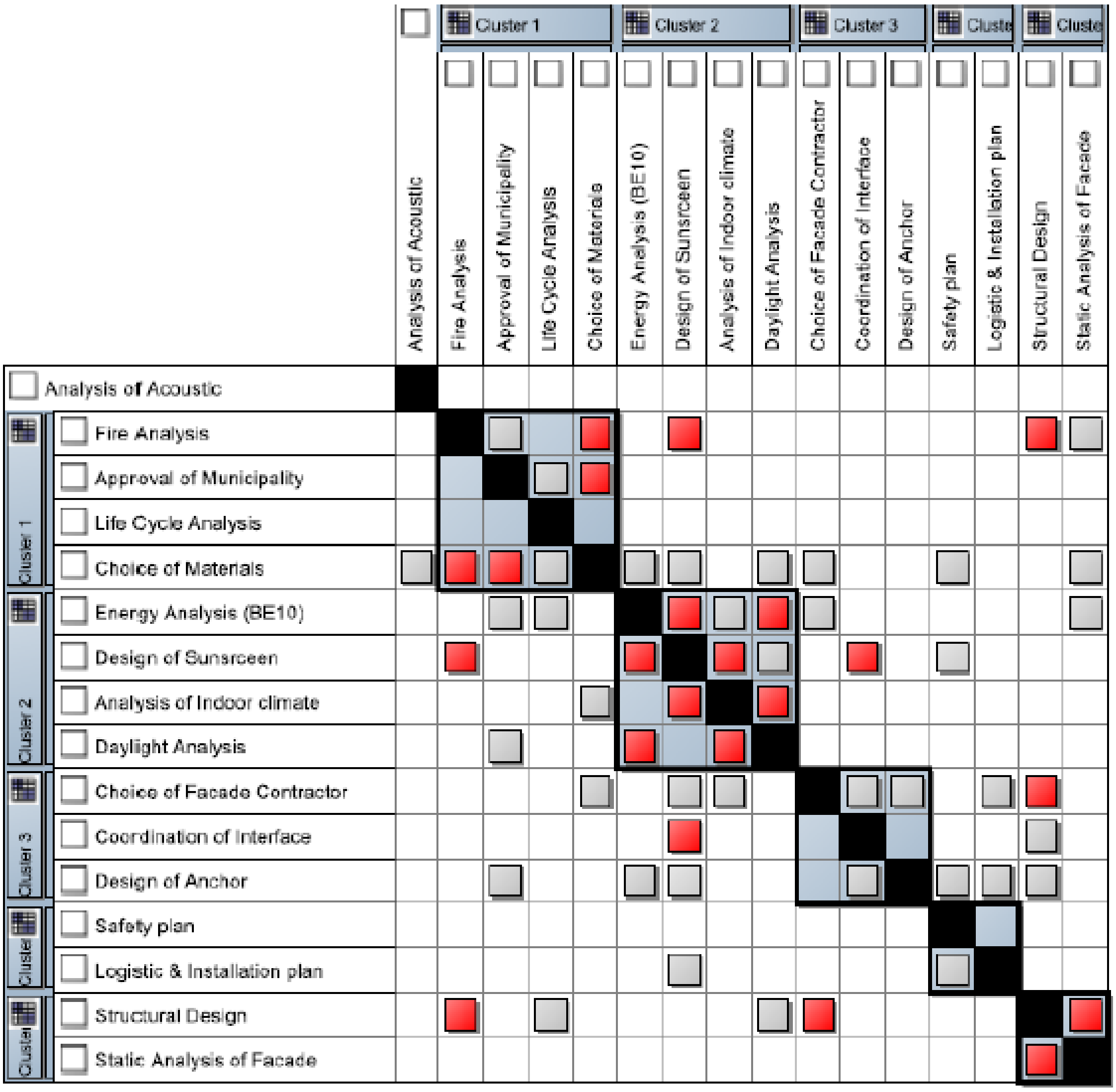


Figure 44. Final DSM with clustered activity element from the workshop output (Wynn et al., 2010) Creating Process Modules.

The research has confirmed that the design process of facades has a high degree of complexity elaborated in Chapter 3. This complexity comes mainly from a large number of independent actors who all are affiliated in the process, creating many interconnections and interfaces with a high degree of dependency, thus resulting in integrity (as detailed in Chapter 3, Section 3.1.1). Moreover, the actors are involved in an iterative process throughout the design phases and additional dependencies make the process fluctuating and difficult to manage (as detailed in Chapter 3, Section 3.1.2.).

The literature study reveals there are few published articles about the DSM and Multi Domain Matrix (MDM) in the construction industry in the recent years (Khan, 2016; Furtmeier & Tommelein, 2010). However, the internal interview results show the building at the industry has not yet adapted to this concept. Furthermore, the time frame in the design phase is limited, and the decision and planning tools are not sufficient. As a result, decisions are often delayed, resulting in project changes and new sets of iterative processes, which further extend the design process. I believe this transition needs to be handled more efficiently with stronger design management and better planning tools.

DSM tool appears to be an excellent tool for managers to use in the design process of facades, as it enables a mapping of dependencies. DSM clusters the work activities and actors into process modules make the design process more manageable and easy to digest. Moreover, to operationalise modularity by applying DSM, design managers could plan the design process, structure meetings, and gather the team of experts.

Through application of modularity, just like module façades can accelerate the execution phase, our proposed design modules will accelerate the design process, because the required geometric coordination of physical and functional performance parameters for each façade system will be managed within the clusters identified as a result of the DSM cluster analysis. This can be explained from theory as the positive effect of the MID to the MIP elaborated in Chapter 3, Section 3.3.3.1.

The DSM method successfully enabled the identification of both visible and invisible dependencies and interfaces between the crucial cross-organisational design activities that are related to the façade design process. Furthermore, the method successfully established cross-functional process modules enabling the symmetry between product and process as suggested by Ericsson and Erixon (1999) in section 3.3.3.2.

The application of the modular approach in design has the advantage of accelerating the execution process, as the workload and coordination are transferred to the design process, which in turn requires enhanced design management. Clustering work activities and thus creating process modules defining work activities and organisations involved in the design process is a way to operationalise the modularity theory (Hölttä-Otto & de Weck, 2007 in mixed perspective 3.3.3.1). Process modules describing organisational dependencies in different stages of the design process are helpful in order to visualise and execute the process both for project participants and managers.

It would be interesting to discover the dependencies and information flow within each cluster discovered in the analysis of the DSM, mapping them in detail and revealing the next level of complexity. The same cluster analysis can be applied to another tool that is MDM, similar to DSM, but in addition adds people responsible for activities.

Although every design process is different, focusing on the similarities across and within the processes show us the potential use of the repetitions effect in the design phase too. While this case of DSM helps us ‘modularising’ the design process of a construction project, the next case will highlight what can be done at micro level as a single trade contractor?

4.4.2 VALUE STREAM MAPPING (VSM)

This study takes as its case company Southland Industries, which produces plumbing solutions for construction in North America (see Paper 7 presented in Appendix G). The company's prefabrication of modules serves to exemplify to what extent a single contractor company can utilise modular technology in order to achieve efficiency and prevent wasted resources (time and material). At the same time the study presents the VSM as a tool to provide a holistic view of the construction process, pointing out possibilities to implement and improve the implementation of modular principles.

Figure 45. Van Ness and Geary Hospital construction site visited in December 2015.

Southland Industries is one of the largest mechanical, electrical, and plumbing (MEP) building system experts in the US. Southland Industries is currently engaged in delivering two large-scale new hospitals located in central San Francisco, California for Sutter Health. St. Luke's Replacement Hospital is a 20,900 m2 (215,000 square feet), 120-bed project and Van Ness and Geary Hospital is a 68,750 m2 (740,000 square feet), 274-bed project. Both projects are under construction as of December 2015 as can be seen on the picture below taken from Van Ness (see Figure 45).

Southland Industries has signed an Integrated Form of Agreement (IFOA) to deliver the mechanical works for these two hospitals using IPD. The increasing uncertainty and complexity in projects work as a driving force for partnering (Thomsen et al., 2009). This approach requires a pain share/gain share approach, where all team members share in the risk and reward for delivering the hospital on time and on budget. But a complete IPD implementation includes choosing the right people and implementing the right processes.(Ballard et al., 2011).

To maximise production efficiency for the two hospitals, the two projects are leasing a large warehouse on Treasure Island in the San Francisco bay. A part of that temporary workshop is dedicated for the case company's prefabrication of modular plumbing fixture carriers. This is in addition to more typical prefabrication of the mechanical ductwork in the case company's permanent shop. The case chosen is a typical example of a large-scale hospital building construction in the context of California that can be taken as an example of worldwide construction professional building large-scale facilities.

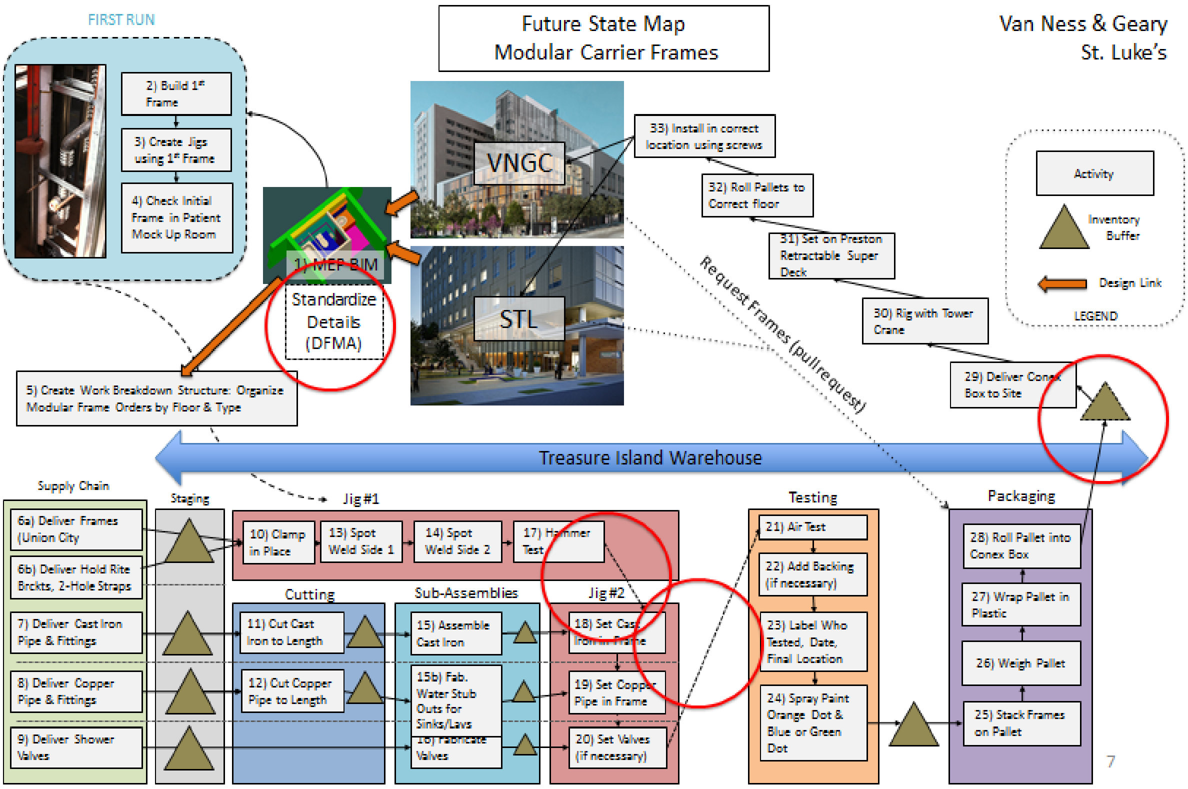


Figure 46. VSM of the modular frames, from paper presented in Appendix G.

VSM appears to be the tool visualising the internal complexity generated by product, process and organisational variety highlighted by Wilson and Perumal (2009) as elaborated in Chapter 3. The entire VSM created is presented in the Figure 46. The areas marked with red circle are the possible identified areas for improvement. VSM flow consists of main stages detailed in paper presented in appendix G. These are: first run, supply chain, cutting and sub-assemblies, jig#1 and jig#2, testing, packaging and storage, and delivery.

The process begins with a fixture carrier design created using Building Information Modeling (BIM). As the creator of the modules states 'it wouldn't really be possible without the BIM.' BIM allows the practitioners to see the overall picture and therefore catch the similarities in design in different parts of the structure. Therefore, it becomes possible to identify each repeating module with number or repetitions and then create a jig (as seen in Figure 47 on the left-hand side) to build it if it is feasible.

To make it clear, a jig is a simple framework created for repetitive usage similar to a mould enabling fast and accurate assembly. As dimensions are predetermined and fixed in a jig, there is no need to use a measurement when making the assembly therefore, there is no space for misplacements and dimensional mistakes. The jigs are deliberately produced of wood making adjustments possible from a batch to another one. In case of mass volume production steel jigs can also be operationalised for long life usage.

By implementing the jigs in production, remarkable man-hour reduction could be obtained at the workshop. According to the company professionals, the man-hour estimates in the planning phase were made based on the similar type of work performed at site. They had foreseen six employees working for both St. Luke's Replacement and Van Ness and Geary Hospital projects but during the execution of the manufacturing the project team realised that three full time employees were sufficient to serve the project pace on-site. Moreover, the project team all agreed that hospital construction required far more sophisticated prefabrication operation than a typical building project would normally do. Therefore, if a prefabrication operation works successfully for a hospital project, which has an extensive amount of MEP works standardised jigs surely will work in an ordinary building project. The application will be a preference though because the piping works in ordinary buildings will not be as heavy as it is the case for hospital buildings.

Improvement areas marked with red in Figure 46 are listed in three categories. First, the attempts to achieve a more continuous flow will help reduce inventory buffers. Currently, because of the pace differences which are elaborated in Chapter 3, Section 3.1.3, between the building site and the workshop the inventory at the workshop is full with stocks of modules ready to be shipped to the site as seen in Figure 47 on the right-hand side. Second, the success at workshop could be used to cross-train others in the company.

This includes management through the lean 'go and see for yourself' philosophy and the workforce through the principle of creating challenging and meaningful work to develop the skills of all employees for further implementations. Last, the opportunity through BIM to standardise the design of future plumbing carriers can be applied to all future projects. This will allow for continuous improvement of the current process using Design for Manufacturing and Assembly (DFMA) principles. In the future, the projects should be designed according to the already present jigs, which are most productive in the manufacturing.

What Southland Industries obtain by following this process is remarkable. First, they achieve a considerable reduction of (material and time) waste by use of the production line and Lean Philosophy. The tasks have been standardised and 'mistake-proofed' (Rother, 2010, p.113). Second, they manage to batch two hospital projects works in one temporary workshop that is an immense savings exercise through economy of scale. Third, they make great use of BIM in order to identify repeating modules to be prefabricated across two projects. It is clear that without presence of complete BIM the economy of scale in the second point would not be possible.

This prefabrication process of mechanical works is a clear example of the achievements that can be made even as a single trade contractor in a large-scale construction. The modules created for the prefabrication process do not require high volume production or high capital investments. Thus it represents a successful application of modularity achieved through entire process visualisation, early and complete BIM implementation.

Figure 47. Welding jig used as frame on the left and stock of prefabricated modules on the right, 13 October 2015.

Finally, although those modules seen in Figure 47 are created to serve the current project design, they represent a proven solution for future projects to move from one-a-kind type of production to standard work.

‘Any organization which designs a system will produce a design whose structure is a copy of the organization’s communication structure.’

Melvin E. Conway

American Computer Scientist

5 DISCUSSION

This chapter presents a description of the productivity problem together with the special conditions adhering to the Danish context. Then, a discussion of the findings of the studies conducted will be facilitated, separately and combined, to lift the insights up to a higher analytical level. Based on this discussion, some final recommendations towards an integrated approach to building construction combining product, process, and organisation are given.

5.1 The productivity problem

To sum up the status quo of the industry, as presented so far in this thesis: The building construction has reached a level where the costs can’t be reduced significantly anymore. Unions and market rules secure the wages, the machinery usage is high and expensive, and materials are procured as economical as possible from all around the world. As a result, the only way left to make improvements in the building industry is to increase productivity.

To start with, any improvement attempt that would help the building construction durations get shortened or make the process more predictable, the design and building phases more foreseeable, is primarily advocated by clients as such improvements would reduce uncertainty and therefore increase the will to invest in building construction. Moreover, increased productivity will make the building projects more affordable and very possibly lead to an early turn over and commissioning to the client that in turn will make the investment payback periods shorter.

Second, increased productivity is also beneficial for the contractors as it would definitely mean less indirect costs for the contractor company as machinery and equipment depreciation or rental periods assigned for the project and monthly salary expenses of the personal working for the project would be reduced accordingly.

Third, with increased productivity as the amount of output per input will increase, the salaries of all involved professionals will increase because there will be more building projects creating more job opportunities. Furthermore, employers will enjoy increasing profitability and they will gladly pay more in order to get competent employees contributing to the productivity.

Finally, a productivity improvement in one field would trigger a chain reaction in others causing positive outcomes for the entire building industry.

All in all, productivity is of course desirable for all parties involved in the building construction process. There is a lot to be gained in handling complexity and increasing predictability. The methods and ways of organisation in building construction seem in many ways archaic compared to other industries. At this point, I suggest we turn our attention to our own Danish context, which I argue is actually very suitable for improvements in product, process, and organisation.

5.2 The Danish setting

The distinguishing characteristics of the construction sector that I have outlined in the introduction chapter are all present in the Danish context. These are: immobility, high cost, durability, uniqueness, high level of impact, time lag, amount of work tasks, subjection to atmospheric conditions, amount of stakeholders, project delivery systems, labour intensiveness, and discontinuity across projects. Moreover, there are some extra local attributes adding to the specific conditions of building construction industry in the context of Denmark.

First, to start with the negative characteristics, poor weather conditions are the first attribute limiting the workability in the building field. Winters are long and dark, making it more difficult to work outside and the strong winds often cause delay in building construction.

Second, labour unions are strong in Denmark, forcing inflexible working hours and pressing salaries upwards. It is not unusual in Denmark to see the tower cranes stop working at 3 o'clock in the afternoon on Fridays and stay still until Monday morning. This, of course, slows down the speed of any building project.

Third, there is high quality demand and personalised solutions are appreciated. However, the prices are continuously compared with other countries and market competition is high at national and international level. This is also negative because local SMEs are pushed towards working with cheaper and often incompetent workers to get costs down in order to survive in the low price wins market rules.

Fourth, the machinery costs are high with respect to other developed countries, due to higher operational and maintenance costs. Finally, yet again as a result of the factors already mentioned, rework costs are high.

The above-mentioned factors might be more or less common in the building construction sector worldwide but they are particular in the Danish context. On the other hand, Denmark represents a favourable cradle to apply modularisation in the building industry.

First, the achievements are already remarkable in the building industry. Concrete elements production in the factories has already become an industry standard. This represents successful application example for non-volumetric pre-assembly by Gibb (2001) as shown in Figure 18 on the upper right-hand side in the theory section.

Second, most of the work force is trained and experienced. The general educational level is high and skilled workers are dominant in the work market.

Third, there is a well-established tradition of industrial working culture going generations back. Kids wake up early, and many work places including the day care institutions start at 07.00 in the morning. The employee attendance is very high and all meetings start punctually on time.

And finally, the companies operating in the industry have intention to improve productivity since they have started to invest in research and development initiatives like the Ph.D. dissertation you are reading now. All the above mentioned conditions present in Denmark makes the country a very favourable place to boost the drive to modularise the building construction which could lead to a possible productivity improvement in the industry.

Now outlining the conditions for this to actually happen, a discussion of the findings throughout the different studies conducted for this thesis will be offered. These findings will be discussed both within studies and across studies. Through this exercise a picture of possible future scenarios of modularity in the Danish construction sector should be drawn.

RQ2: *How does the complexity of the way in which building construction is organised, cause unproductivity?*

5.3 Discussion of Descriptive Study I

As a result of the descriptive I study, the way of the organisation in the building construction industry is identified as the cause for the lack of synergy leading to the unproductivity. It is not that the modular product development steps outlined by Ulrich (1995) in Chapter 3, Section 3.3.3.1 are not known to building industry professionals. Actually, building construction professionals are experts in applying these steps because, contrary to the product developers working with product platforms, building construction professionals do use modular design steps from scratch every time in every project. Rather, than working with a product platform taking already agreed standards and process for granted.

The results of the Danish hospital case analysis show that the building is reinvented in each project through independently running processes leaving behind unrealised potential for leveraging similarity across the projects. The client organisations are uniquely designed for each region with separate user involvement, running parallel to each other. If the projects had been organised in a sequential way, one would have been given the opportunity to gather experience along the way and adjust the future design accordingly.

In Denmark, the majority of organisations are flat supporting the participation and direct democracy in the structure of the society. Speaking on a very general term, every individual is encouraged and expected to take part in the administrative committees, at work, in day care, schools, residential organisations and local communities. You can call your chief or boss at the work place, use her or his first name, and students call their teacher by her his first name. Moreover, the user involvement processes in every big or small decision that will have an impact in life is endorsed in order to achieve the most democratic solution. However, the most democratic solution is not always the most optimal or the best solution in technical terms. The relation between the organisation and product (design outcome) indicated yet again the symptoms described in the complexity cube by Wilson and Perumal (2015) presented in Figure 12. This is also the case when it comes to hospital design.

Each region wants their super hospitals to be the best in the country and a trademark for the region. As a result, the projects are executed in parallel and follow the same phases with a high degree of user involvement in each of the projects. The user involvement implies the active participation of nurses, doctors, patient carriers, and hospital administrators next to architects, engineers, and consultants to form a unique team that creates a unique design.

User involvement processes are very helpful mechanisms to build common identity and increase the commitment level of individuals to their work. Another way of organising would be designing super hospital centrally and multiply exact replicas of it as many times as required. However, decisions taken centrally create distance and tension between the decision-makers and the locals. Moreover, the local and project specific needs are different from case-to-case. Local end users are obviously the ones knowing best the local needs and therefore they are the best to create the solutions.

However, the results of the descriptive I study show that despite detailed user involvement processes in each of the 27 hospital project, the actual final designs of all hospitals look remarkably similar. Taking single patient rooms as unit of analysis, 70% of the projects use the same archetype (the L-type) and others the box archetype (the C-type) with variations. Restricting the user involvement processes to concern the daily usage areas as well as the architectural finishes could have saved a remarkable amount of resources. In that way, end users and regional client representatives could mark their unique fingerprint on the final product instead of creating slightly different single patient rooms again and again.

Furthermore, the variation in single patient rooms is inadequate according to all levels of modularity. For MID, as outlined above, it creates unnecessary variation preventing standardisation and future improvements. For MIP, the opportunity of producing single patient rooms in bulk with higher volumes and repetitions as volumetric units to be shipped to the final locations is missed. Such a repetitive work could boost the productivity and make the Danish single patient rooms a trademark in the health care sector. Finally, MIU appears to be a missed opportunity, as the non-identical rooms will require different improvement in the future. A common upgrading project will not be possible because they all have different locations of pipes running and electrical outlets individually placed. Another outcome of MIU, final users, health care personal changing work places from one hospital to another will have to cope with different designs than the ones that they are used to.

A stronger central coordination, prioritising common needs and potential repetition areas that would allow the use of modular standard solutions (like single patient rooms in super hospitals) could have achieved this. Highly productive modular solutions with standard rooms and components could be reconfigured in every location to create still unique hospital facilities to the benefit of the client and society.

The projects are organised and designed as independent entities not enabling the repetitions and learning across projects. The way the hospital buildings construction is studied in Denmark reveals all the dimensions of the complexity covered in the theory section.

The design solutions in the observed cases differ in size and shape across projects although they share the same functionality and predefined standards. Moreover, the variety in interior design and placement of MEP in/outlets make the interfaces remarkably different from one project to another.

There is a lot of waste (i.e. rework and non-value adding variety) in design and the way the hospital construction is organised.

RQ3: *What are the current understandings and applications of modularity in building construction?*

5.4 Discussion of the Exploratory Study part I

However, implementing modularity in real life is easier said than done. The exploratory study reveals that the reported effects of modularity are not vitalised in the building industry at a level comparable to other industries, as outlined in Chapter 3, Section 3.3.2. Modularity is not known and recognised in building construction industry. Its understanding is limited to the products and pre-fabrication efforts outlined in Chapter 3.

Moreover, in line with Baldwin and Clark's (2000) differentiation of MIP from MID and MIU, the priorities of construction industry producers, such as product manufacturers and house builders, contrast with the priorities of contractors and architects. The producers prioritise creating well-defined modules at the design phase (requiring freezing of the design) so that production can begin. The architect, on the other hand, has still undefined functional needs and most of his or her projects evolve during the project lifecycle illustrated in Figure 41 (and inspired by Winch et al. (1998)).

Reviewing recent studies of modularity (Ericsson & Erixon, 1999; Hölttä-Otto & de Weck Jonsson, 2007; Rudberg, 2014; Pan, 2007; Gibb, 2001) reveals a number of recurring advantages and disadvantages. Again these studies,] focus only on the product platform methods and on off-site production. The effects of modular solutions in construction from a contractor's perspective differ notably from the advantages and disadvantages named in this literature. The results of the first MTH case in exploratory study show exactly this. Producer companies have different motivations when providing modular solutions than contractors operating in the project-based industry. Although some advantages overlap, such as cost, health and safety, logistics and quality, some, such as common unit, carry-over, separate testing, service, maintenance, and waste reduction seem to be less relevant and therefore less important for the contractor.

Moreover, some of the reported benefits of modularity can be seen as weaknesses from the contractor's perspective. For example, fixed technical specifications are mentioned by a PM as a clear advantage. However, as construction projects have different conditions and requirements, and clients have different tastes, the products used in one project may not be accepted or approved for another project; thus, fixed technical specs become an obstacle for the contractor rather than an advantage.

The application of modular solutions can have a significant effect on processes and organisation in construction companies. Time saving and productivity are apparent advantages of modular solutions that can easily turn out to be opposite where the construction process is not well managed. Therefore, the contractors' PMs are sceptical about modular solutions. Modular solutions put heavy demands on the shoulders of contractors: the need to freeze the design very early, the need for even better communication between construction parties, and the redefinition of project responsibilities. PMs believe that modular solutions carry risks that they are not willing to take. They also believe that clients would be open to modular alternatives but that the architects and consultancy companies are risk adverse and, therefore, prefer to stick with the tried and tested methods in their existing practices.

For sure, it is important to apply modularity already early in the design phase in order for it to succeed. In the case of contractors, the conducted case study recommends as early an involvement in the project as possible. Design-and-build projects give more authority and therefore opportunity for the contractor to apply modular solutions compared to the classical design-bid-build projects. In design-and-build projects, the contractor is typically included in the project at earlier phases where important decisions are made cooperatively, and that gives the contractor greater opportunity to influence the design process and construction method. In that way, more space to apply modular solutions is created.

5.5 Discussion of Exploratory Study part II

However difficult it is to apply modularity, as a contractor or as any other actor, companies around the world do apply it in their own ways. The second part of the exploratory study elaborates the perception of the modularity described in the first part by bringing in a variety of cases from different countries of origin, trades, market placements, and sizes. The concept of modularity in a broader context is still not recognised even by the parties implementing it as a part of their businesses. An architect case is the only exception applying modularity consciously in design. Therewithal, the repetitions and standardisation achieved through the repetitions effect are very well acknowledged and utilised by all the cases presented.

This part of the exploratory study supports the idea that modularity, as a strategy in building construction, is an essentially logical and natural approach. Looking back and forth in history confirms this idea: the archaeological site of an ancient Greek town (column structures) next to my hometown shows the existence of same or similar drivers back 2,500 years ago. I see the ghosts of the craftsmen shaping these stone made columns (Figure 32) at the mine several millennia ago when I look at the steel column fabricated in the factory (Figure 33) in the Bay Area in the year of 2016. I also see them when looking at the Polish workers making the final assembly at a day care site in central Copenhagen today (Figure 31) – these workers are not more welcome than slaves were in urban areas of ancient Greece.

Surely, with time technologies change and functional requirements change—but the drivers leading to modular solutions remain constant. The ghosts remind us that modularity was a logical technique in the past and that it will continue to be so in the future. Cost, time savings, construction speed, and site constraints in terms of labour, space, and logistics are the main drivers pushing builders towards the modular way. These drivers can be gathered under the product, process and organisation domains affecting each other as presented in Chapter 4, Section 4.2.2. Paying more serious attention to the different domains and to the dependencies within and between them is the way to make building construction more efficient, as I will argue.

Resembling the MTH case in the exploratory cases interfaces of modules with each other and other components are mentioned as a critical point deciding the success of the modular choice. In accordance with the plug-and-play thinking mentioned in Table 4, the physical dimensions require precision of millimetres otherwise the entire effort of modularisation is wasted. 'If it fits everything goes smooth if it does not fit the amount of rework and frustration swaps all the benefits of the modularity', stated the PM at BSkyB site in London when talking about assembly of modules at site.

Furthermore, it is very important to be at the table when design decisions are made to be able to apply modular solutions successfully. Many case participants, therefore, placed themselves as developers in the market because they wanted to have full control over the design. A PM taking the contractor and consultant role stated, 'if a building project is not designed in accordance with the modular solution to be applied from the very beginning; it is most likely that the application of modular solution will fail'.

So, when considered at the right time with the right process there are great advantages of modularity in buildings. All interviewees acknowledge the repetitions effect as a foundation for productivity. I advocate that the proven advantages of repetitions and dispersed applications of modular solutions in the building industry at product level can be consolidated with the consideration of process and organisation levels as well.

The modularity is associated with off-site production and prefabrication only. There is ambiguity in the way practitioners use terminology.

Although the advantages of modularity is known and acknowledged the application appears to be limited to only product modularity.

All cases focus on product and therefore a comprehensive implementation of modularity covering processes and organisations does not occur.

RQ4: *How can repetitions across the unique projects be traced?*

5.6 Discussion of prescriptive study

So how does one go about this task? To begin with, construction work looks like a war. The construction site is just like a battlefield with clashes of interests and different agendas fighting to overcome one another. Also like wars, building projects have distinguishing characteristics making them different from each other. Still, in accordance with the analogy, there are nevertheless several repeating patterns across projects even if when that may not be the intention, as shown in the descriptive I Danish hospital cases. The challenge lies mostly in tracing and operating these patterns.

I have aimed to trace repetitions across projects in the prescriptive study. If the building projects were all different and no cause and effect relationships were perceivable, the building construction would not be complex but chaotic, according to the Cynefin framework presented in Chapter 3, Section 3.2. However, building construction is by definition complex, making pattern management possible through prescriptive filters. I have used QCA in my analysis as a prescriptive filter to identify patterns leading to particular project results in building construction projects.

In the prescriptive study, the processual and organisational factors coming together in particular combinations lead to foreseeable results as shown in two different case studies. In the first case study, the combination of factors leading to a successful bid is investigated in the MTH example. Having the same point of departure, combinations of factors leading to disputes is researched in the second case study.

Although the cases investigated and the final project results tested were different in two studies, a common factor appeared in both studies. Complementary to Alter's (2006) claim about the integration between participants being a multi-level process (presented in Chapter 3, Section 3.3.3.3. The previous collaboration between the client and the contractor was found to be the necessary factor in all solution sets. However, previous work experience between the client and the contractor work is not sufficient in order to reach the desired project result. Running a QCA before project start is a very viable and relatively easy task that can potentially save many resources.

The above-mentioned dependent variables (tender result and dispute probability) were chosen for the analysis because both were critically important for the contractor. Other project outcomes defining project success that is context dependent may be chosen as dependent variable. Moreover, the factors to be traced in every future project can be elaborated according to the case knowledge and experience.

Furthermore, the descriptive factors such as project size can be supplemented by performance indicators which are more dynamic in order to provide a prescription for the decision makers handling the uncertainty. The results can be forecasted and the resources (e.g. 'experienced managers') can be allocated to the projects accordingly.

So, an operationalisation of modularity requires identification of the complexity first according to the Cynefin framework. Then, in accordance with Koskela and Kagioglu (2005), the actions can be planned based on the existing patterns obtained from previous projects in order to move from complex to knowable, and later to the known. The ultimate goal should be to reach to a legitimate best practice with repeatable and therefore predictable cause and effects and standard processes.

The processual and organisational repetitions leading to particular results are identified for a similar set of projects (products). By identifying repeating patterns having a decisive role in the project outcome, the right combination of factors leading to desired project results can be predicted.

RQ5: *How do we operationalise modularity in building construction?*

5.7 Discussion of the descriptive study II first part

As the first case of the prescriptive study II describes, DSM helps to identify and visualise those process modules from the very beginning. Whereas QCA helps identifying patterns across projects, DSM draws a modular pattern within the project itself.

Coming back to the war analogy, it is no surprise that one of the most widely applied planning techniques in building construction is Program Evaluation and Review Technique (PERT). PERT was originally developed and applied by the U.S. Navy to simplify the planning and scheduling of large and complex projects primarily used in Polaris Sub-marine production. Given the origin of Critical Path Method (CPM) and PERT in the aerospace and military industries, the methods focus on the earliest possible completion (Birrell, 1980). As a response to the typical question in everyone's mind related or unrelated to the building process: 'When the project is going to be finished?' the earliest possible completion date as a result of CPM is declared. This may make sense in both warfare and in construction: both industries work against the clock and completion deadline is out most important. Nevertheless, the CPM application in the building planning treats all resources as infinite, personnel can be hired and fired freely (Büchmann-Slorup, 2012), and iterative processes as linear.

However, in building construction neither the resources are infinitesimal nor the dependencies are one directional. This is particularly the case in the design phase where many trades come together and work with iterations. The socio-political complexity presented in Chapter 3, Section 3.1.4 is the direct consequence of the increasing engineering and contractor specialisation combined with more tight construction schedules (Howell & Koskela, 2000). Iterations are sometimes between two parties providing input to each other's work but they are sometimes between multi-functional activity groups requiring many design professionals who should work together. In that case, work clusters forcing close cooperation with the participation of particular organisational entities representing different parties are needed.

Surely, there are iterations not captured in the modules that need special attention. However, most of the iterative design activities are captured together in process modules. The DSM articulates the mutual dependencies within each project—an insight that may have immense benefits. DSM also highlights the fact that no matter how much deadline pressure may be executed from one party to another during the building process, efficiency does not increase—only by respecting and operating with the iterative nature of the construction process one may strengthen productivity. A DSM created for one project design case can be the starting point for the next one. Therefore, with project specific adjustments, process modules can be used across the projects (as described in Chapter 3) for coming product modules.

It might appear as a burden to collect all the necessary information from all relevant parties in the beginning. Alternatively, the parties involved may not be willing to participate in such effort. It is inevitable that the DSM application will fail if competent trade professionals having the required experience with the design process do not prepare it. Therefore, a common effort from all involved parties is necessary. Only in that way fruits of the process modules as a result of the DSM application can be collected cooperatively.

The activity clusters identified in the study work in accordance with the definition of modularity made in the theory section. That is the dependencies of the activities within the same module are high and the dependencies of the activities across the modules are low.

5.8 Discussion of the descriptive study II second part

The QCA and DSM cases so far have showed us how patterns can be traced across and within projects respectively. The last case of the descriptive study II, presents us with a technique (VSM) to draw a pattern on an even smaller scale: the single trade contractor level. This pattern, used to visualise for the case company the flow of mainly products and materials, again highlights the loops and the circular ways of the building construction process. Like QCA and DSM, the VSM tool speeds up production and at the same provides a corrective to the traditional hierarchical and one-directional way of approaching site work.

In general, the building construction organisation is very fragmented and single project participants have limited authority over other parties in many cases. The regulating role is typically expected from the architect representing the client who has little or no experience with the actual building construction business. All the parties hired for the building project are affected by the decisions made by the client sitting at the top of the pyramidal hierarchy. Speciality contractors working on a single trade have even less influence on the overall process. First, they are often involved in the process at later stages when every major decision is already taken. Second, they have a relatively little share in the building project—typically not big enough for their voice to be heard on a general level. Third, depending on the project delivery system used in the building project, they are often sub-contractors to the other parties in the project placing them on a very low level in the pyramid.

Southland Industries represents a specialty contractor, providing plumbing fixtures for large-scale hospital building construction in the context of California. Now addressing the results of the Southland case presented in the previous chapter, BIM appears to be the first and most important milestone of the entire process. In this case, BIM is so integral that even the foreman working on the floor, creating the jigs, admits its decisive role. The foreman himself doesn't have any competencies in BIM and he claims that he has no time left to learn it because he is already officially retired. However, he is very directly admitting that none of his work would be possible without a complete BIM in the beginning of the process. Southland Industries has the opportunity through BIM to standardise the design of future plumbing carriers so that many of the same jigs can be reused. While this may not always be within the trade contractor's control because of the placement in the pyramidal hierarchy, it would be a great benefit to continue this prefabrication on future projects. Future BIM designs could use the existing jig setups. Furthermore, the case company team has gained valuable insight into what type of fixture design is easy to assemble and which is more challenging. If this feedback can be communicated to the design team of the overall project, future BIM designs could make assembly even more productive. This concept is referred to as DFMA and could leverage the gains at the workshop and increase productivity on the future project.

As a way to overcome the barrier concerning the need for high volume delivery mentioned in the literature, the projects can be considered as a whole. The modules created during the prefabrication process are obtained by batching two projects only. Although those modules are created to serve the current project design, they represent a proven solution for future projects to come. With the repetitive work and the production volume, the productivity will increase and the improvements will become more visible.

The study then presents the VSM as a tool to provide a holistic view of the construction process, pointing out possibilities to implement and improve the implementation of modular principles. The VSM shows the flow of mainly products and materials in the entire production lifecycle, thus providing an overall picture of the process. Presenting a VSM at the very outset of the project would help a sub-contractor like Southland Industries working with a high degree of modularity and BIM to set a standard and secure that the whole supply chain were organised accordingly, thereby making the process much more efficient. Ideally all parties playing a role in the project (i.e. client, contractor, producers, sub-contractors, designers, architects) would come together before project start and each bring their VSM to the table. In that way, challenges due to fragmented organisation and the hierarchical delivery system could be minimised. At the same time a more realistic picture of the production flow could be secured and utilised to implement as much modularity as possible from the outset. Possible bottlenecks could be anticipated and handled to improve productivity further.

The building construction organisation is very fragmented and individual parties have limited influence on the entire work flow. However, the case shows that even a single trade contractor can utilise VSM as a tool to provide a holistic view of the construction process, pointing out possibilities to implement and improve the implementation of modular principles.

5.9 Common discussion

Summing up the discussion chapter, with the studies presented in this thesis, I have intended to evaluate the state of modular solutions in building construction and to investigate possible, viable ways of implementing more modular principles. My main ambition has been to investigate this with the combination of product, process, and organisational perspectives, because an integrated understanding of these has been lacking in literature so far.

Product, process, and organisational perspectives are three barring legs of modularity dependent of each other that should be considered within a given context. It is difficult to study repetitions leading to the formation of modules focusing only on organisation or only on process or on products without mentioning the other two aspects. Therefore, in the analysis of the cases, although special focus is intended on different aspects of modularity separately, each case study covers at least two different perspectives as shown in Figure 48.

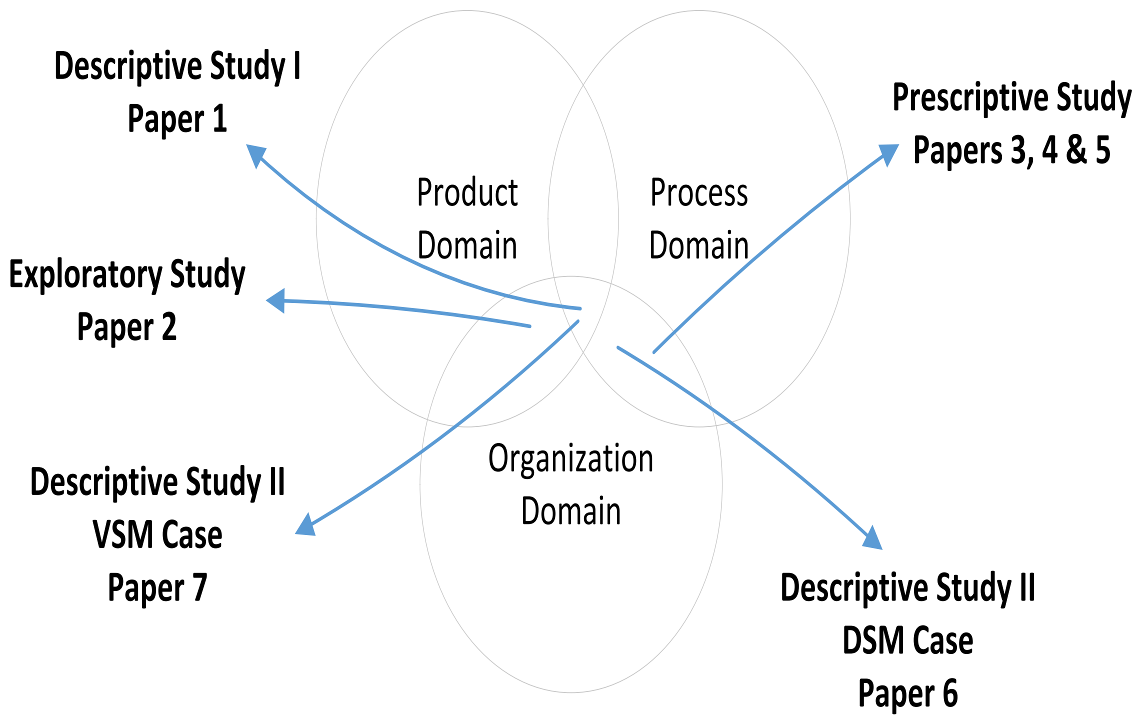


Figure 48. Articles distribution according to the domain.

Moreover, the focus areas of the different studies are deliberately chosen as shown in Figure 48 from the most untouched overlapping product, process, and organisation domains presented in Figure 13 based on the Campagnolo and Camuffo (2009) literature review.

With the hospital case, descriptive study I, I outlined an example of how the current way of organisation leads to a high level of unproductivity. In the first part of the exploratory study, on the other hand, I presented the hesitations contractors have concerning modularity and the reasons they do not immediately embrace the otherwise highly praised opportunities of modular technology. The second part of the exploratory study then showed us how modularity, hesitations with or notwithstanding, is still worked towards as a principle in companies around the world. Typically in fragmented and unconscious manner, modular solutions are present in many and diverse types of construction businesses.

As the next step, I presented three different tools facilitating the use of modularity at product, process, and organisational levels. The prescriptive study introduced QCA as a method to identify repetitions across projects, transferring these into processual and organisational modules. The first part of the descriptive study II demonstrated how the design process through the DSM method can be modularised according to iterative groupings, illustrating a more organic process than the traditionally linear approach to building design. Finally, the VSM tool presented in the second part of the descriptive II study, allowed us to see a holistic picture of the production lifecycle, visualising the opportunities for applying modular techniques.

Again, I argue that the main virtue of the three suggested tools lies in the fact that they all operate within the intersection of the traditionally separated domains of product, process, and organisation. QCA allows aspects of product (such as type of building), process (such as project delivery system), and organisation (such as project manager seniority) to come together to form certain results. DSM highlights which arrangements between organisational parties and their place in the process order are needed in order to deliver a certain product design. And VSM gives us a map of the overall production process focusing on product flow. Furthermore, the three tools have the ability in common that they embrace iterative processes, circular movements and loops with their approaches instead of linear progression, one directional activities and hierarchical chains of command. What they suggest, I argue, is that we shift our methods and ways of handling building construction from military planning strategies towards more comprehensive tactics allowing for repetitions to come forward.

Finally, the different studies also reflect different phases of the building construction life cycle, starting from tender phase to the design and finally construction execution as seen in Table 10. By doing so, the life cycle phases outlined in Table 4 are discussed in detail under relevant studies.

The phases beyond the production concerning design for serviceability, design for reparability, design for environment, design for disassembly, and design for material recycling are missing in all studies. Therefore, these issues deserve further research possibly by coupling facility management, sustainability, and modularity theories.

Table 10. Articles placement in construction project lifecycle.

Articles \ Construction Phases	Tender	Design	Execution
Paper 1: Descritive Study I	X	X	X
Paper 2: Exploratory Study	X	X	X
Papers 3 & 4: Prescriptive Study	X		
Paper 5: Prescriptive Study		X	X
Paper 6: Descriptive Study II DSM Case		X	
Paper 7: Descriptive Study II DSM Case			X

Coming back to the Danish context, there is both awareness in the society and political will for productivity improvement in order to get more sustainable, energy efficient buildings. There might be scepticism in the society about modularisation that will cause over simplification. Standardisation to a degree that the ability to match the personal needs and unpredictable circumstances will disappear might create resistance in the application of modularisation. The trade-off between craft work and mass production in terms of costs, standards and quality is present in the discussion about the building construction as well. Through prioritisation of the application areas for modularisation in building construction the unnecessary worries can be addressed stepwise.

5.10 Research evaluation

In this final section of the discussion chapter the research will be evaluated in terms of validity, reliability, and generalisability.

5.10.1 Validity

Validity is about the collected data representing the reality and results of the research accurately reflecting the studied phenomenon (Collis & Hussey, 2009). The validity is specifically for important for the study because DRM has been modified according to the current circumstances of the research and limitations due to the design of the industrial Ph.D.

Different then the action research and the testing of the artefact DRM originally suggests, the hosting company expected the study to be over in order to proceed with the implementation phase. The size of the company, the division of labour between university and the company, the particular approach of the company leadership all together makes the set-up too large for a traditional DRM artefact testing procedure.

Moreover, the Ph.D. project is limited to three years only. The first studies and suggestion of “artefacts” to be implemented take more than half of the period. Moreover, because of the long-life-cycle of the construction projects, the implementation of the suggested tools and then reporting of the results is not part of the Descriptive II stage as would normally be the case in DRM methodology. Instead, they are presented as suggested tools for the implementation reflecting the ideas and perspectives the study is based upon.

In the studies conducted at different stages in this thesis, some initiatives, such as triangulation, member check and peer debriefing (Lincoln & Guba, 1985), are deliberately taken to create credibility. First, triangulation is applied in all studies in data collection. Different types of data are collected through different qualitative data collection methods to provide consistency. Another triangularity approach was applied by comparing the collected data with existing literature (Eisenhardt, 1989). Secondly, member check was assured in papers presented in the appendices C, D, E, F, and G simply by presenting the results to the participants of the study and asking their feedback. Moreover, it was also necessary to get the consent of the participant prior to publication. By doing so, it was verified that the data and the results reflect the reality and no misunderstanding occurred in data collection and analysis.

Surely, the participants wanted to make sure that the data they provided is realistic and do not harm their reputation and business. Also, peer debriefing took place in different contexts and occasions. Regular weekly meetings with both university and company supervisors provided detailed feedback on the course of the study. Moreover, research dissemination sessions were arranged for each publication at the university during which academicians coming from different fields shared their comments and raised critics.

Furthermore, the research in general and papers in particular have been presented in different industry and academic conferences such as BIM Forum 2016, Engineering Project Organisation Conference (EPOC) 2015. Finally, the papers representing different stages of this dissertation were all peer-reviewed by conferences or journals as it can be seen in the appendices.

5.10.2 Reliability

Reliability can be defined as the absence of differences in results in case the research is replicated (Collis & Hussey, 2009). To provide reliability is difficult as case studies represented at different stages are all highly context dependent. Both study participants and the interviewer can be biased by the purpose of the study and the identity of the researcher (Flick, 2006). Audits are used for the purpose of increasing reliability (Lincoln & Guba, 1985).

Audits mean letting other researchers or professionals check the analysis (Lincoln & Guba 1985). Different forms of audits have been used at different stages. In the descriptive I stage, academicians from the same research group at the university were asked to interpret and analyse the data. The results were than cross-checked with their own findings. In the prescriptive phase another Ph.D. candidate was asked to duplicate the QCA analysis with the same data set. In the last descriptive II phase, practitioners were asked to interpret the data and results according to their own experiences and standpoints.

5.10.3 Generalisability

Generalisation is defined by the degree to findings can be extended to wider social settings (Bryman & Bell, 2011). Case studies are often criticised imposing constraints upon the generalisability of findings given the explicit focus on a certain event and the fact that qualitative research usually uses small samples compared to quantitative studies (Yin, 2009). The mentioned constraints were taken into consideration and therefore large numbers of case studies have been conducted for each stage in order to increase generalisability. Moreover, learning from examples is a valuable outcome of case studies and transferability of this new knowledge from single or multiple case studies to similar contexts is more important than formal generalisability (Flyvbjerg, 2006). In order to increase generalisability, purposive sampling targeting maximum variation (Flyvbjerg, 2006) and representability (Lincoln & Guba, 1985) was applied in case selection.

5.10.4 ASSESSMENT OF THE RESEARCH BY THE HOST COMPANY

The industrial Ph.D. set-up in general has been highly appreciated by the host company which is also the financial supporter of the research study. This thesis is a result of the fourth industrial Ph.D. research that MTH finances and hosts. In that sense, the host company is an experienced partner in designing, executing and assessing the industrial Ph.Ds.

MTH considers the industrial Ph.D. an ideal way to create and transfer knowledge in collaboration with academia. The execution of the research is closely supervised by the company supervisor. In addition to regular supervision of the research activities, quarterly reference group meetings were arranged at the industrial partners headquarter with the participation of company and academic supervisors, CEO of MTH and board member of the foundation financing the Ph.D.

According to the company, the following objectives stated in introduction (previously approved by the Danish Educational Minister, Innovation Agency) are met:

- Consideration of the product, process and organisational modularity together
- Deeper understanding of the challenges related to the knowledge and learning processes in a project based organisation
- Discovering the possibilities to create learning, project-based environments based on product, process, and organisational modularity
- A study of the “repetitions effect” on MTH projects

Finally, as a sign of the trust in the study and the researcher, the hosting company offered a fulltime contract for the implementation of the ideas and tools suggested by the study.

6 Conclusion

This chapter provides the conclusions of the research. First, the key findings of the research and contributions are presented. Second, possible implications of the research in theory and practice are outlined. Finally, suggestions for future research are discussed.

6.1 Key Findings and Contributions

The main purpose of this thesis has been to study the conditions for improving productivity in building construction, an industry characterised by unique products and fragmented organisations. On a general record, the thesis problematises the overly complex organisations proliferating within the sector and argues that the remedy is an implementation of modular principles as early as possible. Early implementation of modularity implicates bringing into focus the intersecting area of product, process, and organisation, and preparing this area for modular solutions while projects are still in their incubatory phase. Concrete moves for facilitating this preparation are suggested with analytical tools, such as QCA, DSM, and VSM. By shaping 'intelligent' modules and standards on all levels with these tools, the thesis argues, valuable knowledge is preserved and made available for continuous, systematic refinery.

The abovementioned purpose is addressed through the following RQs:

1. *What are the relevant theories to base the research upon in order to address the productivity problem of building construction?*

The productivity challenge in building construction has been described with complexity theory. Complexity theory allows one to decide to what extent and in what way a project is complex. Parameters such as *structural complexity* (for example number of stakeholders), *uncertainty* (the dynamic factors of uncertainty effecting the building project, such as weather, financial situation, and changing user requirements), *pace* (different processes running at different pace in the same project), and *socio-political complexity* (the diversity of stakeholders' interests, backgrounds and agendas) are considered in complexity theory. This allows for an estimation of the type of the complexity in question, which can then be managed the best way possible. Modularity theory is the core theory chosen to handle the complexity in building construction. Modularity theory identifies repetitions and transforms them into standards which in turn enhance productivity. The main theoretical contribution of this thesis is to look at modularity theory in the separate domains of product, process, and organisation, which secures an all-round perspective. All of these three sides as well as the whole lifecycle of a building project need to be considered in order to really address the productivity problem, the thesis argues.

2. *How does the complexity of the way in which building construction is organised cause unproductivity?*

Buildings, which represent the final product, are designed and constructed by independent processes and organisations, allowing very limited or no learning from one project to another. As a result of this fragmented organisation, slightly different design solutions are being recreated again and again. As the Danish hospital case study shows, 27 slightly different patient rooms are created almost in parallel within the same time frame but independent of each other (see Section 4.1 and also Paper 1 presented in Appendix A). It is important to note there are no two identical patient room designs in those selected hospital projects. The design variations in different project parts arguably do not add any value to the final product and prevent productivity improvements from one project to another.

Developing standard designs for the same needs and same functional requirements would attain productivity improvements in design, production, and use. Through standardisation of repetitive space, more patient rooms would be built with the same budget and/or valuable resources would be allocated to other parts of the building.

3. *What are the current understanding and applications of modularity in building construction?*

Modularity theory is not yet acknowledged in the building construction industry. However, repetitions in products, work methods, and organisations are intuitively applied by all building construction organisations regardless of size and role in the building process. A common conclusion among practitioners is that project owners have to consider modularity well in advance as an initiative that will benefit the project and project participants (see Section 4.2.1 and Paper 2 presented in Appendix B).

Considering modularity 'well in advance' has several implications. The modular product solutions that are not designed for specific project requirements cause friction when it comes to building construction; thus, the interfaces between the modular solution and the rest of the building project have to be studied thoroughly. Physical, processual, and organisational requirements must be examined at the conceptual design phase. Moreover, the product lifecycle involving design, production, and use must be anticipated. Otherwise, the documented advantages turn out to be disadvantages. The need to cooperate in early stages of the building project is so vital for a successful implementation of modularity that alternative forms of system deliveries must be considered—for example, Project Developments, IPD Systems.

The need to redesign the process according to the modular building production is forcing many case companies to implement modularity to relocate themselves in the market as developers (see Section 4.2.2).

4. *How can repetitions across the unique projects be traced?*

Repetitions exist in different forms without being acknowledged. Projects sharing similar time frame and context contain many repetitive patterns that can be traced and learned from. Different factors originating from product (type of the project), process (project delivery system), and organisation (PM seniority) domains come together to form patterns leading to particular project outcomes. The identification of these patterns is absolutely necessary for decision-makers willing to learn from the experiences of previous projects. By means of QCA, combinations of factors leading to desired project outcomes can be identified. The solution sets obtained as a result of the QCA would provide a guide to future projects. As a result of two different case study analyses, solutions sets leading to successful tendering and dispute respectively in building projects execution are obtained. Decisions concerning the process, such as choice of contract type, or about the organisation, such as choice of PM, would be made according to the predefined solution sets. Finally, the resources would be allocated according to the likelihood of the occurrences. To make it more specific, a company can choose not to bid on a project that will probably not give a positive result (see Section 4.3.1 and also Papers 3 and 4 presented in Appendices C and D) or not to assign a senior PM in a project that contains a risk of ending with a costly dispute (see Section 4.3.2 and also Paper 5 presented in Appendix E).

5. *How do we operationalise modularity in building construction?*

Modularity can be operationalised in building construction at all levels and by project participants of all sizes. However, individual efforts will bring partial benefits only. In order to maximise the benefits of modularity at the project level, the modular solutions and work methods must be considered well in advance at the conceptualisation phase with the participation of all related parties. DSM and VSM represent helpful tools to visualise the dependencies and non-linear design and building construction process respectively.

Through the implementation of DSM at the beginning of the design phase process, modules clustering the groups of activities with high interdependencies can be created (see Section 4.4.1 and also Paper 6 presented in Appendix F). Moreover, project participants can know in advance about the design iterations and schedule their activities accordingly. Finally, successful applications of the design process modules could be standardised for implementation in future projects. By developing previously applied design process modules, continuous productivity improvements would be possible.

Similarly, as shown in the final case study, early implementation of the full BIM model gives opportunities to boost the repetitions effect in the building construction even at the trade contractor level (see Section 4.4.2 and also Paper 7 presented in Appendix G).. As shown by the Southland Industries case study, piping installations can be produced in batches at the workshop with high productivity by way of modular frames. What makes the case successful is the fact that modular production is designed from the very beginning, with overall process thinking and the participation of all relevant parties. VSM allows a full picture of both material and information flows for the entire production and assembly. Finally, the implementation of VSM could identify bottlenecks and possible improvement areas for further improvements.

6.2 Implications in Theory

As pointed out by Fixson (2007) and Campagnolo and Camuffo (2009), there is a gap in the literature with respect to studying modularity from perspectives other than that of production. Their extensive literature review does not consider modularity within construction. Therefore, this study embraces modularity with product, process, and organisational aspects together. It not only contributes to the modularity literature, in general, but also it intends to open up a new way of thinking in the construction industry.

Modularity represents a divide and conquer strategy. It does not concern only the product modularity, which is relatively easy to pursue through parts and components. It also concerns the process modularity achieved by activity clusters and organisational modularity vitalised by different system deliveries in which roles and responsibilities are defined differently. Moreover, modularity brings the opportunity to work on still unique products through standard solutions and well-defined elements. Only through these standards can stability and predictability be increased. Standards preserve the valuable experiences and competencies gained at the project level and transfer it to other projects. Knowledge is embedded and utilisable within the 'modules' themselves.

The main theoretical contribution of the study is to adapt the complexity conceptualisation by Wilson & Perumal (2015) concerning the combined approach of product, process, and organisation domains to modularity theory and use it to increase productivity within building industry in specific instances.

The three different domains of modularity together are not studied in literature covering construction practices. Taking "non-value adding complexity" as the cause of the productivity problem the study attempts to operationalise modularity theory to identify value-adding repetitions and promote them as best practices.

6.3 Implications in Practice

In summary, modularity cannot be reduced to one single dimension. In building construction, over the years, the implementation of modularity has been reduced to merely prefabrication. The reason we fail to leverage modularity in building construction is that the focus is so narrowly given to products. Applications of modularity with product as the main focus jeopardise the overall understanding of modularity.

At the project level, modularity requires early involvement. Scandi Byg, which is an independent subsidiary of MTH, represents a perfect example of a modular product solution with limited application simply because the process and organisation of the building projects are not thought and designed accordingly (see Section 4.2.1 and Paper 2 presented in Appendix B). Even the general contractor MTH treats the modular solutions offered by Scandi Byg as an alternative product for each individual project. MTH compares it with other product alternatives in the market with respect to the cost. Instead, process and organisational aspects must be considered along with product in the execution of the building projects (see Section 4.4.1 and Section 4.4.2 also Papers 6 and 7 presented in Appendices F and G).

At the company level, the valuable experiences from previous projects can be used as a leverage to perform better in future projects. The patterns leading to particular project results can be identified to predict the results and take precautions accordingly. The QCA method provides a useful tool to identify the combination of factors causing particular project outcomes (see Section 4.3.1 and Section 4.3.2. also Papers 3, 4, and 5 presented in Appendices C, D, and E). In that way, the companies would be able to trace the patterns across the projects and execute the projects as part of a bigger project platform rather than beginning from scratch with each new project.

At the industry level, the application of a modular solution should be considered collectively as an alternative combining product, process, and organisation domains. The parties involved should be aware of the requirements of the modular solutions from the very beginning. The entire process and organisation must be reconsidered according to the modular solution desired. In that way, all parties involved can experience the benefits from the value created through the application of the modularity. The building industry would experience improved productivity accordingly.

Improving productivity through modularity must be the ambition at the authorities' level, too. The standardisation and cooperation of different building parties, such as clients, architects, consultants and contractors, must be regulated by legislation, imposing further cooperation, usage of BIM-VDC, and IPD systems at national and international levels (e.g. EU). Implementing standardisation and boosting the repetitions effect can build more effectively spaces, such as hospital patient rooms, day care classrooms, and elder care rooms. Consequently, valuable resources can be used elsewhere to create value-adding variation in the buildings by making them special and personal (see Section 4.1 and Papers 1 presented in Appendix A).

The main contribution of the study for the industry partner is the description of the ways and methods to identify repetitions within and across projects and to turn the value adding ones into best practices as well as to avoid the non-value adding repetitions wherever possible.

6.4 Suggestions for future Research

The application of the presented approaches and tools in multiple real life cases would be a natural extension of this thesis. By doing, so the results can be tested and the methods can be further developed.

By use of QCA, various project outcomes such as 'on time completion' and 'client satisfaction' can be tested with respect to patterns across the realised projects. Moreover, DSM can be operationalised as a management tool in different design tasks. Finally, VSM can be used in almost any process mapping as a point of departure for the improvement.

Most importantly, each application of the above-mentioned tools would provide a basis for the future applications as a point of reference. The more examples accumulated, the more mature the methods.

Application of modularity theory taking standardisation of product, process and organisational modules would be a catalyser for the other fields trying to improve productivity in building construction, such as BIM-VDC, DFMA, Project Portfolio Management, and facility management.

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8 APPENDICES

8.1 Appendix A: Descriptive I Study EPOC2016 Paper 1 (published)

REINVENTING THE HOSPITAL – A STUDY OF LOST SYNERGIES IN DANISH HEALTHCARE

Baris Bekdik and Christian Thuesen

Abstract

The purpose of this study is to identify the effects of inter organizational relationships in construction projects by investigating how complexities are manifested in variance and repetitions across projects. The case is a set of 27 hospital projects in Denmark including new buildings as well as extensions of existing hospitals. The key empirical material consists of detailed drawings of each of the projects along with information of the participating organizations. The implications of the inter organizational relationships is studied thorough a theoretical framework of modularity by looking for variance and repetition. The analysis shows that the projects are designed for each specific location (region) with unsystematic and limited use of processual, organizational and technical repetitions. Overall, the projects are executed in parallel and follow the same phases with a high degree of user involvement in each of the projects; here inputs are gathered for the specific project that subsequently is designed by a unique team of architects and consultants. Although some of the participating companies are involved in several projects (especially as the client consultant), there is a high degree of variance in the project teams. Despite the variance of the project teams the overall and detailed design of the hospitals look remarkably the same. However, a detailed analysis of the patient rooms reveals that although 70% of the projects use the same architype (the L-type) they are different from each project. This lead us to the conclusion that the hospital is reinvented in each project leaving behind unrealized potential for leveraging similarity across the projects. This could have been achieved by a stronger central coordination, thinking of super hospitals as programs and portfolios rather than individual projects.

KEYWORDS: Hospital construction, interdependencies in project network, modularity, complexity, standard solutions.

Background

The completion of any task requiring more than a single individual introduces interdependencies (Chinowsky, 2011). "Project-based organizations revolve around the concept that a group of individuals or firms join together with the explicit purpose of producing a tangible set of outputs that can be physical (e.g. a building), logical (e.g. software code) or social (e.g. a marketing or public relations campaign)" (Chinowsky, 2011).

A large variety of heterogeneous participants has to collaborate temporally in order to realize new, unique projects (Schreyögg & Sydow, 2010). The main characteristics of projects such as temporariness, uniqueness, heterogeneity of participants, variety of disciplines involved, and lacking organizational routines results in complexity challenging managers (Hanisch &

Wald, 2011; Geraldi et al., 2011). Moreover, the size of the projects, the number and the degree of interdependence of its elements add to the structural complexity as all this elements need to be coordinated (Sommer & Loch, 2004).

A hospital construction project is highly complex in terms of task interdependencies, the newness of tasks and the heterogeneity of the actors involved (Pauget, 2013). The planned numbers of people to use the hospital together with all the professionals who work in the hospital make the place really densely populated. The aging population and need for specialization increase the demand on health-care services. Therefore, the construction of new hospitals imposes a heavy burden on society as both the central and the regional governments are struggling with budget-deficits and imposed austerity measures (Pauget, 2013)

Research ambition

The purpose of this study is to identify the effects of inter organizational relationships in a program of Danish hospital construction projects. More specifically, we want to investigate how the complexities of the projects are manifested in variance and repetitions across the projects.

Theoretical framework

The research is based on an analytical framework combining theories of complexity, and modularity.

Complexities

Complexity is not a new science but rather a new way of looking upon systems. Ever since the seventies, as Simon (1962) points at; “multiple levels of hierarchy and a wide range of architectural choices in system specification characterize the architecture of complex systems” (Simon, 1962). Following this statement the variety product and multiple organizations will add significantly to the magnitude of complexity in a given production system. Hofer and Halman supports this argument; “We argue that the deliberate restriction of architectural choices (i.e., through a layout platform) is a powerful means to reducing engineering complexity and risk” (Hofer & Halman, 2005). They further argue that efficiently reducing complexity will create a competitive advantage (Hofer & Halman, 2005, s. 56).

In a large research program on project complexities Geraldi et al., (2011) describe complexity in five different dimensions as a result of an extensive literature review. These dimensions are structural, uncertainty, dynamics, pace and socio-political complexity. As a result, managers have to cope with challenges presented by each of these dimensions of complexity both in individual level and organizational level (Geraldi et al., 2011). The theoretical categories was subsequent simplified based on extensive empirical research to three types of complexities structural (e.g. product), emergent (e.g. process) and socio-political (e.g. organizational).

In addition to the root causes of complexity, a large literature exists aiming to describe where the complexity hides. Many researchers (Aspinall & Gottfredson, 2006, Hansen et al., 2012) focus on the product complexity and defend that process and organizational dimensions are direct result of product variety and therefore complexity. While some others (Sivadasan et al. (2002) trace organizations passing each other operating in supply chains exporting or acquiring complexity. Wilson & Perumal (2009) argue that analyzing either process or product by themselves still does not address the problem of complexity hindering organizational efficiency. The product, process and organization are integrated and they all have their own role of complexity and by managing each subject alone will not provide much improvement compared to a combined approach as illustrated in Figure 1 (Wilson & Perumal, 2015).

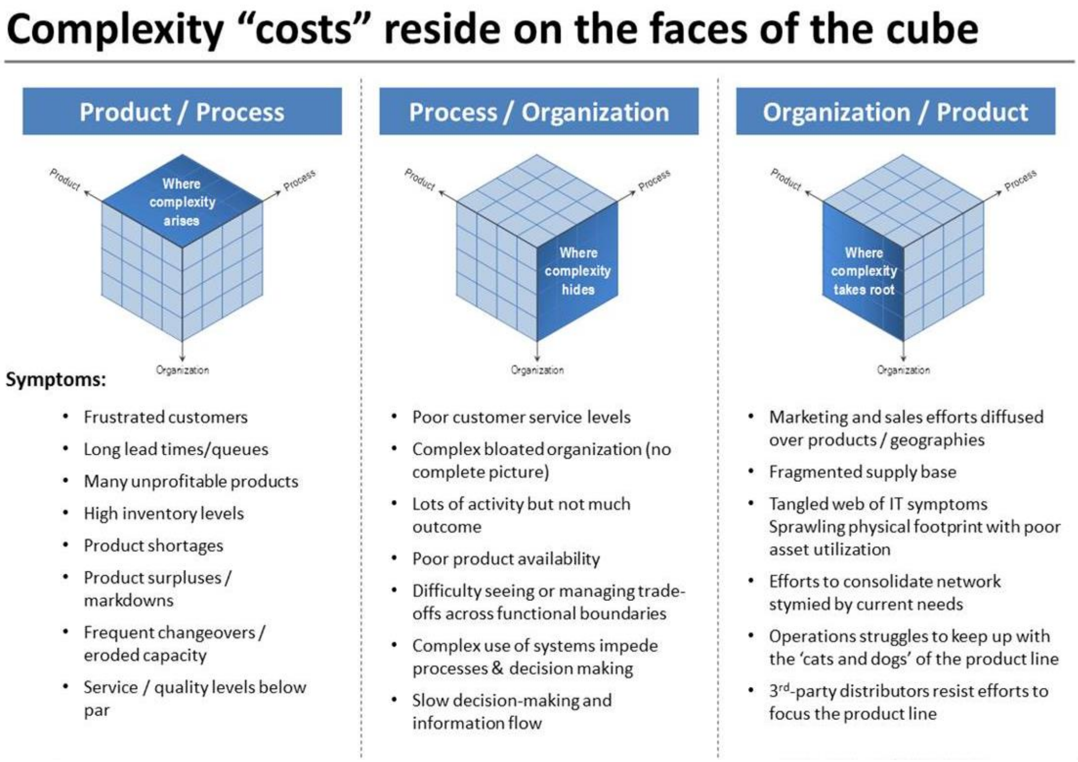

Figure 1: Illustration of the cost of complexity and how the Product, Process & Organization affect one another (Wilson & Perumal, Complexity Cube, 2015)

Modularity

In the journey to manage complexity, modularity appears as a crucial strategy enabling organizations to create products and services meeting individual customers' needs while still leveraging the benefits of similarity and standardization (Oehmen et al., 2015)

A module is an element of a complex system. Modularity is considered a design of production systems or parts of a production system, that attempts to "minimize interdependence between modules and maximize interdependence within them" (Campagnolo & Camuffo, 2009, p. 259). The individual modules are assumed to follow Ulrich & Tung's (1991) application of swapping and sharing of modules, so they can be applied in different systems and be interchanged. In order to apply modularity as a design principle for production systems the concepts of architecture, interfaces and standards from Baldwin & Clark (1997) also are applied. The architecture provides the basic platform for how the hierarchy is structured while the interfaces define relations between the modules and prescribed standards.

The rising complexity of production practices leveraging the benefits of similarity and standardization while at the same time enables the production of individualized products and services (see e.g. Ulrich & Tung, 1991; Ericsson & Erixon, 1999; and Sosa et al., 2004). In particular, the concept of modularity is used to explore different types of production-related structures such as computer, automotive industries within products, processes, organizations and supply chains (Salvador, 2007 and Campagnolo & Camuffo 2009).

In Campagnolo & Camuffo's (2009) review of the concept of modularity, they identify three streams of literature clustered around three different units of analysis: (a) product design modularity, (b) production system modularity; and (c) organizational design modularity (p. 260). In the following, these categories are referred to as product, process and organizational modularity.

Product modularity (product design modularity)

Among the different units of analysis Campagnolo & Camuffo (2009) find that the product design modularity has received the greatest attention from scholars and practitioners probably because it's primarily technically, material and normative orientation.

With the outset in platforms thinking, Meyer & Lehnerd (1997) describe the architecture of a product as being the combination of subsystems and interfaces. They argue that every product is modular and that the goal is to make that architecture common across many variants. Ulrich (1995) believes that product modularity is the scheme by which the functions of the product are mapped towards the physical components, thus defining the product architecture as the arrangement of functional elements, the mapping from functional elements to physical components and the specification of interfaces between these.

The use of product architecture with well-defined modules has in several cases proved to contribute to significant increases in industrial productivity, since implementation of product architecture with well-defined interfaces maintained over many years, makes it possible to develop production processes that are more productive. One reason is that the well-defined interfaces make it considerably simpler to coordinate the individual sub-processes that are typically carried out by different organizational groups.

Process modularity (production system modularity)

Building on the insights from platform thinking and product architectures Baldwin and Clark (1997) defines modularity as a strategy for organizing products and processes efficiently (p. 86). According to Campagnolo & Camuffo's (2009) this type of modularity "within and among organizations mirrors the degree of product modularity, with the main consequence that independent companies (e.g. suppliers) may develop, produce and deliver self-contained modules consistent with the scope and depth of their core competences." (p. 269)

Thereby modularity not only is a characteristic of a product but also the processes / task / activities for producing it. One of the consequences of focusing on modular processes is that the end product might be intangible like a service or experience (Pine & Gilmore 1999).

Organizational modularity (organizational design modularity)

Organizational modularity might be referred to as the way organizations are structured. Since the seminal work by Daft and Levin (1993) where they first coin the concept of the modular organization, several scholars have devoted much effort to develop new organizational paradigms "characterized by flatter hierarchies, decentralized decision-making, greater capacity for tolerance of ambiguity, permeable internal and external boundaries, empowerment of employees, capacity renewal, self-organizing units, and self-integrating co-ordination mechanisms" (Campagnolo & Camuffo 2009, p 274).

A strand of these scholars is particularly interested in the relation between product and organizational modularity identifying the following relation: "Integral products should be developed by integral organizations (tightly connected organizational units to maximize ease of communication and minimize the risk of opportunism). Modular products should be developed by autonomous, loosely coupled, easily reconfigurable organizations. Indeed, the adoption of standards reduces the level of asset specificity (Argyres, 1999) and, in turn, the need to exercise managerial authority. Product modularity also reduces the need for communication due to information hiding, whereby knowledge about the 'interior' of each module does not need to be shared." (Campagnolo & Camuffo 2009, p 274).

The above mentioned theoretical approach will be applied to the nationwide hospitals design and construction case in the context of Denmark. Although the complexity and modularity references are from many braches of the engineering management practices they appear to be consistent explaining the complexities from product, process and organizational perspectives in hospital construction. Finally, modularity theory reflects possibilities to create new still unique design solutions based on the reconfiguration of the repeatable standard solutions.

Methodology

The analysis is based on three perspectives complexity and modularity the physical, processual and organizational. Each of these perspectives is guided by three questions. What is being built? How is it realized? And who is doing it? In doing so we are looking for patterns of repetition.

Our focus is to investigate the way new super hospitals constructions organization has been designed in a complex temporary setting. It is important to understand the context in which the new hospital construction projects were thought, planned and organized. More than 30 hospital projects have been studied across Denmark in terms of main actors; such as the client, investor, architect, consultant, contractor (organizational perspective), current project phases (process perspective), and design outcomes (product perspective). In the end, 27 Hospital projects in Denmark are chosen for further analysis as the others were not suitable for a comparative study in terms of size (they were to small) or scope (they were renovation projects only).

The empirical material covers project material from each project including drawing floorplans and overviews, information about the participating companies, reports and articles on the specific hospitals as well as general information about the program. The research process was based on three phases: 1. Gathering of material from each of the projects specifically focusing on drawings and organizational design. 2. Analysis and review of the material. Here the material was analyzed by two PhD students with a background with architecture and construction. 3. Presentation and review of finding at different meetings and workshops involving researchers, practitioners and civil servants.

The main perspective is to search for the repetitions and variance and the effects of these within and across the projects. Because of such an investigation, a network of project participants was obtained enabling, the results of participants network positions generates in terms of particular design patterns. As a project requirement, all hospital projects have patient rooms involved in the design material. To compare the different project's patient room design across the projects made it possible to observe the influence of particular project actors on the design outcomes.

Results of the organizational repetitions and interdependencies in design outcomes will be presented with network perspective. Project networks present the concept of intra and inter organizational relationships between individuals and organizations that interact within the scope of one or several projects. This concept of networks is particularly significant as temporary organizations are governed through networks of relationships rather than the formal structures (Manning, 2005).

Cases

Similar to the development in other western European countries the Danish healthcare system is facing major of challenges in the coming years. The higher proportion of elderly in the society, continuous development of treatment options, requirements for coordination across levels of government and sectors as well as increased requirements for renewal, just to name a few. In order to meet these challenges one of the central political parties announced before the election in 2007 that they wanted to spend 80-90 billion Danish Kroner (DKK) to modernize the dilapidated hospitals of which 50-60 billion DKK would be used in construction of new hospitals (Martini, 2007). After winning the election the 80-90 billion DKK was reduced to 60 billion DKK and later even to 41.4 billion DKK (Juhl, 2010).

All these projects was initiated as a part of a major reorganization for the Danish healthcare system concentrating the public healthcare in 6 different regions only responsible of delivering healthcare to the citizens. These regions represent a governance structure between local municipalities and the central government with elections every 4 year. Since the regions are the public owner of the healthcare infrastructure, they are also the clients for the new hospital projects. The overall timeline of the projects are illustrated in the table below along with information about the size of the project (in billion DKK) the project type (Green vs Brown field) and patient room type (L or C).

Case	Region	Budget G. DKK	Project type	Room type	2005 2010 2015 2020 2025
NAU	North	4,10	G	L	
DNV	Midt	3,15	G	L	
RV	Midt	1,15	B	L	
DNU	Midt	6,35	B	L	
KS	South	0,90	B	C	
SSA	South	1,25	B	L	
OUH	South	6,30	G	L	
NFA	Zealand	0,30	B	C	
GAPS	Zealand	1,05	G	L	
USK	Zealand	4,00	B	L	
NHN	CPH	3,80	G	L	
NBH	CPH	2,95	B	-	
DNR	CPH	1,85	B	C	
NHE	CPH	2,25	B	L	
NHV	CPH	1,45	B	C	
SHH	CPH	0,55	B	L	

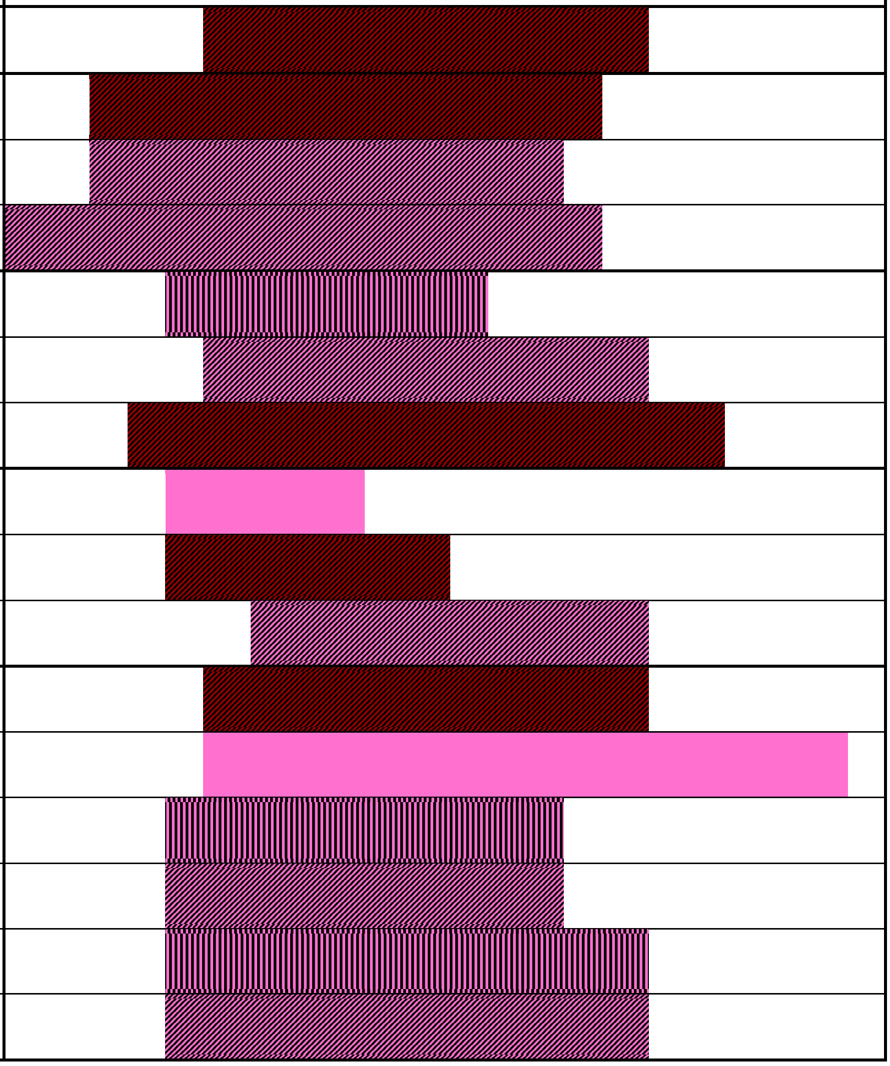

Table 10: Case overview

Analysis

Process perspective

From the central overview of the program, each of the projects was organized into eight phases:

- Phase 0: Concept and nomination of consultants
- Phase 1: Feasibility and Project Planning
- Phase 2: Construction Planning

- Phase 3: Project Modeling
- Phase 4: Detailed Project Design and The Bill of Quantities
- Phase 5: Bidding and Contract Signing
- Phase 6: Construction
- Phase 7: Commissioning and operation

Initially, all hospital projects were launched almost simultaneously, but this was subsequently changed to two main stages (Juhl, 2010) and finally due to various regional / local political reasons, the current organization of the projects is divided into three main phases. Thus, currently 1/3 of the projects are currently under construction (e.g. DNU), 1/3 is in the planning phase (e.g. NAU) and the last 1/3 is in the programming and design phase (e.g. NHN). The table above illustrates the overlapping timelines of the projects.

The concurrent scheduling of the projects has meant that the client organization (regions) and consultancies of the projects started almost simultaneously, without the opportunity to benefit from each other's experiences and expertise. Consequently, the client organizations are uniquely designed for each region with separate user involvement, which potentially has led to sub-optimization. If the projects had been organized in a sequential way, it would be given the opportunity to gather experience along the way and adjust the future design accordingly.

Product perspective

Overall design (whole)

A part of the analysis investigated the overall design of the hospitals specifically focusing on the five green field projects, as the architects in these projects had more or less the same basis to design from while at the same time having fewer design constrains as these construction projects not directly have to take account of existing buildings and urban spaces. The figure 2 below illustrates the overall design of these green field projects.

Figure 2: Overview of green field projects

As the pictures illustrates are there a general trend in the design of the green field projects with the exception of the NHN project (in the bottom left corner). Four of the green field projects share more or less the same rectangular form. The predominance of this architectural principle can be explained by the constraints of packing rooms together, and the flexibility of dimensioning allowed by rectangular arrangements (Steadman, 2007). Completely different is the design of the NHN project. This construction differs from the others with its curved outline and experimental design. One reason for this difference can be ascribed to the main architect not originating from Denmark. The architect Herzog & De Meuron is a Swiss architect, among other known buildings such as the Beijing National Stadium "Bird's Nest", built for the Olympic Games in 2008.

Detailed design (part)

Looking at the details of the projects another pattern emerge, throughout all the projects two different archetypes of patient rooms is used. Due to the different requirements serving different purposes many of the hospital sections is arguably be designed differently. However, patient rooms are the most repetitive building parts in the hospital projects. The patient rooms are designed for more or less same purposes and thus an interesting object of analysis. As technology and patient ergonomic needs do not vary in the projects realized within the same country of a size as small as Denmark, patient rooms appears as an obvious field to standardize. Moreover, through such standardization, accumulated knowledge from one project can be transferred to new hospital projects.

Another reason for choosing patient rooms as the object of analysis is, to have comparability between different hospital projects as all projects includes realization of new patient rooms.

The central ministry arranged an expert panel in order to identify the average area requirements and dimensions. Through such efforts, the need to identify the standards is underlined however no specific standard design were made. The areal norm of single patient rooms is described to be approximately 33-35 m^2.

The specific analysis of the patient rooms reveals two architypes: Type L and type C including various variations of these as illustrated below.

Patient Room Type L:

Patient room with architype L is identified with two mirror-symmetrical L-shaped rooms coming together as seen in

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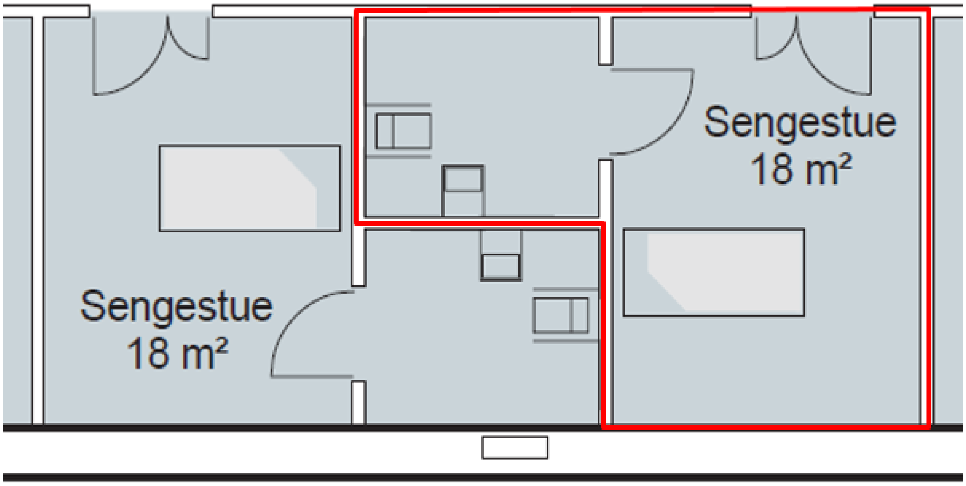

Figure 3: Patient room Type-L. Example is from NAU

Patient Room Type C:

Patient room type C is identified with box-shaped rooms having the bathroom unit within the same box. In this design solution two neighboring units are place in a mirror-symmetrical way so toilets of the neighboring rooms share the same wall as seen in the figure 4 given below.

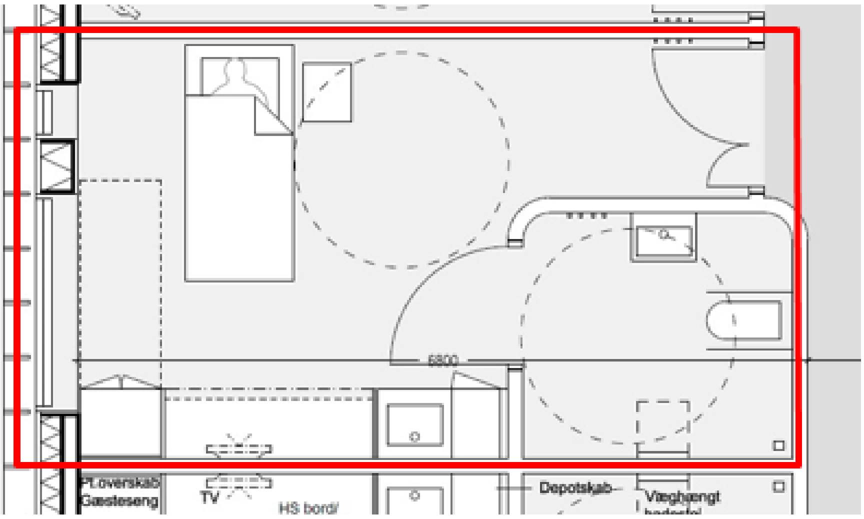

Figure 4: Patient room design Type C. Example is from NHH.

It is seen in **Error! Reference source not found.** that all the green field projects uses archetype L as structure for the patient rooms. Even the architecture of NHN uses a variant of the L form where the rooms are tilted making the overall curved design possible. The popularity of the L form is also found in the rest of the projects thus are 70% of the projects using the L type and only 30 % are using the C type. With the existence of the two types of patient rooms, one could expect that is was based on one common standard solution. The analysis however reveals that each of the 27 hospital project have their own specific design, with different dimensions, m2 and interior. Consequently, the patient rooms have been reinvented 27 times - one for each project. In other words, there is no standard solution repeated across the projects missing the opportunity to increase efficiency and productivity of the building process. In order to understand this outcome, we have to look into the actors doing the design – the participating companies.

Organizational perspective

A network map showing the relations between the different regions, projects, and participating companies was developed. The network map as shown in Figure 5 is based on a review of on information about all the participating companies in the hospital projects gathered through the online platform (godtsygehusbyggeri.dk). In total 98 companies are participating in the projects out of which 12 represent foreign countries.

The size of the nodes reflects their relative importance. The size of the projects is defined by their budget. While the regions that projects are located in and companies involved in the projects are defined by their connectedness (degree). The figure shows the centrality of project participants. Here, it can be observed that the company C.F. Møller appears to be the most frequent company as it is described with a large central node. Moreover, C.F. Møller has the most central placement in the network since C.F. Møller has the maximum amount of direct links to projects. Thus, it is possible to reach other participants by minimum required amount connections taking C.F. Møller as a starting point.

Interestingly, in the projects in which C.F. Møller played a central role (mainly as client consultant), the L-shape patient room design architype is observed with minor variations. This observation clearly supports the relation between organization and final product.

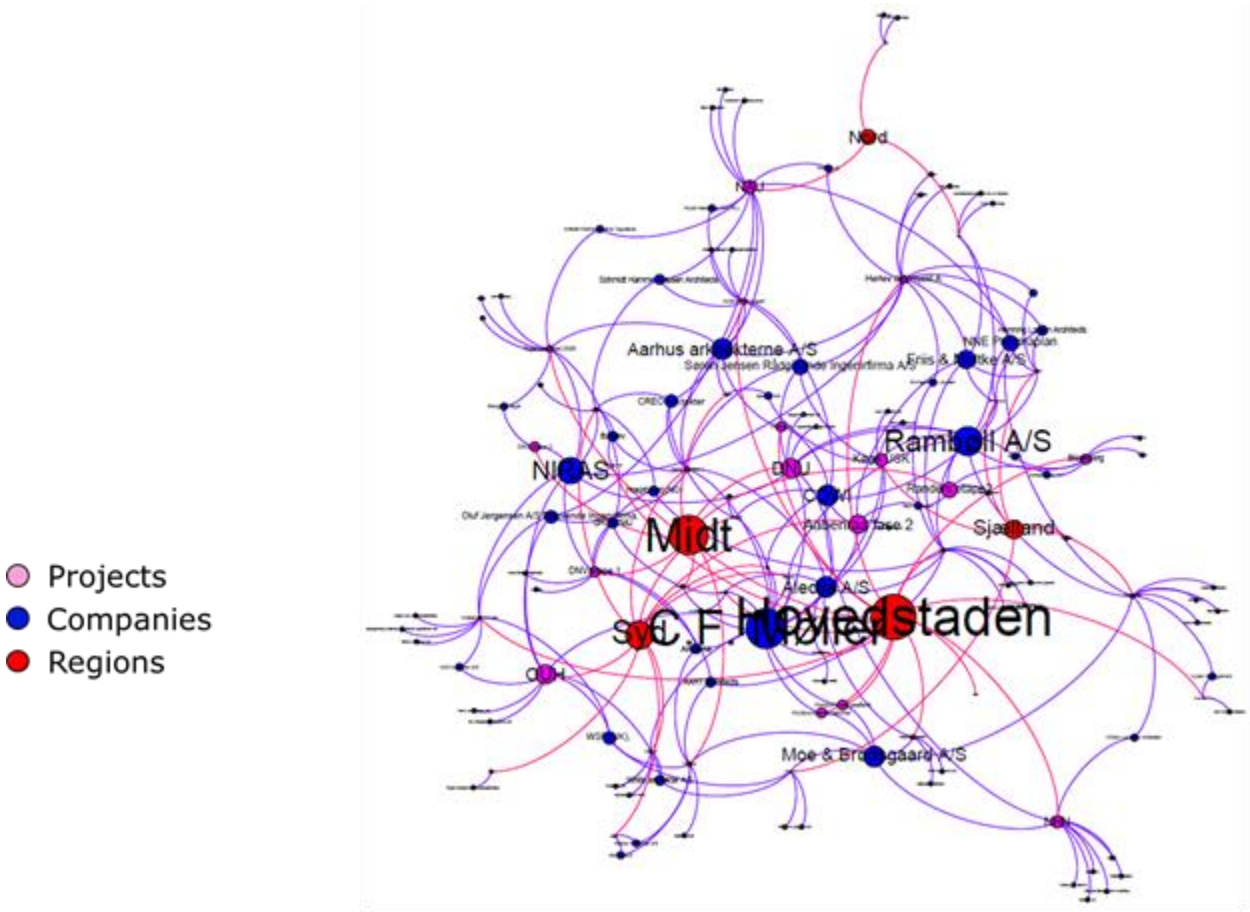

Figure 5: Network map of dependencies between the regions, project and companies

As seen in frequency diagram of companies taking roles in the 27-hospital construction projects in Denmark, presented in **Error! Reference source not found.**6, most of the companies re only getting involved in these projects only once or twice. This long tail is arguably one of the reasons why there exists no standard solutions observed in the projects. It is a good illustration of the complexity cube presented in the literature section (organizational/product interface). Although variety of companies involved the projects increases the chance to get new inputs and ideas, parties involved in only one or few projects are not able to make use of the experience they gain in one project to other. Therefore, the design processes are run for each project separately and the risk to make the same mistakes increases as there is no or limited learning across the projects. This is particularly the case for the green field projects where the organizational repetition is very limited.

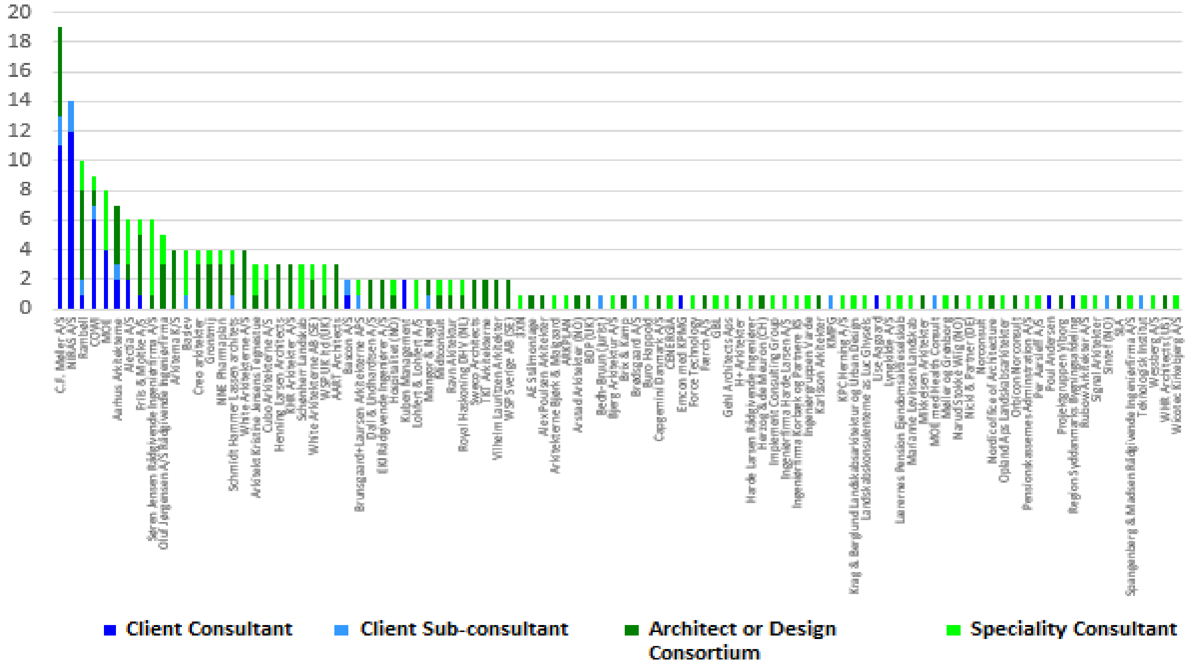

Figure 6: Organizational repetitions: All hospital projects

The frequency diagram also illustrates that it mostly is client consultants that are involved in multiple projects like the companies CF Møller and Niras. This of course creates an infrastructure for informal knowledge sharing between the different projects. However only very limited repetitions within the consortiums exists creating project teams that are unique and thus designing their own super hospitals including unique variants the patient room design.

Besides C.F. Møller playing a central role behind the L shape patient room design there exists no organization-product (design outcome) pattern as illustrated in **Error! Reference source ot found.** juxtaposing companies and room types. It can be concluded that there is no central authority making the standard room design through organizational repetition across the projects. Different variants increasing the product complexity designed by different project teams reflecting the organizational complexity.

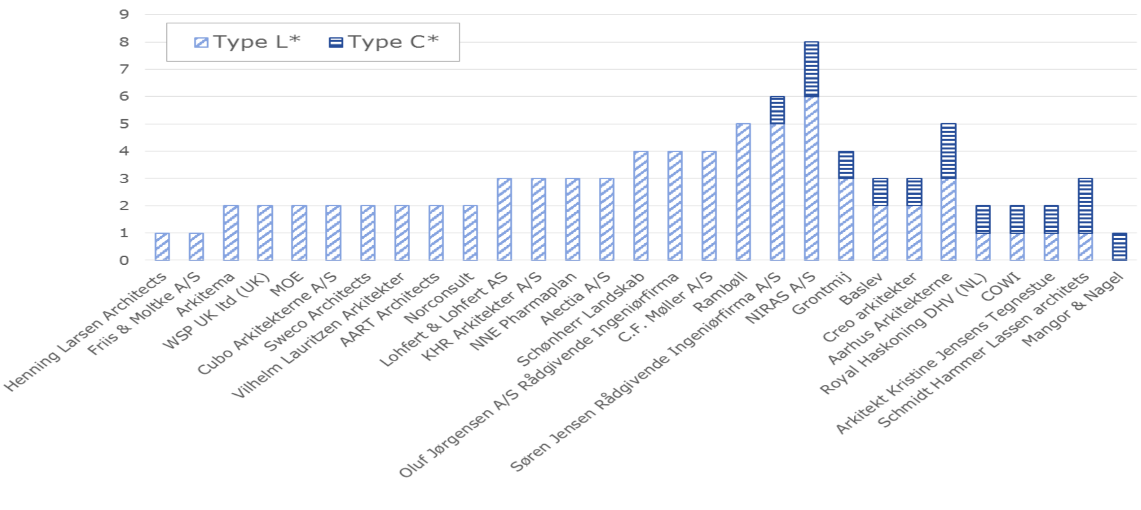

Figure 7: Companies vs room types

Discussion

As the analysis show are all the green field projects designed to be unique pieces in their own way. Each region wants their super hospitals to be the best in the country and a trademark for the region. The observed way of project delivery exemplifies clearly the product/process symptoms described in Figure 1 in literature section. Long lead times in other words delayed projects, unprofitable products in construction terms running over budget and finally frustrated costumers meaning clients and end-users are all the result of the complexity cost (Wilson & Perumal, Complexity Cube, 2015).

Nevertheless, four out of five green field projects shares the same rectangular from structures, despite the fact that it is not the same companies that designed them. When the result in most of the projects overall are of the same nature, it is debatable whether it would be more effective and efficient to design a central model for buildings. In this way design costs could be significantly reduced, since the same process didn't have to be repeated several times.

One of the projects stands out from the others in its design. NHN has a unique architecture. It is debatable whether this is a good or bad solution compared to the other green field projects; if this kind of architecture ensures better treatment and helps to promote healing of the patients, why is the rest of the hospitals projects not designed the same way? Conversely, if it cannot be documented that such kind of architecture creates more value for patients and the employees, the funds could have been used better using the design principle of the other projects. All things being equal it would be cheaper to build a hospital using rectangular building, as this favors the possibility of using standard elements. Thus, the funds could instead be invested in equipment, IT, logistics, etc.

Furthermore, the analysis shows that all the green field projects use the room architype L, or a variation thereof. Almost 70% of all centrally funded projects use the L type of patient rooms. It seems strange that the different design teams use costly resources inventing the same type of patient rooms that overall looks the same but in the details are different. The relation between the organization and product (design outcome) indicated yet again the symptoms described in the complexity cube by Wilson and Perumal presented in Figure 1. Fragmented supply base, many parties involved resisting the efforts to create a standard product that would be cost effective and finally geographical differences and local marketing efforts to shadow the standard design creation. By centralizing the design this project-oriented sub-optimization could have ensured that all buildings are fully optimized for the construction and subsequent operation, while saving money?

Throughout the regions and project user involvement practices among both patients and future staff is widely used. It is puzzling that health care professionals should evaluate and conclude much the same design for each of the projects. Despite the fact that the spatial frame seems quite controlled centrally in our immediate European and particularly Scandinavian neighbors, user processes are repeated on rooms that should be standardized nationwide. There could be guaranteed a greater parity of treatment and staff optimization nationally if the most used rooms (an estimated 85% of the total area required) was standardized. E.g. previous work demonstrates that standardized space reduces errors because of recognition and familiarity in stressful situations. This should be scalable to the majority of the projects.

By implementing standard modular solutions in repeating products such as patient rooms, instead of the creation of the overall architecture over and over again, user involvement processes can have focus on daily usage areas and architectural finishes so that health care professionals, regional client representatives and end-users will feel their touch on the final product.

Another possible side effect of the nationwide standardization of the most obvious space will emerge as new technologies are developed. During the long lifecycle of the projects, new tools and workflows will be developed. By having a nationwide uniformity it will be easier to implement new initiatives. It will only be necessary to conduct pilot projects on individual hospitals and the same module will be repeated nationwide because if the technology works on a standardized hospital, there is a high chance that it also works on another.

Conclusion

This study reflects how inter organizational relationships shapes the complexities of construction projects in numerous ways. The analysis shows that even though the different projects are run independently by different project teams not communicating with each other, there are some repeating patterns. The projects are designed for each specific location (region) with unsystematic and limited use of processual, organizational and technical repetitions. Overall, the projects are executed in parallel and follow the same phases with a high degree of user involvement in each of the projects; here inputs are gathered for the specific project that subsequently is designed by a unique team of architects and consultants. Although some of the participating companies are involved in several projects (especially for the client consultancy role), there is a high degree of variance in the project teams. Despite the variance of the project teams the overall and detailed design of the hospitals look remarkably the same. However, a detailed analysis of the patient rooms reveals that although 70% of the projects use the same architype (the L-type) they are all different from each project. In other words there exists no identical patient room design being used in two different hospital projects. This lead us to the conclusion that the hospital is reinvented in each project leaving behind unrealized potential for leveraging similarity across the projects. This could have been achieved by a stronger central coordination, thinking of super hospitals as programs and portfolios making use of modular standard solutions rather than independent individual projects. By reconfiguration of the repeatable modular solutions resources such as time, money and professional health care and design personal can be used more effectively in order to create super hospital projects which are still unique.

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8.2 Appendix B: Exploratory Study MT Højgaard Cases Paper 2 (unpublished)

Perceived effects of modularity in construction - A general contractor's perspective

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Abstract: Current research on the advantages and disadvantages of using modular solutions in the construction industry overemphasizes the product. More work is required, however, to explore the value of modular solutions from the contractor's perspective, including how modular solutions affect construction processes and organisation. The purpose of this study is to identify the perceived effects of modular solutions seen from a contractor's perspective. Empirical material collected from site visits and interviews of 7 project managers of a general contractor company were combined with the results of a review of the modular solutions literature, specifically literature dealing with the advantages and disadvantages of modular solutions in systems engineering, product platforms and off-site construction. Seen from the contractor's perspective, contrary to the literature not only the disadvantages outnumber the advantages but also negative effects such as delivery lead times and interface problems put question marks to the positive effects that the literature suggests. Contractors generally question the positive effects of modular solutions reported in the literature, as their perceptions of the benefits contrast considerably with those of producer companies such as house builders.

Keywords: Complexity, effects of modularity, general contractor, offsite construction, industrialized building

INTRODUCTION AND PAPER SCOPE

Construction projects have evolved into highly complex phenomena. Construction practices today involve the complicated organisation of labour including unskilled and skilled workers, such as labourers, masons, carpenters, plumbers, electricians, and designers, and higher-level managerial roles such as architects, engineers, and contractors. These roles are organised into processes from the initial programming of the detailed design, to procurement, off-site manufacturing and assembly on site, all coordinated to realise a unique building of increasing complexity. This increasing technical complexity is seen in the rapid development of new building materials such as facades, insulation, IT and automation technologies. In particular, high priority is given to the holistic performance of the building including fire protection, energy efficiency and indoor climate. As a result, construction practices are characterised by high complexity within the build product, processes and organisation.

This growing complexity has been highlighted by researchers as one of the primary challenges in the further development of construction practices. Gidado (1996) takes an ordered approach to assess complexity in construction projects. Williams (1999) describes complexity as structural uncertainty and uncertainty in goals and methods only, whereas Wild (2002) looks at the complexity of the social system in construction. Finally Bertelsen (2002) states that the failures, delays, cost overruns and even grief in construction stem from a lack of understanding of the complexity of construction projects and argues for more deliberate approaches to deal with these problems.

The concept of modularity has witnessed an increasing attention from practitioners and academics as a strategy for handling the rising complexity of production practices leveraging the benefits of similarity and standardization while at the same time enabling the production of individualized products and services (see e.g. Ulrich and Tung, 1991; Ericsson and Erixon, 1999; and Sosa, et al., 2004). In particular, the concept of modularity is used to explore different types of production-related structures within products, processes, organizations and supply chains (Salvador 2007 and Campagnolo & Camuffo 2009).

Despite the growing interest in modularity, it has limited use in the construction industry and has mostly been associated with efforts of industrialised construction (Gibb, 1999; Pan, 2007; Jonsson and Rudberg, 2014). Here, through off-site construction and pre-fabrication, modularity is seen as a strategy to address the problems of productivity in the industry.

Modular solutions have been classified by Voordijk et al. (2006) into three categories: (1) modular, (2) integral, and a combination of these two, (3) hybrid modular. The classification made by Gibb (2001) however is more tangible as it identifies four degrees of off-site construction. The four modularity degrees are:

- Component manufacture and sub-assembly: The traditional approach in construction. Raw materials and components are used for to build on site.
- Non-volumetric pre-assembly: In this concept, 'two-dimensional' elements are prefabricated off site and assembled on site.
- Volumetric pre-assembly: Volumes of specific parts in the building are produced off site, and assembled on site within an independent structural frame.
- Modular building: In this concept, much of the production is carried out off site, with modules fabricated to a high level of completion. The only work performed on site is the assembly of the modules and finishing operations.

Common to the different perspectives on modularity in construction is a focus on the product and therefore on the producer (Gibb, 2001; Pan, 2007; Jansson, et al., 2014; Jonsson and Rudberg, 2014), whereas limited attention is paid to the other actors' perception of the role and relevance of modular construction. An exception is Voordijk et al. (2006) who analyse three cases of general contractors' projects from a modularisation perspective covering product, process and supply chain modularity. This research however omits a thorough investigation of the effects of modularisation in construction. This is the starting point for this paper in which we investigate how the contractor perceives the effects of modularity in construction.

Firstly, the research design and method are explained. Next, the state-of-the-art within modularity in construction is presented along with a summary of the advantages and disadvantages (Table 1). The relevancy of the identified effects is then analysed alongside the empirical material from site visits and interviews with professionals from a Danish contractor. Finally, in the conclusion and discussion we deal with the implications of these findings, and suggest future research topics within the field..

RESEARCH DESIGN AND METHOD

The results presented in this paper derive from an abductive study at a general contractor's company based in Denmark. The focus is to delineate a contractor's approach to modular solutions in the construction industry as opposed to a producer's approach. Studies covering modular products and product platform design (Ulrich and Tung, 1991; Ericsson and Erixon, 1999; and Fixson, 2006) as well as off-site production systems in the construction industry (Gibb, 1999; Pan, 2007; Jonsson and Rudberg, 2014) naturally take their points of departure in the product platform methods and off-site production. When considering the advantages and disadvantages of modular solutions based on these studies (Table 1), arguments for or against modularity in construction rely heavily on the producer's context and conditions. To draw more balanced conclusions, seven general contractor's project managers (PM) were asked to comment on the relevancy to them of the advantages and disadvantages presented in the existing literature.

Although numerious interwievs were planned initialy, the empirical data collection was limited to seven interviews as it was observed that the information collected reached a level where no new data were gathered. Individual semi-structured (Kvale and Brinkmann 2008) interviews, which were recorded and transcribed and lasted for approximately one hour, were conducted in person at the interviewees' offices. The interviewees, all employed by the same major general construction company in Denmark, were selected based on their expertise in different phases of the construction process such as tendering, designing, planning and construction. The scope of the research was limited to the buildings and modularity in building construction only, so PMs working in other areas such as infrastructure, bridges and offshore platforms were excluded from this research. The interviewees had experience in all decision-making processes both with external parties such as clients, architects and consultants, and internal project organisation from early contact with the client to the final delivery of the project. On average, the interviewees had more than 20 years of experience in the field

The table of advantages and disadvantages of modular solutions (Table 1), which was the basis for each interview, is derived from the Module Indication Matrix presented by Ericsson and Erixon (1999). For the purpose of this paper, Ericsson and Erixon's table was annotated with the literature sources, and in this way served as an overview of the effects of modularity within the current literature. The table was discussed item by item, allowing each PM to relate their perception of the relevancy of every item to their own work. After transcription of the interviews, similar responses were grouped and these are summarised in the analysis section of the paper. At this point, the positive and negative effects of modularity in the construction process and organisation are described in separate sections of the analysis.

THEORETICAL BACKGROUND

Modularity is gaining popularity as a concept in several disciplines related to construction management. However, the meaning of modularity, its definition and, more importantly, the value it is ascribed differ from discipline to discipline. In this section, we demonstrate that academic debates concerning modularity are biased towards the producer, and that the view of the contractor should be added to achieve a more inclusive, balanced debate.

The following subsections provide:

- a literature review of modularity as a concept
- an overview of modularity in different areas
- examples of the application of modularity in construction

Modularity as a concept

Modularity as a concept is gaining attention in research circles. As a way of looking at products and processes, modularity has been relevant in certain industries for a considerable time. For example in automotive manufacturing, producers seek to combine modules to optimise process, time consumption and costs. Outside production and manufacturing industry, however, the modular perspective may be difficult to reduce to a level of operationalisation. The literature on modularity is large, wide-ranging and difficult to absorb (MacDuffie, 2013). However, studies in industrial and operations management suggest that the concept of modularity recurs as a relevant analytical tool in several research communities (Fixson, 2006).

A review of the recent literature on modularity reveals a consistent focus on product. Fixson (2007) includes 168 references in the field of modularity and commonality, and Campagnolo and Camuffo (2009) investigate 125 studies in the area of modularity. Both reviews agree on the lack of understanding of the interrelations between product, product system and organisation modularity (Campagnolo and Camuffo, 2009). In general, the studies are biased towards the product, favouring the product as the decisive factor and ignoring other dimensions of modularity. This tendency is clear as researchers such as Ericsson and Erixon (1999), Sosa et al. (2004) and Campagnolo and Camuffo (2009) claim that the organisational and process modularity should follow the product architecture.

The working definition of modularity of this paper derives from Simon's (1962) description of the focus of modularity as "creating high intracomponent dependency and low intercomponent dependency". This definition is further elaborated by Ulrich and Tung (1991), who highlight the similarities that should ideally exist in functional and physical design while having a minimum of interactions between components. The authors take their starting point in the interchangeability of modular components and then move on to emphasise that the number of interactions between them must be minimised. This independency can be obtained by functional design (Ulrich and Tung, 1991). This definition is useful in understanding modularity in a construction context with building components being built separately in different locations, but compatible with each other on the construction site.

Langlois (2002) supplements Simon's (1962) description by emphasising the ability of the product to decompose into modules. His focus is on decomposing the complexity of a product into fully separable components, such that each component can be developed independently without necessary coordination with other components. This definition also helps us visualise modularity in construction as the bringing together of separate and independent modules into a complex final product, the building.

A particularly relevant classification of modularity to help understand the different perspectives of parties involved in the process is put forward by Baldwin and Clark (2000). They differentiate Modularity-in-Production (MIP) from Modularity-in-Design (MID) and Modularity-in-Use (MIU). A product designed and produced according to the MIP perspective may not satisfy the other approaches. According to MacDuffie (2013), it may be possible that a given modular boundary and interface specification successfully satisfies both MID and MIP, but often these two objectives need different specifications, presenting trade-offs and requiring prioritisation. The classification of modularity into different parties' perspectives helps us understand the importance of a process view of modularity. As will be argued, the gaps in the application of modularity in construction may be due to an excess focus on the producer's perspective. Baldwin and Clark (2000) remind us of the importance of including the considerations of all parties involved. In this paper, we especially seek to demonstrate how including these parties will force aspects such as organisation and process, rather than the product alone, to be considered.

This theoretical outline introduces the definitions and uses of modularity as a concept that underlie and inspire this paper.

Modularity in different areas

In the following section, we show examples of the successful application of modularity in areas and industries other than construction, and also highlight the potential benefits of applying modularity in the construction industry. Fine (1998) describes the evolutionary development of product, process and supply chain in the computer industry and claims the same lifecycle can be adopted in other industries.

In their work on the drivers of modularisation in implementation of modular product platforms, Ericsson and Erixon (1999) develop a matrix to identify the degree of modularity in production systems, and describe their Modular Function Deployment method. This approach achieved the best rating result in a case study conducted by Bauer (Bauer et. al., 2014), which compared twelve methods of modular platform design. The drivers used by Ericsson and Erixon (1999) in their Module Identification Matrix with their different characteristics are taken as a base and developed further in this research as shown in Table 1.

Complexity provides the natural grounds to study modularity. The degree of modularity in product platforms is an issue in the study undertaken by Hölttä-Otto and de Weck (2007) in which the authors list the advantages and disadvantages of modularity in developing product platforms. Within the computer systems industry, modularity has been studied by Baldwin and Clark (1997) as a way to manage complexity, enable parallel work and accommodate future uncertainty. They investigate the impact of design modularity in computer systems in companies, with clear figures showing the links between modular design applications and competitive advantages gained (Baldwin and Clark 2006). Focusing on how organisational decisions are affected by the companies' choices of product modularity, Brusconi and Prencipe (2001) study aircraft engines and chemical plants to investigate modularity in product development. Together these studies illustrate an intense interest in modularity as a tool to optimise processes and increase efficiency in several industries.

Modularity in construction

The examples above suggest that many sectors could benefit from adopting modularisation. In the following section, examples of the application of modularity in construction are presented.

Bonelli and Guerra (2012) create a design structure matrix of the construction process to help visualise the interrelations and dependencies of activities both in the case of traditional and modular construction methods. They conclude that their success depends to a great extent on the early definition of the project design; early integration of the client and external parties; and coordination and integrated project delivery methods where all parties work for the same purpose and do not simply provide a service.

Other research shows that the application of modularity in construction, for example off-site technologies or modern methods of construction, offer potential to reduce cost, time, defects, health and safety risks and environmental impact, and therefore to increase predictability, whole life performance and profits (Gibb, 2001; Housing Forum, 2005; Buildoffsite, 2014).

In work to identify the drivers of and barriers to modern construction methods, Pan (2007) investigates the top 100 UK house builders and observes that they prefer to allow others to take the risk of developing new products before they adopt them themselves.

Besides classifying modular construction, Voordijk et al. (2006) build on the three-dimensional modularity concept of product, process and supply chain modularity (Fine, 1998). In the work by Voordijk et al., three contractor companies in the construction industry are investigated to test how time and space aspects affect product, process and supply chain modularity. The importance of Information and Communication Technologies within the company, especially where operations are geographically dispersed, is emphasised. (Voordijk et al, 2006).

In summary, these studies conclude that modularity is beneficial in terms of cost, time, productivity and quality

Effects of Modularity in construction

As suggested earlier, disproportional attention may have been given allocated to the producer. Ulrich and Tung (1991), Ericsson and Erixon, (1999) and Fixson (2006) have studied the drivers of and barriers to modularity, covering product platform development and design. Similarly, Gibb (2001), Pan (2007), Jaillon and Poon

(2008), and Jonsson and Rudberg (2014) have treated the drivers and barriers in the context of off-site construction and production systems in construction. The effects of modularity reported by these authors can be seen in Table 1. However, although they concentrate on different drivers and barriers, they all tend to see the application of modularity from the product or producer's perspective..

Table 1. Effects of modularity in the literature

References in the Literature / **Effects of Modularity**	Gibb (2001) Pre-Assembly	Blismas et al. (2006) Off-site Production	Pan et al. (2007) Off-site Production	Jaillon and Poon (2008) Prefabrication	Jonsson and Rudberg (2014) Industrialized building	Ulrich and Tung (1991) Product Modularity in Design / Manufacture	Ericsson and Erixon (1999) Product Platform Design	Fixson (2006) Product Platform Design
Cost	X	X	X	X	X			
Logistics					X			X
Health&Safety	X	X	X	X	X			
Quality	X	X		X	X	X		
Common Unit							X	
Carryover							X	X
Separate Testing						X	X	X
Service/Maintenance						X	X	X
Recycling/Waste reduction	X			X	X	X	X	X

Time		X	X	X	X	X		X
Productivity	X	X	X	X	X			
Customization/Styling						X	X	
Supplier Available							X	X
Flexibility / Planned Design Changes	X	X	X	X	X	X	X	
High production volumes			X	X	X	X		
Organization		X	X	X	X		X	
Process							X	

As pointed out by Fixson (2007) and Campagnolo and Camuffo (2009) there is a gap in the literature when it comes to studying modularity not only from product perspective but also from perspectives other than that of production. Moreover, in their extensive literature review they do not take modularity within construction into consideration. In this paper, we attempt to fill in part of that gap by reflecting the contractor's perspective.

The effects of modularity as identified in the literature are shown in Table 1, which is used as a template to investigate the contractor's point of view in the paper. In the following analysis section, the thoughts, ideas and points of view of the contractor's project managers concerning modular solutions are presented.

ANALYSIS

The purpose of this section is to investigate the contractor's point of view to the effects of modularity listed in the literature.

The responses of seven interviewed project managers concerning the positive and negative effects are summarised together with the interviewees' opinions on the effects of applying modular solutions in the construction process and organization. As a consequence, this leads to a better understanding of modularity and its benefits and obstacles for the construction industry.

The project managers' perspectives are presented in the following section. A discussion of these perspectives compared to the perspectives reported in the literature is given in the results and discussion section of this paper.

Part I Positive Effects

Lower *cost* is mentioned by the majority of interviewees as the main driver making modular solutions interesting for any contractor. According to the interviewed PMs, given that quality and deliverability are assured; a modular solution mainly proves attractive for the contractor because it is likely to reduce project costs significantly. When choosing between a modular and a non-modular solution reduced square meter costs tend to be the decisive factor for the project manager.

Project managers also agree that modularity facilitates *logistics*. In cases where everything runs smoothly, modularly built elements simplify logistics at the construction site: they arrive together, quickly, and intact; they are packed and arranged in the most systematised way possible, thereby improving both security and space utilisation. Even the reduced amount of space modular elements occupy while waiting to be installed becomes an important factor in the analysis of the site cost-benefits.

"*It is a great advantage to work with modular solutions when they are delivered in ready-made packages. They occupy less space at site as they are already pre-assembled compared* *to the other methods. Due to fast installation, the modules use less time between arrival to site and installation*," says one of the interviewed PM's. Project managers unanimously agree that module deliveries are much simpler and more efficient than the traditional method deliveries.

Another advantage repeatedly mentioned is the facilitation of site *organisation*. "*Fewer elements mean fewer people to handle them and that simplifies the logistics of not only materials, but also of employees,"* comments one respondent.

Fewer employees on site is also an advantage as far as *health and safety measures* are concerned. "*Fewer people on site means less risk for accidents,"* say the project managers. One interviewee observes that most accidents happen in the shell construction phase and, therefore, the application of any modular solution that would require less work on site in that phase reduces the risk of accidents. In addition to fewer people on site, risk planning is made easier by the repetitious nature of installing modular elements. As a result, fewer skilled workers are required as installation teams replace specialist crews. The plug-in solutions will require less skilled workers to be employed.

Similarly, instead of working with 5 to 10 suppliers and subcontractors, working with modular solutions bring advantages at the level of site organisation as just one single producer is needed and just one single team is necessary for installation. In the light of the reasons listed above, the personnel costs together with other problems associated with the workers will be limited. As a PM emphasised, "*Absence of workers, weather conditions, strikes and work accidents will be less of an issue where the contractor's site organisation are shaped by the applications of modular solutions"*.

Projects managers also acknowledge *quality of products* is an advantage. With standardised modular solutions and off-site production, more consistent quality can be expected as a result of the working conditions and production teams not being subject to changes as is the case with on-site production. Therefore quality is more manageable: *"In terms of quality, it is a great advantage to receive a factory built product rather than a site built product. The physical conditions of working under a roof in dry space with fixed production lines and quality procedures definitely strengthen the quality of the products,"* says an experienced PM.

Project managers also mention carry-over, separate testing and common units as possible advantages. In the instance of *carry-over,* one project manager remarked that *"Even though it isn't possible to use the same product throughout different projects, using solutions across projects might still bring value. Things like similar packing techniques, use of the same tools and machinery help the practitioners on site to work more efficiently."* Similarly, due to *separate testing* and use of *common unit products*, units with defects or that simply do not fit into place can easily be identified and replaced without causing delays to the other tasks.

Part II Negative Effects

All interviewees perceive *limitations to free design and creativity* to be a major problem with modular solutions. They also mention the discrepancy between the typical dreams, thoughts and ideas of the architect and owner to create an outstanding, unique final product on the one hand and the mass-produced anonymity of modular solutions on the other hand. The PMs spell out how, from their experience, mainly in projects such as company headquarters, residential buildings, and publicly owned building projects, both the owner and the architect are driven by the will to have each project remembered in their names and therefore wish for as individual an expression as possible. From their experience, clients also tend to prefer houses with a degree of personalization. One project manager mentions the buildings built in Denmark during the 60's and 70's as examples of modern period style and points to their low market value partly as a consequence of their anonymous mass-produced appearance. Therefore, according to the PMs, modularity in construction is a drawback on an individualized-oriented market, since it produces standardization in composition and looks of the final product.

Also according to the PMs, the *risk of design changes* is another major drawback. The inability to change design along the way makes it necessary to freeze design at a very early stage. As one PM said,"*the earlier the modular solutions are considered in a construction project, the greater the possibilities are to apply them. As a consequence the design is completed in the early phases of construction projects using modular solutions."* From the interviews, it was clear, that it might be difficult to have all parties agree on the design completion, especially the designers themselves who perceive design to be a flexible and living process. Moreover, it is very likely that unforeseen elements occur during the building process, requiring design changes. Modular solutions do not accommodate this need, or they do so only at high cost.

Another recurring disadvantage is the *high volume deliveries of products* when the contractor wishes to purchase only a small amount. The producer of modular solutions needs high volumes to reach an economy of scale. However, when only a few units are needed, it can be more efficient and more economical for the contractor to produce on-site. As one project manager explained: "*In the case of renovation projects where, for example, 200 houses are going to be renovated, the modular solutions are the most convenient solutions - but how often do you have 200 houses to deal with?*" In order to reduce costs significantly, high volumes are needed to apply modular solutions.

Reuse of technical specifications is an aspect of modularity, which at the outset appears to be an advantage. However, it is rarely the case in practice because standardised technical specifications actually tend to prove a challenge to the constantly changing interests of client, architect and consultant from project to project. In the hypothetical case that parties agree on the binding issues from project to project, there would be much to gain by reusing technical specifications: design and quality assurance documents are provided by the supplier, facilitating not only the contractor's job but the entire construction process; and the approval process is shorter and requires less energy as the previous project can be shown as a reference, and so on. However, even if the method and modular solution applied in the previous project remain the same, the project parties such as the client, architect and consultant can change, bringing the same challenges back to the surface.

The interviewees also identified *country-specific standards* of buildings as a potential disadvantage. Despite the existence of Eurocode and free market regulations within the EU, an experienced PM raised the issue, stating: *"To work with foreign suppliers who have no experience in the Danish market can cause problems. In many cases Denmark has higher standards, for example in sound insulation and fire resistance, than neighbouring countries."* That may mean that a well-known modular method commonly used in Germany for example may not to be approved for use in Denmark.

Although, the PMs admit the importance and advantages of working with stable organizations and crews, the interviewed PMs see it as unrealistic. Typically, they are used to to project teams being dissolved after every project. "For every project a new team with relevant competencies in a new organization is created in order fulfil the specific project requirements", says one PM. In general, PMs rely on the ability to find the people with the required skills for the particular constellation of a particular project.

PMs point out that in such conditions, price competition among suppliers does not exist, so the contractor risks losing projects because it is forced to submit a higher bid. Several PMs point out that there have to be alternatives in the bidding phase in order to secure an optimal price but also in the construction phase so that the agreed delivery can be assured.

Furthermore, one PM remarks, that it is not unusual for a supplier to be busy with another project and therefore not able to fulfil obligations on time, adversely affecting the construction process and time schedule. For these reasons therefore, the contractor should always have an alternative supplier to work with.

Finally, *time* is an aspect of the construction process where modular solutions can easily become disadvantageous. Time is one the most attractive promises of modularity as it reduces the time required for on-site production to only a matter of installation. However, this time saving is only realised if the process is described clearly, agreed in advance and well coordinated by all parties. Otherwise, it adds more complexity, chaos and inflexibility to the construction process. By using modular solutions, traditional work activities are clustered into modules that are more independent of each other. As a result, the buffer times between activities disappear and the construction process becomes more sensitive to changes such as failure to design, produce or deliver on time. A modular solution therefore makes the project design and project planning phases even more critical for the success of the overall construction project.

The manufacturing period for the modular products has to be known by all the parties so that in case a change occurs in the design or in the agreed process, the consequences will be accepted. One of PMs illustrated the problem by comparing an alternative method to the existing off-site concrete elements in current Danish construction. The typical precast concrete element takes 10 weeks to produce from order to delivery and as this is more or less common knowledge for all parties, all the work tasks are planned accordingly. The consultant knows that design changes are not tolerated after off-site production starts, and construction teams at site know when to expect the delivery from factory. "*In case of an alternative modular construction method application, the necessary production time and delivery should be clarified by the producer and it has to be agreed by all parties. It is simple for the planning* *but for the execution it is hard to work against the habits.*" Modular solutions create inflexibility in time schedules and therefore remove the exchangeability of subsequent construction activities and cause buffer zones to disappear. PMs in the contractor's team mention this. All interviewees mention that planning and execution are often done alongside each other, leaving no space for the application of modular solutions.

Similar to time, *productivity* is another clear advantage of modularity that can easily turn into unproductivity if the construction process is not planned and managed properly. Productivity highly depends on early planning, however, "*the challenge in the company and in the construction industry is that we often end up planning while we are executing. As a natural consequence of that there is not enough space left in our time schedules for using modular solutions,"* states a PM.

These observations made by PMs place time, supplier availability, and productivity in a fluctuating position between being an advantage but also a barrier depending on the success of the construction management.

As can be seen, PMs perceive modularity as having certain advantages and disadvantages. However, when discussing modularity, it is rarely considered that modular solutions also affect processes and organisations.

RESULTS AND DISCUSSIONS

The general finding of this study is that the effects of modularity reported in the literature do not fully reflect the aims and ambitions of contractors, and that this explains why modular solutions are not used at the desired level in the construction.

In line with Baldwin and Clark's (2000) differentiation of Modularity-in-Production (MIP) from Modularity-in-Design (MID) and Modularity-in-Use (MIU), the priorities of construction industry producers, such as product manufacturers and house builders, contrast with the priorities of contractors. Reviewing recent studies of modularity (Ericsson and Erixon (1999), Hölttä-Otto and de Weck Jonsson (2007) and Rudberg (2014), Pan (2007), Gibb (2001)) reveals a number of recurring advantages and disadvantages. These studies, however, focus only on the product platform methods and off-site production. The interviews conducted for this article was, firstly, to test the relevancy of the mentioned effects of the modularity for the project managers operating in the construction sector and, secondly, to see what project managers had to say about each element when asked directly about their experience with them. The effects of modularity on the construction process and organisation are the final point of concern in understanding why modular solutions are not used despite the advantages ascribed to them in the literature.

Although some advantages overlap, such as cost, health and safety, logistics and quality, some, such as common unit, carry-over, separate testing, service, maintenance, and waste reduction seem to be less relevant, and therefore less important for the contractor.

Moreover, some of the reported benefits of modularity can be seen as weaknesses from the contractor`s perspective. For example, fixed technical specifications are mentioned by a PM as a clear advantage. However, as construction projects have different conditions and requirements, and clients have different tastes, the products used in one project may not be accepted or approved for another project.

It is notable that some advantages mentioned in the literature for product developers or off-site manufacturers, such as time, productivity, customisation and supplier availability are not necessarily seen as benefits by the contractor. The producers accept supplier availability as an advantage while from contractor's perspective it is a possible treat in choosing the modular solutions. Time and productivity are apparent advantages of modular solutions which can easily turn out to be opposite where the construction process is not well managed. Therefore, contractor's PMs are sceptical about modular solutions.

In addition, roles and responsibilities need to be redefined when applying modular solutions. For example, producers, rather than the engineering consultant, prepare the detail drawings and shop drawings. That requires the producer to know his own product rather than the contractor. In cases where a problem occurs in the product, it is then the supplier's responsibility to detect it and provide a solution. These shifts of authority, and the need to redefine roles and responsibilities in the early construction process also lead contractors to reject modular solutions.

As reported above, PMs believe that modular solutions carry risks that they are not willing to take. They also believe that clients are open to such alternatives but that the architects and consultancy companies prefer to stick with the tried and tested methods in their existing portfolios.

Design and build projects give more authority and therefore opportunity to the contractor to apply modular solutions compared to the classical design-bid-build projects. In design and build projects, the contractor is typically involved in the project at earlier phases where important decisions are made cooperatively, and that gives contractors greater opportunity to influence the design process and construction method. In that way, more space to apply modular solutions is created.

CONCLUSIONS

The aim was to identify the advantages and disadvantages of modular solutions from the contractor's perspective and to compare and contrast these findings with those reported in the literature covering systems engineering, product platforms and off-site construction.

The effects of modular solutions in construction from a contractor`s perspective differ notably from the advantages and disadvantages named in the literature for modular products and producer companies such as house builders. Producer companies have different motivations when providing modular solutions than contractors operating in project based construction industry.

Cost, logistics, health and safety, and quality of products, then, are parameters on which modular solutions are perceived by the contractors to give an evident pay-off, given that the process runs as planned. In addition, the application of modular solutions can have a significant effect on processes and organisation in construction companies. The need to freeze the design early, the need for even better communication between construction parties, and the redefinition of project responsibilities are some of the main consequences. These effects should be considered together with the project-based nature of the construction industry.

While this study has added the contractor's perspective to the debate, an even broader view on the use of modular solutions in the industry could be obtained by including perspectives from parties such as architects, consultants and clients in future research. A longitudinal case study may also be helpful in investigating the consequences of applying modular solutions in construction process and organisation in construction companies.

Finally, modular solutions differ by category, as well as having a variety of starting points, interface solutions and customer order decoupling points. Future research could identify and compare the different modular production systems relative strengths and weaknesses from the contractor's perspective.

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8.3 Appendix C: Prescriptive Study EPOC2015 Paper 3 (published)

EXPLORING FACTORS LEADING TO TENDER SUCCES USING QUALITATIVE COMPARATIVE ANALYSIS (QCA) – THE STUDY OF ORGANIZATIONAL REPETITIONS

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ABSTRACT

The purpose of this paper is to introduce and evaluate Qualitative Comparative Analysis (QCA) as a method for exploring the complexity of practices of project organizing and management combining the benefits of top-down and bottom-up research strategies. The QCA method is used in order to describe combinations of conditions leading to particular results in the tendering process. Empirical material collected through data mining in previously completed project records (quantitative data) is supported by data obtained from project managers of a general contractor company (qualitative data) in order to holistically describe the combination of conditions resulting in particular tender results. As a result of the analysis, a solution set is found explaining the path leading to project contract winning; previous work experience between client and general contractor together with either previous work experience between architect and general contractor for design-bid-build projects or senior project responsible involvement from the contractors side in design-build projects. The analysis illustrates how QCA is a powerful strategy for exploring the complexity of project practices being able to bridge the divide between top-down and bottom-up research strategies.

KEYWORDS: Organizational repetition, project organizing, QCA, successful bid, tender practices.

INTRODUCTION

It is widely acknowledged e.g. Cicmil & Hodgson (2006) and Blomquist *et al* (2010) that the structural approach traditional has dominated research in project management. This is characterised by being structured, mechanistic, top-down, system-model-based approaches to project management that rely on systems design, tools, methods, and procedures (Blomquist *et al.*, 2010, pp.6) and usually studies using quantitative methods for collection of data and hypothesis testing.

In contrast to the structural perspective, a growing amount of research has been focusing on understanding project organizing and management as situated and contextual practices. This was initially driven by a Scandinavian school of research into project management and temporary organizing (Morris, 2013) but has recently sparked a development of a pure bottom-up research perspective focusing on what individual actors actually ”do” when they work on projects - viewing project as practice (Blomquist *et al* 2010).

The different perspectives make the study of practices of project organizing and management a matter of choosing the proper method using either (1) large amount of quantitative data and well defined hypothesis testing (top-down) or (2) qualitative data and more explorative research questions.

The purpose of this paper is to introduce and evaluate Qualitative Comparative Analysis (QCA) as a method for exploring the complexity of practices of project organizing combining the benefits of top-down and bottom-up research strategies. This is done by a study of the tendering practices form a major Danish contractor.

QCA methodology allows researchers to draw different combinations of conditions leading to create a particular outcome Thereby it lies between quantitative and qualitative research approaches for testing hypothesis combining statistical analysis and case studies (Jordan et al., 2011).

The research question therefore is; what are the combinations of factors leading to successful tender results for a bidder (general contractor) in construction projects?

The premises for using QCA are a careful selection of relevant cases and an in-depth understanding of the research in terms of identifying interesting outcomes and relevant independent variables. Thus are QCA always based on a rigorous mapping of the current state of the art combining literature reviews and empirical investigations (Ragin, 1987; Rihoux and De Meur, 2009). Hence, the paper opens with a literature review of tendering practices followed by a detailed introduction to applied methodology QCA. Subsequent the analysis of the selected cases is presented and the results are discussed. Finally, a solution set together with implications of the findings has been presented in the conclusion section.

LITERATURE REVIEW: TENDERING PRACTICES

There exists a large body of literature covering contractor prequalification and decision-making in the project tender phase from the client perspective (e.g., Hatush, and Skitmore, 1997; Russell, 1992; Diekmann, 1981 and Nieto-Morote & Ruz-Vila, 2012); however, there is a gap in the literature when it comes to investigating the factors leading to contract win or lose from the contractor's side. This paper addresses this gap by studying the complexity of tendering practices from the bidder perspective.

It is a well-celebrated fact among academics and practitioners that decisions made in the beginning of a project have the most significant consequences for the success or failure of the project. Becker (2004) addresses the circumstance that uncertainty in decision-making is problematic, because the likelihood of each outcome from a set of possible specific outcomes is initially unknown, as it is the case in the early project phases (see Figure 1). In handling the uncertainty it is important to understand the tender phase and contractor prequalification. As seen in Figure 1 presented by Winch *et al.* (1998) uncertainty is dominating the early stages of projects and certainty gradually increases by time and as completion approaches. Therefore, the tendering phase can be regarded as a critical stage in the realization of projects.

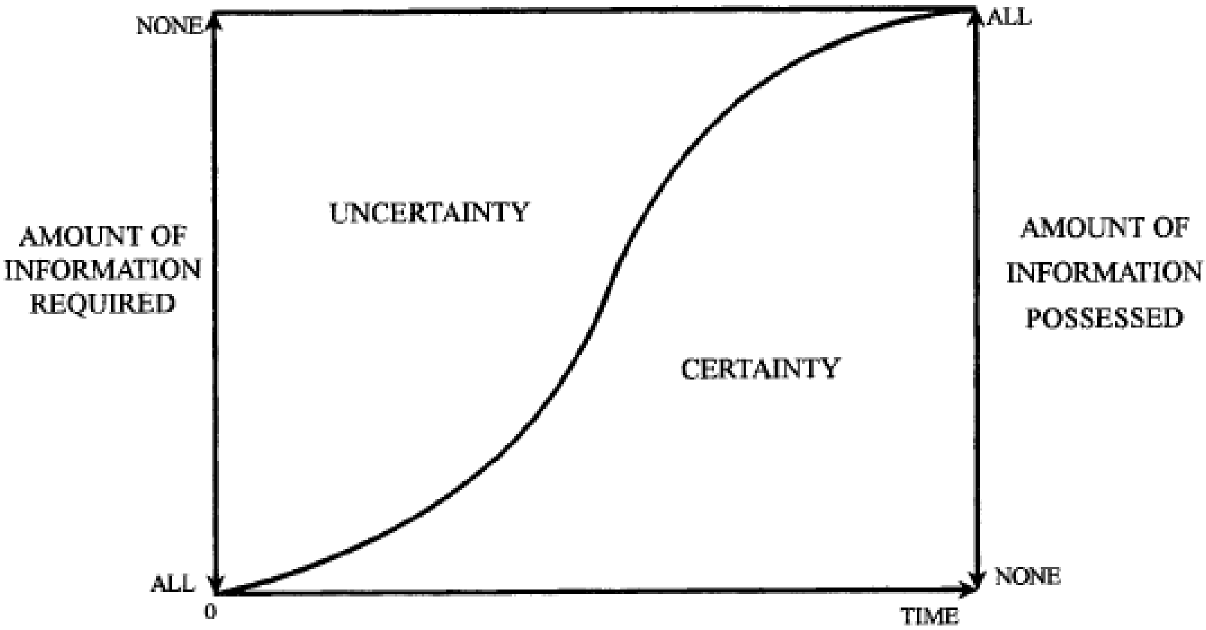

Figure 1 The project process (Winch *et al.*, 1998)

Moreover, project parties, including owners, architects, and contractors, all with their separate backgrounds and separate agendas, have to come together in order to carry out their normal project practices. This is performed through traditional contractual arrangements (Cornick and Mather 1999). Thus, there are obvious uncertainties in the early project phases, especially during tender phases, since different organizations and different organizational entities come together to share and create information for the first time.

Tenders are complex and they involve many engineers and managers who have to work as a team, share information and deal with the interface problems that arise between the various responsible subsystem-engineers (Bernold and AbouRizk, 2010). The decision on who should be awarded the contract is made according to the prequalification criteria, the contractor's attributes and the prequalifier's judgment. Despite the effort made by researchers, contractor prequalification remains largely an art where subjective judgment, based on the individual's experience, becomes an essential part of the practice (Nguyen, 1985).

Subjectivity is the most difficult attribute encountered by researchers and practitioners due to a diversity of prequalification criteria (see Table 1) and the variability of the same contractor's ratings, which is differently assessed by different prequalifiers according to their own perceptions. One tool that has been developed in order to track and control the uncertainties better is the so-called multi-attribute utility functions. These are used in an attempt to list the criteria for the decision-maker's preference (Diekmann, 1981; Hatush and Skitmore, 1998). Following this more and more advanced tools for contractor selection have been developed (e.g. Cheng & Li 2004). However, they all reflect the decision-maker's perspective.

Table 1 Decisive conditions in the contractor selection (Nieto-Morote and Ruz-Vila, 2012)

Main Criteria and Sub-criteria for Contractor Prequalification

Criteria	Sub-criteria
Technical capacity	1. Qualification of staff 2. Experience of staff 3. Innovate method 4. Labor and equipment
Experience	1. Type of past project completed 2. Size of past project completed 3. Number of projects completed 4. Experience in local area
Management ability	1. Organisational culture 2. Management knowledge 3. Quality policy
Past Performance	1. Quality level of projects performance 2. Projects completed on time 3. Projects completed on budget
Financial stability	1. Financial soundness 2. Credit ranting 3. Liquidity
Occupational health and safety	1. Management safety accountability 2. Safety performance

Taking the uncertainty in the projects or, more precisely, in the tender phases into consideration, the necessity of investigating factors affecting the bidding success becomes evident.

Stability provides safety to achieve the targeted results and increase predictability (Langlois, 1992; Tyre and Orlikowski, 1996). In the construction projects each party has its own mundane practices and agendas, which are not necessarily known to the others. In the process of construction the different parties develop certain working habits and practices that create a bound between one another (Marshall, 2014). Moreover, as mentioned by Nelson (1994), whenever there is a change in the participants, understandings or contracts, a mode of executing a particular task needs to be identified and adjusted. This always has an additional cost aspect.

In situations of uncertainty, routines and already known solutions have an important effect on the way decision makers, in this case qualifiers, make their choices (Gersick and Hackman, 1990; Langlois and Everett, 1994; Becker, 2004). In a recent case study on hospital construction projects in Norway and USA, the importance of informal mechanisms to stimulate collaboration between project parties in decision-making processes was emphasized .(Bygballe et al., 2015). This suggests that previous contact and collaboration between the general contractor, client, architect and consultant are important factors affecting the result of the tender practice.

Summarizing previously done research, it is relevant to explore the effect of repetitions and previous experiences in tendering practices in project organizing. The question is *What are the combinations of factors leading to successful tender results for the bidder?* Factors can be observed across projects that affect contract gains or losses. These factors, such as previous work experience between the parties client, architect, contractor and general contractor as well as a variety of project attributes and finally the contractor tender responsible's experience, will next be investigated holistically by means of Qualitative Comparative Analysis (QCA) method.

RESEARCH DESIGN AND METHOD

In order to explore the tendering practices this study applies Qualitative Comparative Analysis (QCA). QCA is a relatively new approach, first propounded by sociologist Charles Ragin in 1987, but its principles have since been applied extensively, primarily in the fields of sociology (Rihoux, 2006) and political science (Ragin, 1987) but also in management, economics and engineering (e.g. Jordan *et al.*, 2011) in the study of complex phenomena. Recently it has been introduced in the study of various construction practices like Public Private Partnerships (Gross 2010) and Building Information Modelling (Homayouni et al., 2011).

QCA allows researchers to draw combinations of different factors of practices (conditions) leading to a dependent outcome. As illustrated in Figure 2 the research process is highly iterative involving top-down and bottom-up strategies. Countless of iterations are used to investigate all sorts of different combinations of factors in order to draw meaningful solution sets explaining pathways leading to particular results. During this iterative process literature is revisited (top-down) and additional empirical material is gathered in order to solve occurring contradictions (bottom-up).

Thereby QCA lies in-between quantitative and qualitative research approaches for testing hypotheses, combining statistical analysis and case studies. The method, though, is closer to qualitative methods due to its sensitivity to individual cases (Rihoux and Ragin, 2009). This is also mirrored in the highly iterative processes, which to some degree is similar to the iterative interpretations within qualitative studies.

However, QCA has certain advantages and limitations that one should be aware of. These are identified by Jordan et al. (2011) in the following table 2.

Table 2 QCA Advantages and limitations (Jordan et al., 2011)

Advantages	Limitations
• Ability to work with smaller set of data compared to quantitative approaches • Ability to work with large number of cases compared to qualitative approaches • Easy to understand for the reader • Transparent • Replicable	• Dichotomization of data: Transformation of data into a binary notation • Difficulty in selecting conditions (independent variables) and cases • Lack of temporal dimension

In the following analysis section, the process given in Figure 2 will be exemplified step-by-step in a detailed way for the reader to follow the QCA research method and for future re-searchers to duplicate the study with different cases with different data sets.

To make best use of the data set available to describe a solution set with factors leading to particular project tendering outcomes, a crisp set Qualitative Comparative Analysis (QCA) method was chosen for this study. Contrary to the fuzzy sets that make use of partial member-ships such as 0.5, the crisp set is based on full membership and full non-membership, in other words absences as 0 and presences as 1 binary notation (Thomas, et al., 2014).

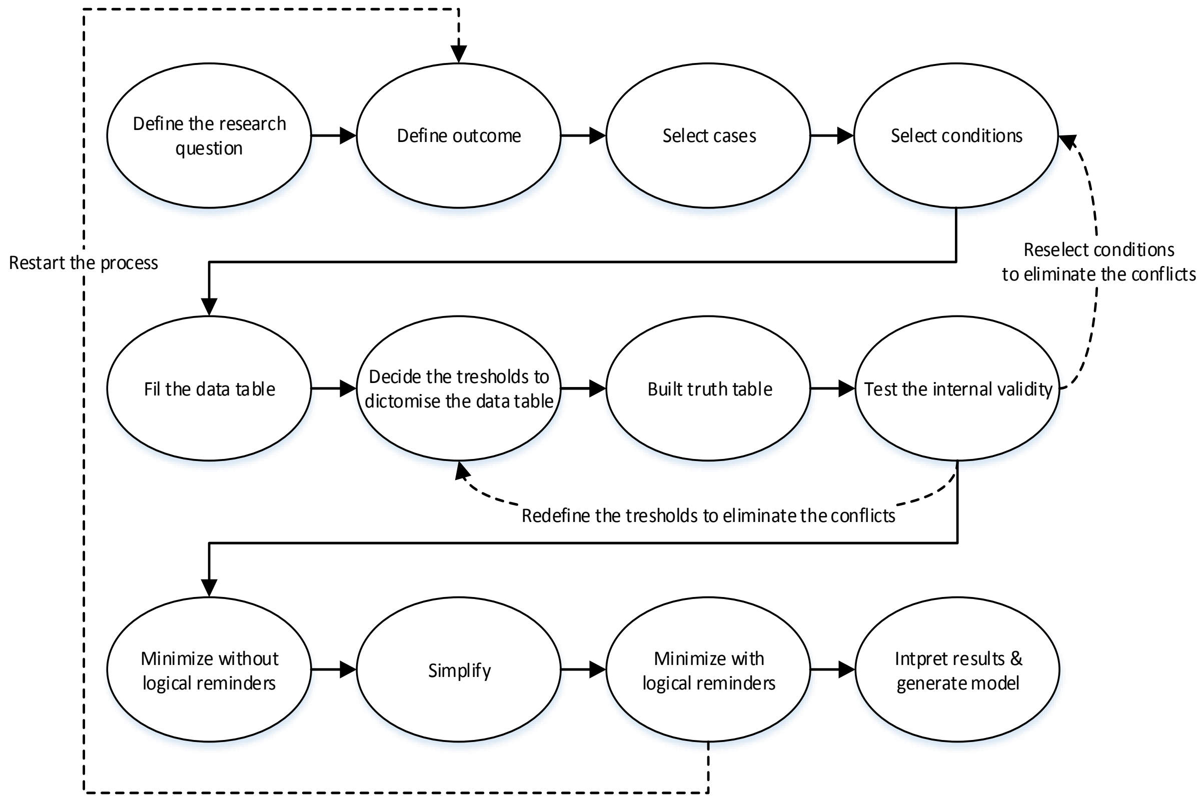

Figure 2 QCA Research Process

However, as there has previously been difficulties in understanding some papers using the QCA method, the research process illustrated in Figure 2 is explained in detail, and frequencies and descriptive results are presented in the appendix. In doing so it is intended for the reader to follow the preliminary results and changes in the data set, as before and after, on the way to the final solution.

The results presented in this paper derive from a combination of quantitative and qualitative data. On one hand a quantitative set of data was obtained through a data mining work conducted in the database of a general contractor company based in Denmark. The company's project data base consists of all completed, ongoing projects and projects that was given an unsuccessfull bid. The data base contains information on project type, project size, location, contract type, parties involved such as clients, architects, consultants etc., contract price, project responsible, tender responsible and many other factors. For the sake of comparibility only the building projects within the last 5 year's time frame were chosen. This amount of data was then combined with a collection of qualitative data: six of the cases from the data base were elaborated through in-depth semi-structured interviews with their given project responsibles. A similar number of other cases from the quantitative data set were cross checked and elaborated through brief phonecalls and conversations with project responsibles. All the project names together with names of the responsibles were fully anonymized. A description of the concrete case selection process will be presented in the next section.

ANALYSIS

The initial step of any QCA analysis (see Figure 2) is to select the outcome (dependent variable) to be investigated in order to answer the research question. For the purpose of this study, to investigate the combination of conditions (independent variables) leading to project tender results for a construction company, it was straight-forward to identify the outcome as whether the company won or lost the projects. This is simply represented in the dichotomous table as 1 for the project contract won and 0 for the project tender results lost.

The second step of QCA is to select cases (see Figure 2) in other words sampling. Case selection is critical in QCA just like in other statistical or qualitative methods. The selected cases should be diverse enough to ensure explanatory strength in the QCA minimization, while still having comparability (Jordan *et al.*, 2011).

First of all, in order to maintain the comparability aspect only building projects have been considered. Secondly, only projects from during the last five years were chosen, in order to be able to cross check or elaborate their data through interviews with the project responsibles, still employed in the company. Thirdly, a pareto analysis was conducted in order to eliminate the relatively less turnover generating projects. All the 178 projects' tender price amounts were added together and as a result of the pareto analysis, the 22 building projects creating 80% of the total tender prices (in this case an approximate turnover of 1 Billion Euro combined) were selected. Finally, two cases were excluded from the analysis, because the projects were financed by the general contractor himself. The remaining 20 cases are all currently in the execution phase or warranty period, which made it possible to contact the project responsible in order to verify the data or ask more information in order to judge the case qualitatively.

For the lost cases, in order to keep the balance with win cases, the 22 biggest lost and dropped cases according to the total project prices were chosen within the last five years period. One of the cases was discarded from the analysis as it was later found out that the project has not been realized at all as a consequence of the landlord's bankruptcy. As a result, 21 lost or dropped building project cases were selected with an approximate turnover of 1.5 Billion Euro all together.

41 Cases represent only a very small portion of the entire population if one considers the total number of cases about 10.000. However, the strength of QCA is based on its workability with relatively small amount of data sets compared to the other statistical tools (Jordan *et al.*, 2011). Moreover, by the use of QCA, it is intended to draw patterns resulting in particular outcomes rather than identifying correlations between independent variables and the dependent variables (Ragin, 1987). Recently, Boudet, et al. (2011) performed a QCA study with 26 infrastructure cases to define the factors leading to conflicts in in developing country infrastructure projects. This is a typical example of a QCA study working with a middle range data set.

The third step of the QCA is to select the conditions. For the causal conditions (independent variables) selection Yamasaki and Rihoux (2009) present a list of strategies to follow. These are;

1. The comprehensive approach, where the full array of possible factors from existing theory is considered in an iterative process.
2. The perspective approach, where a mixed set of conditions representing two or three theories from empirical literature are tested.
3. The significance approach, where the conditions are selected on the basis of statistical significance criteria.
4. The second look approach, where the researcher adds one or several conditions that are considered as important although dismissed in a previous analysis.
5. The conjuncture approach, where conditions are selected based on joint interactions among theories, which predict multiple causal combinations for a certain outcome.
6. The inductive approach, where conditions are mostly selected on the basis of case knowledge and not on existing theories.

For the purpose of this study, a mixture of the comprehensive and the inductive approach was applied: conditions were to some degree selected on the basis of existing theories, but mostly on the basis of case knowledge (Yamasaki and Rihoux, 2009). The literature study summarized in Table 1 was used as inspiration in the selection process. However, following the observation that the reviewed literature covering tender practices reflects decision makers' perspective only, the inductive approach favouring case knowledge and i.e. also the bidders' perspective, was preferred.

Going over the interviews with project responsibles, certain elements, such as ‘previous work experience between the general contractor and other parties’ and ‘seniority of the project responsible’ turned out to be decisive throughout the material. Moreover, ‘organizational working history’ as well as certain project attributes like ‘project delivery system’, ‘contract form’, and ‘client type’ were consistently referred by project responsible as conditions having decisive effect in the way the bidding processes are run. Therefore these factors were chosen for the final conditions selection.

Table 3 Final conditions table used in the analysis

Gccl	The previous collaboration between the general contractor and client
Gcarch	The previous collaboration between the general contractor and architect
Gccon	The previous collaboration between the general contractor and consultant
Cltyp	Client type as private or public: Public (1), Private (0)
Delsystem	Construction delivery system: design and build projects (1), others (0)
Saanc	Contractor’s case responsible: >10 years (1); <10 years (0)
Taanc	Contractor’s tender responsible: >10 years (1); <10 years (0)
Prwnls	Outcome as whether the company won or lost the projects: won (1), lost (0)

Table 3 represents only half of the initial conditions. In order to illustrate the calibration process of collected data the steps taken from the initial set of conditions to the final conditions table will be presented below.

As described by Berg-Schlosser and De Meur (2009), there exists no predefined proportion for the number of conditions and cases, thus the number of combinations and cases should be determined in most applications through a trial and error process. To exemplify, for an intermediate-N analysis containing 10 to 40 cases, from 4 to 6–7 conditions can be selected. (Berg-Schlosser and De Meur, 2009) Each condition is tested together with other conditions separately in 2, 3, 4 and 5 conditions sets to detect the less complex meaningful pathways, combination of conditions leading to an outcome.

The initial selection of conditions with their thresholds for this QCA study looked like the following:

- The previous collaboration between the general contractor and client within the 10 years: if there is take 1; if not take 0
- Client type as private or public: for public clients take 1; for private take 0

- Construction delivery system: for design-build projects take 1; for the others take 0
- Project type: for residential projects take 1; for the others take 0.
- Contractor's case responsible: for number of years in the company 10 and more than 10 take 1; for less take 0
- Contractor's tender responsible: for number of years in the company 10 and more than 10 take 1; for less take 0

After building the initial above mentioned table it was noticed that the number of years in the company was not a good indicator as only in 28 cases out of 82 the number of years spent in the company were equal to 10 or more than 10. This contradicts the common sense notion that tender and project responsibles are mostly gray haired, experienced professionals. The data was revisited to find out the actual number of years' experience in the field rather than the numbers years in the company. The corrected table for general contractor's tender professionals has now 47 persons with the same 10 years threshold.

The conditions mentioned below were not distinctive, and therefore were not used in the analysis. The first two derived from the literature presented in Table 1 and the third derived from case knowledge:

- Previous experience of a similar type of project: general contractor has wide range of experience in almost all different types of projects
- Technical capacity of the general contractor: similarly the general contractor has both human resources and equipment to realize the projects given a bid
- Project type as residential, office, hospital, hotel vs.

After making these corrections the truth table based on binary codes was formed. Certain contradictions were observed for cases having the same conditions, but giving different results. The truth table including contradictions is presented in the appendix section as the first truth table. This step is shown in Figure 02 as the "Internal validity test". In order to eliminate the contradictions the methods offered by Rihoux and De Meur (2009) are addressed:

1. Add conditions to the model. This should be done cautiously and in a theoretically justifiable way.
2. Remove one or more condition(s) from the model and replace it/them with another condition(s).
3. Re-examine how the conditions are operationalized and where the threshold values were placed.

4. Reconsider the outcome variable. If the outcome is too broad, it is possible that contradictions will occur.
5. Re-examine the cases in a more qualitative way to determine what differentiates the contradictory cases but has not been considered in the model.
6. Reconsider whether all cases are truly part of the same population.
7. Recode the outcome of all contradictory con figurations as [0]. This treats all contradictory configurations as 'unclear' and accepts fewer explanatory configurations in exchange for more consistency.
8. Use frequency criteria to 'orientate' the out- come. For instance, if a contradictory configuration leads to a [1] outcome in eight cases and a [0] outcome in one case, all of the configurations would be considered as having a [1] outcome. Even so, this probabilistic method is disputable from the case-oriented perspective.

From the above list, suggestions number 1, 2, 5 and 6 were used to eliminate the contradictions in the truth table. The process is an iterative trial and error process and here the steps that have a positive effect will be mentioned only.

First of all, two additional conditions were added to the analysis. They are relevant to the hypothesis claiming that organizational repetitions affect the project outcome. Similar to the previous collaboration between the general contractor and client, previous collaborations have been investigated between architect and consultants of the projects chosen as cases. In cases the architectural works and consultancy services are provided by partnerships and consortiums, the general contractor's case responsible were asked about the qualitative differentiation of the data to identify previous collaboration between parties. The conditions added to the analysis are;

- The previous collaboration between the general contractor and architect within the 10 years: if there is take 1; if not take 0
- The previous collaboration between the general contractor and consultant within the 10 years: if there is take 1; if not take 0

Moreover, as a result of the deeper qualitative investigation of the data two cases were distinguished from the rest of the sample population. One of the contradictory cases was designed as public-private-partnership project that does not follow the ordinary tender processes. The other contradictory case was part of a bigger project executed in phases and thus it could not account for an independent project.

Finally, after trial and error the condition concerning the project type was found redundant as it did not have an effect in building the truth table without contradictions. For the sake of simplicity, the condition 'Project type: for residential projects take 1; for the others take 0', was taken out of the analysis. The final dichotomized table is presented in the appendix in order to give the reader an overview of the data set. Moreover, the final software analysis can be found in the appendix section as well.

It is important to note that the project type was found redundant for this particular data set combination. Other projects of the same general contractor or another contractor might give different results.

In the next results and discussions section, only solutions with full consistency, based on the final contradiction free truth table will be presented.

RESULTS AND DISCUSSIONS

It is important to remark that the software does not recognize cases but rather the configurations specified in the truth table. Thus different from statistical methods, the number of cases in each configuration is not relevant in the course of the minimization process (Rihoux and De Meur, 2009). They are treated as a representative of a possible configuration in the logic space.

As a result of working with 7 conditions describing a solution space=128 solutions (2^n with n being number of conditions), the final function of this study was a complex one.

prwnls = f(gccl, gcarch, gccon, cltyp, delsystem, saanc, taanc)

The frequency cut-off is 1.0000 meaning that all cases were taken into consideration even though the sample size was relatively large, 39 cases, to conduct QCA analysis. The following solution space was found as a result of the standard analysis with a solution consistency of 1.000 since all contradictory cases were eliminated. The solution sets are presented in the appendix.

To simplify the complexity further, the two pathways represented below were used. Each of the solutions has 0.40 coverage with total 80% of coverage together making a satisfactory solution coverage according to the csQCA expectations that are above 0.750 (Jordan *et al.*, 2011).

The two pathways are:

gccl*gcarch*~delsystem

gccl*delsystem*saanc

To extract the solution sets, previous work experience between client and general contractor (gccl) was a necessary but not sufficient factor, as it existed in both solutions together with other factors. One can conclude that it is the most important factor as it is present in both solution sets. Moreover, in the first solution path, the previous work experience between architect and general contractor (gcarch) is decisive in the cases that another project delivery system is chosen different from the design-build system such as the traditional design-bid-build. In the projects where the design-build delivery system is applied, the seniority level of the general contractor's project responsible (saanc) plays a decisive role. As in the design-build delivery system, the design task is expected to be delivered or coordinated by the general contractor alongside the construction execution. Therefore, the experience of the project responsible plays a more important role.

The factors not presented in the solution are actually counter intuitive. The previous work experience between consultant and general contractor is expected to be an important factor as well; however, it is not present in the solution set. This might be because of the limited number of consultants undertaking such big projects included in the data-set. The same consultant groups in the country where this paper's case company operates mostly undertake the consultancy works of projects above a certain size.

Another factor absent in the solution set is client type, describing whether the client is public or private. The public sector as project client makes out only 28% of the client types in the final data set. This unbalanced distribution might be the reason for the factor's absence in the solution set.

Although some factors are not present in the solution set it is still important that all factors are considered together holistically in order to obtain a contradiction free data set leading to the end solution.

As a result, we can combine two pathways using Boolean algebra into one:

gccl*(gcarch*~delsystem+ delsystem*saanc)

The solution is highly reliable as it has coverage of 80% which is above the csQCA acceptable limit (0.75) and has a consistency of 1.0000. Moreover the solution has a necessary (but not sufficient) condition to high coverage: gccl= previous work experience between client and general contractor in the last ten years.

That necessary condition, gccl= previous work experience between client and general contractor in the last ten years should be supported by either gcarch= previous work experience between architect and general contractor in the last ten years for projects that are not planned to be delivered as design and build; or saanc= contractor's case responsible having more than 10 years of experience for design and build projects.

It makes full sense to have previous work experience with the architect in non-design-and-build cases, in other words in traditional delivery systems where tasks are separated, meaning simply that the architect designs and the contractor builds. Whereas, for design-and-build projects the general contractor's project responsible plays an important role as the design works are expected to be performed by the contractor as well together with the construction project execution. The performance of both tasks under the same roof means more responsibility and risk for the general contractor. This special condition is therefore expected to be handled by the more senior project responsibles.

A similar analysis was performed in order to describe combination of conditions leading to loosing contracts. In order to conduct this analysis the same conditions and cases were used but this time the outcome was set into the negation.

~prwnls = f(gccl, gcarch, gccon, cltyp, delsystem, saanc, taanc)

The solution set obtained has also satisfactory solution coverage being 0.79 and therefore still above the acceptable 0.75 and a consistency level of 1.00. However, this time the solution set presented below is rather a complex one making it difficult to minimize or draw meaningful results. It is therefore not included in the conclusion.

Pathway leading to losing a contract for a general contractor;

~gccl*~cltyp*saanc + ~gccon*~cltyp*~saanc + ~gcarch*~delsystem*saanc

(coverage 0.79 and consistency 1.00)

In other words, lack of previous work experience between client and general contractor together with non-governmental clients and senior case responsible or lack of previous work experience between consultant and general contractor together with non-governmental clients and non-senior case responsible or lack of previous work experience between architect and general contractor together with non-design and build contract system and senior case responsible was the long and complex solution set leading to unsuccessful tendering process.

As construction projects are typical examples of project-based work, companies operating in the construction sector have to deal with challenges of project-based organization. Due to the temporality of projects, the companies operating in the sector constantly need to get new projects in order to perform and survive.

Although the projects that contractors bid on depend on the current project portfolio, technical and financial ability to execute the project and the risk acceptance level, it might be beneficial for the bidder to be aware of the combinations of different factors that are more likely to result in particular outcomes. This study advocates that such combinations lead to either project winn or loss.

Finally, factors affecting the project outcomes are various and it is debatable to highlight particular ones, since projects are argued to be unique. However, 39 projects with similar size and scope along a 5 years' time frame give an opportunity to describe a pathway of factors working together to lead to a particular tender result.

CONCLUSIONS

In this study QCA was used to identify the combination of factors creating pathways leading to particular project tender results, or more precisely, to win or to loose project contracts (seen from the bidder's perspective). The QCA method enables one to work with midsize data sets (in this case 39 projects), as well as to deepen the research qualitatively combining the benefits of top-down and bottom-up research strategies.

The tender phase is the critical stage in the project life cycle where many important decisions such as contractors and subcontractors are chosen and uncertainty is the highest. In this paper, factors affecting the qualifiers' decisions covered in literature, have been researched (top-down) with the aim to name the factors might affecting the bid results.

Moreover, the importance of organizational repetition and case studies in a project based work environment in the tender phase has been researched (bottom-up). The factors investigated were; previous work experience between client and general contractor, previous work experience between architect and general contractor, previous work experience between consultant and general contractor, the type of project delivery system, project type, seniority of general contractor's project responsible, and the seniority of the general contractor's project tender responsible.

For the case chosen, two solution sets were obtained and then they were minimized to one solution set. The frequency cut-off was set as 1 meaning that all observed cases represented in the solution set have been considered.

Pathway leading to winning a contract for a general contractor;

gccl*(gcarch*~delsystem+ delsystem*saanc)

(coverage 0.80 and consistency 1.00)

In other words, previous work experience between client and general contractor together with either previous work experience between architect and general contractor for design-bid-build projects or senior project responsible involvement from the contractors side in design-build projects was the path leading to signing the contract. It is important to note that previous work experience between client and general contractor appears to be a necessary condition that requires to be supported by other factors depending on the project attributes.

The implication of the research is that QCA represents a promising research strategy for studying the practices of project organizing and management due to its ability to shed light on a complex phenomenon. The results showing the importance of working with a previously known customer are believed to be important for contractors whose survivals depend heavily on winning new contracts in order to keep performing in a project based work environment. Furthermore, this study adds the contractor's perspective to the picture. More case studies concerning e.g. conflicts or financial results may also be helpful in investigating the consequences of work repetitions in construction practices.

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APPENDIX

The final dichotomized table prior to the analyses

Project Conditions Outcomes

case id	gccl	gcarch	gccon	cltyp	delsystem	saanc	taanc	prwnls
1	1	1	1	0	1	1	1	1
2	1	1	1	0	1	1	0	1
3	1	1	1	0	1	1	0	1
4	1	1	1	0	0	0	1	1
5	1	1	1	1	1	1	1	1
6	1	1	1	0	1	1	0	1
7	0	0	1	1	1	1	0	1
8	1	0	1	0	1	1	1	1
9	1	1	0	0	0	1	0	1
10	1	1	1	0	0	1	1	1
11	1	1	1	1	0	1	1	1
12	1	1	1	1	0	1	1	1
13	1	1	1	0	0	1	0	1
14	1	0	1	0	1	1	0	1
15	1	1	1	1	1	1	1	1
16	0	0	1	0	1	0	0	1
17	0	0	1	1	0	0	0	1
18	1	1	1	1	0	1	1	1
19	1	0	0	1	1	0	0	1
20	1	1	1	1	0	1	1	1
21	1	0	0	0	0	1	1	0
22	0	0	1	0	1	1	0	0
23	1	0	1	0	1	0	1	0
24	0	0	1	0	1	1	0	0
25	1	1	0	0	1	0	1	0
26	0	0	0	0	1	0	0	0
27	1	1	0	0	1	0	0	0
28	0	1	1	0	1	1	1	0
29	0	1	0	0	0	0	1	0
30	1	0	0	0	1	0	1	0
31	0	0	0	0	0	0	0	0
32	1	1	1	0	1	0	0	0
33	0	0	0	0	1	1	0	0
34	1	0	1	0	0	1	0	0
35	1	0	1	1	0	1	1	0
36	0	0	1	0	1	1	1	0
37	1	0	1	0	1	0	0	0
38	0	0	0	0	1	0	1	0
39	1	1	1	1	1	0	0	0

The results of final data set

ANALYSIS5.csv: Descriptive Statistics

Variable	Mean	Std. Dev.	Minimum	Maximum	N Cases	Missing
gccl	0.6923077	0.4615385	0	1	39	0
gcarch	0.5128205	0.4998356	0	1	39	0
gccon	0.7179487	0.4499982	0	1	39	0
cltyp	0.2820513	0.4499982	0	1	39	0
delsystem	0.6410256	0.47969	0	1	39	0
sagtype	0.4358974	0.4958738	0	1	39	0
sa anc	0.6153846	0.4865043	0	1	39	0
ta anc	0.4871795	0.4998356	0	1	39	0
prwnls	0.5128205	0.4998356	0	1	39	0

****

TRUTH TABLE ANALYSIS for winning projects

****

Model: prwnls = f(gccl, gcarch, gccon, cltyp, delsystem, saanc, taanc)

Rows: 32

Algorithm: Quine-McCluskey

True: 1-L

--- PARSIMONIOUS SOLUTION ---

frequency cutoff: 1.000000

consistency cutoff: 1.000000

	raw coverage	unique coverage	consistency
	----------	----------	----------
~gccl*gccon*~saanc	0.100000	0.100000	1.000000
gccl*gcarch*~delsystem	0.400000	0.400000	1.000000
gccl*delsystem*saanc	0.400000	0.400000	1.000000
~gcarch*cltyp*delsystem	0.100000	0.100000	1.000000

solution coverage: 1.000000

solution consistency: 1.000000

--- COMPLEX SOLUTION ---

frequency cutoff: 1.000000

consistency cutoff: 1.000000

	raw coverage	unique coverage	consistency
	----------	----------	----------
gccl*gccon*~cltyp*delsystem*saanc	0.300000	0.250000	1.000000
gccl*gcarch*gccon*saanc*taanc	0.400000	0.300000	1.000000
gccl*gcarch*~cltyp*~delsystem*saanc*~taanc	0.100000	0.100000	1.000000
gccl*gcarch*gccon*~cltyp*~delsystem*taanc	0.100000	0.050000	1.000000
~gccl*~gcarch*gccon*cltyp *~delsystem*~saanc*~taanc	0.050000	0.050000	1.000000
~gccl*~gcarch*gccon*~cltyp *delsystem*~saanc*~taanc	0.050000	0.050000	1.000000
gccl*~gcarch*~gccon*cltyp *delsystem*~saanc*~taanc	0.050000	0.050000	1.000000
~gccl*~gcarch*gccon*cltyp *delsystem*saanc*~taanc	0.050000	0.050000	1.000000

solution coverage: 1.000000

solution consistency: 1.000000

--- INTERMEDIATE SOLUTION ---

frequency cutoff: 1.000000

consistency cutoff: 1.000000

raw unique

	coverage	coverage	consistency
	----------	----------	----------
delsystem*cltyp*~gcarch*gccl	0.050000	0.050000	1.000000
~saanc*delsystem*~cltyp*gccon*~gccl	0.050000	0.050000	1.000000
~saanc*~delsystem*cltyp*gccon*~gccl	0.050000	0.050000	1.000000
saanc*~delsystem*~cltyp*gcarch*gccl	0.150000	0.100000	1.000000
saanc*delsystem*cltyp*gccon*~gcarch	0.050000	0.050000	1.000000
saanc*delsystem*~cltyp*gccon*gccl	0.300000	0.300000	1.000000
taanc*~delsystem*~cltyp*gccon*gcarch*gccl	0.100000	0.050000	1.000000

solution coverage: 0.700000

solutionconsistency:1.000000

****

*TRUTH TABLE ANALYSIS*for losing projects

****

Model: ~prwnls = f(taanc, saanc, delsystem, cltyp, gccon, gcarch, gccl)

--- PARSIMONIOUS SOLUTION ---

frequency cutoff: 1.000000

consistency cutoff: 1.000000

	raw coverage	unique coverage	consistency
	----------	----------	----------
~gccon*~cltyp*~saanc	0.368421	0.368421	1.000000
~gccl*~cltyp*saanc	0.263158	0.263158	1.000000

gccl*gccon*delsystem*~saanc	0.210526	0.210526	1.000000
~gcarch*~delsystem*saanc	0.157895	0.157895	1.000000

solution coverage: 1.000000

solution consistency: 1.000000

--- INTERMEDIATE SOLUTION ---

frequency cutoff: 1.000000

consistency cutoff: 1.000000

Assumptions:

~taanc (absent)

~saanc (absent)

~gccon (absent)

~gcarch (absent)

~gccl (absent)

	raw coverage	unique coverage	consistency
	----------	----------	----------
~saanc*~cltyp*~gccon*~gccl	0.210526	0.105263	1.000000
saanc*~delsystem*~gccon*~gcarch	0.052632	0.052632	1.000000
~taanc*saanc*~delsystem*~gcarch	0.052632	0.052632	1.000000
~saanc*delsystem*~cltyp*~gccon	0.263158	0.105263	1.000000
saanc*delsystem*~cltyp*~gccl	0.263158	0.263158	1.000000
saanc*~delsystem*cltyp*~gcarch	0.052632	0.052632	1.000000
~saanc*delsystem*~cltyp*~gcarch*gccl	0.157895	0.052632	1.000000
~taanc*~saanc*delsystem*gccon*gccl	0.157895	0.105263	1.000000

solution coverage: 1.000000

solution consistency: 1.000000

8.4 Appendix D: Prescriptive Study EPOJ2016 Paper 4 (submitted)

UNTANGLING THE COMPLEXITIES OF SUCCESSFUL TENDERING PRACTICES: EXPLORING FACTORS LEADING TO BIDDING SUCCES FROM A GENERAL CONTRACTOR'S PERSPECTIVE

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ABSTRACT

The purpose of this paper is to explore the complexity of tendering practices from a contractor perspective by investigating the combination of conditions leading to successful bid results. Qualitative Comparative Analysis (QCA) method is used in order to describe combinations of conditions leading to particular results. Empirical material collected through data mining in previously completed building projects in Denmark (quantitative data) is supported by data obtained from project managers of the same general contractor company (qualitative data) in order to holistically describe the combination of conditions resulting in particular tender results. The major finding of the analysis is a solution set explaining the path leading to project contract winning; previous work experience between client and general contractor together with either previous work experience between architect and general contractor for design-bid-build projects or senior project responsible involvement from the contractors side in design-build projects. The analysis illustrates how contracting companies whose existence highly depends on winning new contracts can learn from patterns abstracted from previous project examples. The results will contribute to the development of more predictable project organizations and thereby they might be useful for construction organizations in order to allocate valuable resources in the bidding phase the best way possible.

KEYWORDS: Organizational repetition, project organization, QCA, successful bid, tender practices.

INTRODUCTION

Construction companies are typical examples of project-based organizations (Chinowsky, 2011) working in dynamic environments and short term collaboration patterns. After the projects are terminated project teams are usually dissolved and a core team is kept depending on the size, capacity and future projects in the pipeline (Bower, 2003). Operating in a very volatile environment construction companies are required to adjust their organization according to the market of future projects. Moreover, as projects are meant to be completed these types of companies are highly dependent on their ability to win new contracts in order to keep the businesses running.

It is a well-celebrated fact among academics and practitioners that decisions made in the beginning of a project have the most significant consequences for the success or failure of the project (Winch *et al.*, 1998). One of the main decisions affecting the overall project is how to bring the right companies together. Given this importance, tender practices have been subject to a considerable amount research primary taking a client perspective covering topics as contractor prequalification (Nieto-Morote and Ruz-Vila, 2012) and decision-making in the project tender phase (e.g., Hatush, and Skitmore, 1997; Russell, 1992; Diekmann, 1981).

However, there is a gap in the literature when it comes to investigating the factors leading to contract gain or loss from the contractor's perspective. This paper addresses this gap by studying the complexity of tendering practices from the bidder's, i.e. contractor's perspective.

The purpose of this paper is to deliver a mechanism for enabling successful tenders by general contractors. In this case study taking tendering practices of a Danish general contractor into focus, the patterns leading to successful bids is studied from the contractor's perspective. The research question therefore is; *what are the combinations of factors leading to successful tender results for a bidder (general contractor) in construction projects?*

Untangling complexity requires understanding of the various factors and interaction of these factors in different settings such as organizations, people and culture (Geraldi and Adlbrecht, 2007). QCA has proven to be a promising method for studying the complexity of institutional practices (Thomas *et al*., 2014). QCA is chosen for analysis as the method allows researchers to draw different combinations of conditions leading to create a particular outcome. (Jordan *et al*., 2011). The QCA method appears recently in built environment studies to analyse different fields of areas such as sustainability (Kaminsky *et al*., 2014), disaster recovery taking the Katrina Hurricane as focus of analysis (Jordan *et al*., 2014) and contract elements leading to success in case of Public Private Partnership (PPP) projects (Gross and Garvin, 2011).

The premises for using QCA are in-depth understanding of the research results in terms of identifying interesting outcomes and relevant independent variables. Thus, QCA are always based on a rigorous mapping of the current state of the art combining literature reviews and empirical investigations (Ragin, 1987; Rihoux and De Meur, 2009). Hence, the paper opens with a literature review of tendering practices followed by a detailed introduction to the applied methodology, QCA. Subsequently, the analysis of the selected cases and conditions such as previous work experience between different parties like client, architect, contractor and general contractor as well as project attributes such as project type, delivery system, seniority levels of the contractor tender responsible and the project manager are investigated. Finally, a solution set leading to the successful bid for contractors is presented in the results, discussion and conclusion section.

LITERATURE REVIEW: TENDERING PRACTICES

Becker (2004) addresses the circumstance that uncertainty in decision-making is problematic, because the likelihood of each outcome from a set of possible specific outcomes is initially unknown, as it is the case in the early project phases (see Figure 1). In handling the uncertainty it is important to understand the tender phase and contractor prequalification. As seen in Figure 1 inspired by Winch *et al.* (1998) uncertainty is dominating the early stages of projects and certainty gradually increases by time and as completion approaches. Therefore, the tendering phase can be regarded as a critical stage in the realization of projects.

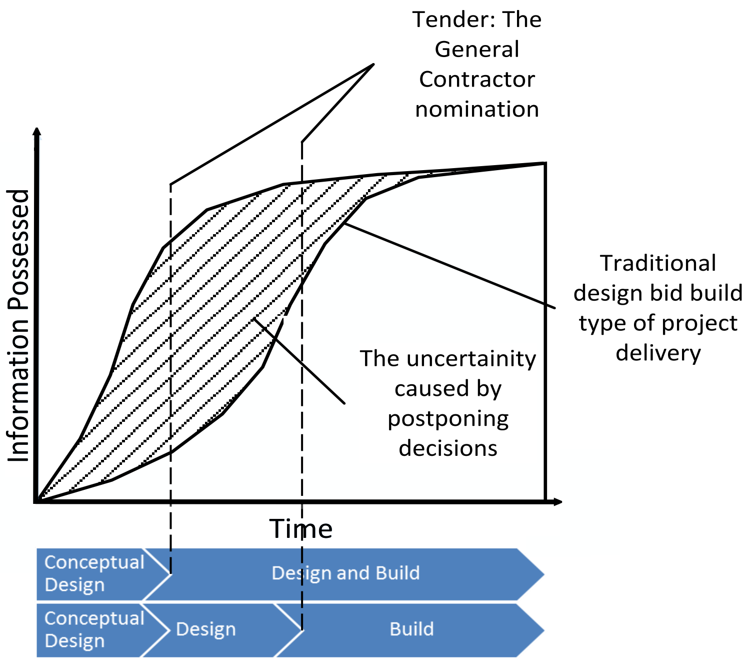

Figure 1 The uncertainty related to the project lifecycle in different project delivery systems (Inspired by Winch *et al*., 1998)

Moreover, project parties, including owners, architects, and contractors, all with their separate backgrounds and separate agendas, have to come together in order to carry out their normal project practices. This is performed through traditional contractual arrangements (Cornick and Mather 1999). Thus, there are obvious uncertainties in the early project phases, especially during tender phases, since different organizations and different organizational entities come together to share and create information for the first time. As a result, each new project starts with the same uncertainty curve from bottom again every time.

To overcome this cycle, partnering of two or more parties across projects is mentioned in Egan's (1998) report as a way to resolve disputes as well as to improve the performance and sharing the gains. Therefore, Winch *et al*. and Egan's arguments support "previous work experience between project participants" as an important condition to achieve successful projects. Thus, the previous work experience between the general contractor and the client is chosen as an initial condition for this study. As it will be elaborated in the analysis section based on case knowledge the previous work experience between the general contractor and other parties such as architects and consultants is also added as a condition leading to winning or losing the tenders in this study. Tenders are complex and they involve many engineers and managers who have to work as a team, share information and deal with the interface problems that arise between the various responsible subsystem-engineers (Bernold and AbouRizk, 2010). The decision of who should be awarded the contract is made according to the prequalification criteria, the contractor's attributes and the prequalifier's judgement. Despite the effort made by researchers, contractor prequalification remains largely an art where subjective judgment, based on the individual's experience, becomes an essential part of the practice (Nguyen, 1985).

Subjectivity is the most difficult attribute encountered by researchers and practitioners due to a diversity of prequalification criteria (see Table 1) and the variability of the same contractor's ratings, which is differently assessed by different prequalifiers according to their own perceptions. One tool that has been developed in order to track and control the uncertainties better is the so-called multi-attribute utility functions. These are used in an attempt to list the criteria for the decision-maker's preference (Diekmann, 1981; Hatush and Skitmore, 1998). Following this more and more advanced tools for contractor selection have been developed (e.g. Cheng and Li 2004). However, they all reflect the decision-maker's i.e. the client's perspective and not the bidder's.

Table 1 Decisive condition in contractor selection (Nieto-Morote and Ruz-Vila, 2012)

Main Criteria and Sub-criteria for Contractor Prequalification

Criteria	Sub-criteria
Technical capacity	1. Qualification of staff 2. Experience of staff 3. Innovate method 4. Labor and equipment
Experience	1. Type of past project completed 2. Size of past project completed 3. Number of projects completed 4. Experience in local area
Management ability	1. Organisational culture 2. Management knowledge 3. Quality policy
Past Performance	1. Quality level of projects performance 2. Projects completed on time 3. Projects completed on budget
Financial stability	1. Financial soundness 2. Credit ranting 3. Liquidity
Occupational health and safety	1. Management safety accountability 2. Safety performance

In a recent case study it is been emphasized that collaboration and trust is primarily need in projects where uncertainty is high. Therefore, many relational requirements are essential to trust-based collaboration (Dewulf and Kadefors, 2012). Taking the uncertainty in the projects or, more precisely, in the tender phases into consideration, the importance of people involved in the process becomes evident. Müller and Turner have been studying the importance of project leader and his/her leadership style on project success. (Müller and Turner 2007). They defend that the impact of the project manager, and his/her leadership abilities, on project success has not been researched. The authors published in two separate papers stating the leadership style and competence of the project manager is a success factor on projects and different styles are appropriate on different types of projects (Müller and Turner 2007). The project manager's role is even more remarkable in the tender phase as the project manager reflects all his previous experience and network of companies in his background in order to shape the final bid.

Moreover, stability provides safety to achieve the targeted results and increase predictability (Langlois, 1992; Tyre and Orlikowski, 1996). In the construction projects each party has its own mundane practices and agendas, which are not necessarily known to the others. In the process of construction the different parties develop certain working habits and practices that create a bound between one another (Marshall, 2014). Moreover, as mentioned by Nelson (1994), whenever there is a change in the participants, understandings or contracts, a mode of executing a particular task needs to be identified and adjusted. This always has an additional cost aspect.

In situations of uncertainty, routines and already known solutions have an important effect on the way decision makers, in this case qualifiers, make their choices (Gersick and Hackman, 1990; Langlois and Everett, 1994; Becker, 2004). In a recent case study on hospital construction projects in Norway and USA, the importance of informal mechanisms to stimulate collaboration between project parties in decision-making processes was emphasized (Bygballe *et al*., 2015). This suggests that previous contact and collaboration between the general contractor, client, architect and consultant are important factors affecting the result of the tender practice.

Summarizing previous research, it is relevant to explore the effect of repetitions and previous experiences in tendering practices. Recalling the research question; *what are the combinations of factors leading to successful tender results for the bidder?*, the literature covered identifies the following factors: previous work experience between the parties such as client and general contractor, the contractor tender responsible's and project manager's seniority. Factors observed across projects causing contract gains or losses will be investigated holistically by means of the Qualitative Comparative Analysis (QCA) in the following section.

RESEARCH DESIGN AND METHOD

In order to explore the tendering practices this study applies Qualitative Comparative Analysis (QCA). QCA is a relatively new approach, first propounded by sociologist Charles Ragin in 1987, but its principles have since been applied extensively, primarily in the fields of sociology (Rihoux, 2006) and political science (Ragin, 1987) but also in management, economics and engineering (e.g. Jordan *et al.*, 2011) in the study of complex phenomena. Recently it has been introduced in the study of various construction practices like Public Private Partnerships (Gross 2010), Building Information Modelling (Homayouni *et al*., 2011) and school sanitation project in Bangladesh (Chatterley *et al*., 2014).

The different approaches make the study of project organizing and management a matter of choosing the proper method using either (1) large amount of quantitative data and well defined hypothesis testing or (2) qualitative data and more explorative research questions. In contrast to working with quantitative data, focusing on numbers and statistical correlations without interfering with the individual project participants, a growing amount of research has been focusing on understanding project organizing and management as situated and contextual practices. This was initially driven by a Scandinavian school of research into project management and temporary organizing (Morris, 2013) focusing on the narratives of the individuals. As the type of the data is rarely large enough to make statistical analysis in hardly comparable construction projects, Qualitative Comparative Analysis (QCA) method appears to be the middle ground solution using the positive sides of both the quantitative and the qualitative perspective.

QCA allows researchers to draw combinations of different factors of practices (conditions) leading to a dependent outcome. As illustrated in Figure 2 the research process is highly iterative. During this iterative process literature is revisited and additional empirical material is gathered in order to solve occurring contradictions.

Thereby QCA lays in-between quantitative and qualitative research approaches for testing hypotheses in addition to allowing the researcher to work with small cases compared to statistical methods. The method, though, is closer to qualitative methods due to its sensitivity to individual cases (Rihoux and Ragin, 2009). This is also mirrored in the highly iterative processes, which to some degree is similar to the iterative interpretations within qualitative studies.

To make best use of the data set available to describe a solution set with factors leading to particular project tendering outcomes, a crisp set Qualitative Comparative Analysis (QCA) method was chosen for this study. Contrary to the fuzzy sets that make use of partial memberships such as 0.5, the crisp set is based on full membership and full non-membership, in other words absences as 0 and presences as 1 binary notation (Thomas *et al*., 2014).

However, csQCA has certain advantages and limitations that one should be aware of. These are identified by Jordan *et al*. (2011) in the following table 2.

Table 2 csQCA Advantages and limitations (Jordan *et al*., 2011)

Advantages	Limitations
• Ability to work with smaller set of data compared to quantitative approaches • Ability to work with large number of cases compared to qualitative approaches • Easy to understand for the reader • Transparent • Replicable	• Dichotomization of data: Transformation of data into a binary notation • Difficulty in selecting conditions (independent variables) and cases • Lack of temporal dimension

In the following analysis section, the process given in Figure 2 will be exemplified step-by-step in a detailed way for the reader to follow the QCA research method and for future researchers to duplicate the study with different cases with different data sets.

However, as there has previously been a difficulty in understanding some papers using the QCA method, the research process illustrated in Figure 2 is explained in detail, and frequencies and descriptive results are presented in the appendix. In doing so it is intended for the reader to follow the preliminary results and changes in the data set, as before and after, on the way to the final solution.

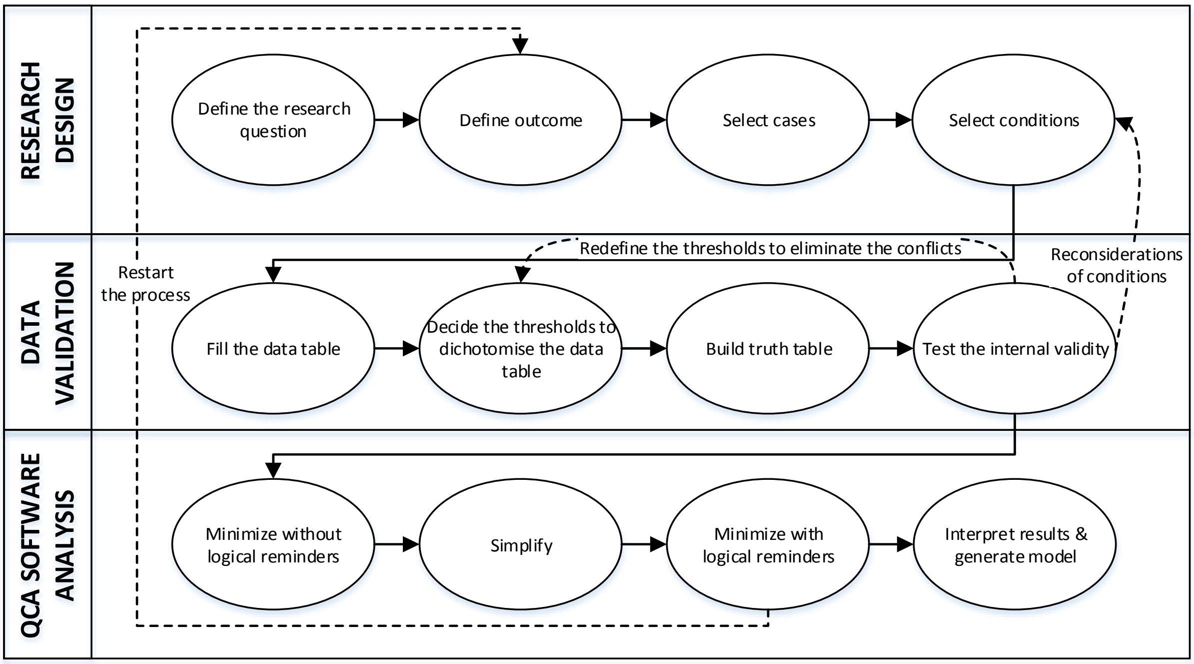

Figure 2 QCA Research Process

The results presented in this paper derive from a combination of quantitative and qualitative data . On one hand a quantitative set of data was obtained through a data mining work conducted in the database of the case company. On the other hand qualitative data through semi-structured interviews and phone calls with responsible personal were gathered. The case company is one of the leading general contractors operating in Denmark with a centurey old history behind. The annual turnover is about 1Billion $ and the number of employees is about 5.000. The company's project data base consists of all completed, ongoing projects and projects that was given an unsuccessful bid. Therefore, many researched conditions taken into consideration in the analysis such as project type, contract type, parties involved such as clients, architects, consultants etc., , project responsible, tender responsible and many other factors that helped selecting the projects to be investigated cases such as contract price, project size, locationwere extracted from the data base. This data was then combined with a collection of qualitative data. Six of the cases from the data base were elaborated through in-depth semi-structured interviews with their given project responsibles which were involved in the projects from the very initial bidding phase to the commisioning. The interviewees job titles differ a lot from tender responsible to the senior project manager depending on their level of experience, department and size of the project. The case knowledge was still fresh in the interviewees' memories because only building projects completed within the last 5 years time frame were chosen for the sake of comparibility. The interviews took place in the headquarter of the company and they lasted about an hour each. They were recorded and then transcribed. The transcription results of the interviews following the same structure were helpful both to compare the projects and to gain the case knowledge. A similar number of other cases from the quantitative data set were cross checked and elaborated through brief phonecalls and conversations with project responsibles. All the project names together with names of the responsibles were fully anonymized. A description of a concrete case and it's conditions selection process will be presented in the next section.

ANALYSIS

Phase 1 Research Design

The steps presented in Figure 2 are followed in order to answer the research question mentioned in the introduction: "What are the combinations of factors leading to successful tender results for a bidder (general contractor) in construction projects?

Step 1: Outcome Selection

The initial step of any QCA research method (see Figure 2) is to select the outcome (dependent variable) to be investigated in order to answer the research question. For the purpose of this study, to investigate the combination of conditions (independent variables) leading to project tender results for a construction company, it was straight-forward to identify the outcome as whether the company won or lost the projects. This is simply represented in the dichotomous table as 1 for the bids won and 0 for the bids lost.

Step 2: Case Selection

The second step of QCA is to select cases (see Figure 2). Case selection is critical in QCA just like in other statistical or qualitative methods. The selected cases should be diverse enough to ensure explanatory strength in the QCA minimization, while still having comparability (Jordan *et al.*, 2011).

First of all, in order to maintain the comparability aspect only building projects realized in Denmark have been considered. Secondly, only projects from during the last five years were chosen, in order to be able to cross check or elaborate their data through interviews with the project responsible, still employed in the company. Thirdly, a pareto analysis was conducted in order to eliminate the relatively less turnover generating projects. All the 178 projects' tender price amounts were summed up. As a result of the pareto analysis, the 22 building projects creating 80% of the total tender prices (in this case an approximate turnover of 1 Billion Euro combined) were selected. The reasoning behind the pareto analysis is to work only with projects that would make sense to compare. A very large queue of projects of all sizes, distributed in very different locations, takes away the comparability aspect because different local dynamics are involved in smaller size projects. However, according to the data base and interview results similar competitive bidding process was run in all large scale projects. Finally, two cases were excluded from the analysis, because the projects were financed by the general contractor itself. The remaining 20 cases are all currently in the execution phase or warranty period, which made it possible to contact the project responsible in order to verify the data or ask more information in order to judge the case qualitatively.

For the lost cases, in order to have the balance with win cases, the 22 biggest lost and dropped cases according to the total project prices were chosen within the last five years period. One of the cases was discarded from the analysis as it was later found out that the project had not been realized at all as a consequence of the landlord’s bankruptcy. As a result, 21 lost or dropped building project cases were selected with an approximate turnover of 1.5 Billion Euro all together.

41 Cases represent only a very small portion of the entire population if one considers the total number of cases in the data base being about 10.000. However, the strength of QCA is based on its workability with relatively small amount of data sets compared to the statistical tools (Jordan *et al.*, 2011). Moreover, by the use of QCA, it is intended to draw patterns resulting in particular outcomes taking each case equally important in weight rather than identifying correlations between independent variables and the dependent variables (Ragin, 1987). Recently, Boudet, *et al.* (2011) performed a QCA study with 26 infrastructure cases to define the factors leading to conflicts in in developing country infrastructure projects. This is a typical example of a QCA study working with a middle range data set.

Step 3: Conditions Selection

The third step of the QCA is to select the conditions. For the causal conditions (independent variables) selection a mixture of the comprehensive and the inductive approach was applied: conditions were to some degree selected on the basis of existing theories, but mostly on the basis of case knowledge (Yamasaki and Rihoux, 2009). The literature study summarized in Table 1 was used as inspiration in the selection process. However, it has been observed that the reviewed literature covering tender practices reflects decision makers’ perspective only. Therefore an inductive approach favouring case knowledge and i.e. also the bidders’ perspective was preferred. The final conditions used in the analysis together with description and root of the condition are presented in the below table 3.

Table 3 Final conditions table used in the analysis

Condition	Description and the threshold	Source
Client & GC	The previous collaboration between the general contractor and client within the last 10 years: if there exists take (1); if not take (0)	Literature (Becker, Bygballe, Egan, Dewulf and Kadefors, Gersick and Hackman, Langlois, Marshall, Nelson, Tyre and Orlikowski & Case Knowledge
Architect & GC	The previous collaboration between the general contractor and architect within the last 10 years: if there exists take (1); if not take (0)	Case Knowledge

Consultant & GC	The previous collaboration between the general contractor and consultant within the last 10 years: if there exists take (1); if not take (0)	Case Knowledge
Client Type	Client type as private or public: for public clients take (1); for private take (0)	Case Knowledge
Project Delivery System	Construction project delivery system: design & build projects (1), others (0)	Case Knowledge
Project Type	Project type if residential (1), others (office, hospital, hotel vs) (0)	Case Knowledge
Tender Respon-sible Seniority	Contractor's tender responsible seniority in the sector: for years 15 and more than 15 take (1); for less take (0)	Literature (Kog and Loh, Muller and Turner) & Case Knowledge
Project Manager Seniority	Contractor's project manager seniority in the sector: for years 15 and more than 15 take (1); for less take (0)	Literature (Kog and Loh, Muller and Turner) & Case Knowledge

Going over the interviews with project responsibles, in addition to the literature based client and general contractor work history some other elements, such as 'previous work experience between the general contractor and other parties' and 'seniority of the project responsible' turned out to be decisive throughout the material. Therefore previous work collaboration between general contractor and other parties like client, architect and consultant within the last 10 years is chosen as condition with the assumption that people and organizations that have worked together beforehand know each other's manners and have built a relation of trust. The threshold of 10 years is chosen with the assumption that after 10 years people tend to change places and organizations evolve making the work collaboration similar to a newly established one.

Furthermore, the threshold 15 years of experience for the construction manager and the tender responsible is chosen after the study made by Kog and Loh (2012). According to Kog and Loh (2012) the judgement with regard to of respondents with less than 15 years of experience differs from that of the more experienced respondents and hence may not be good enough and views of respondents with less than 15 years' experience in construction are likely to be biased and misleading.

Moreover, 'organizational working history' as well as certain project attributes like 'project delivery system', 'contract form', and 'client type' were consistently referred by project responsible as conditions having decisive effect in the way the bidding processes are run. Therefore, these factors were chosen for the final conditions selection.

Phase 2 Data Validation

Table 3 represents only half of the initial conditions. In order to illustrate the calibration process of collected data the steps taken from the initial set of conditions to the final conditions presented in table 3 is given below.

As described by Berg-Schlosser and De Meur (2009), there exists no predefined proportion for the number of conditions and cases, thus the number of combinations and cases should be determined in most applications through a trial and error process. To exemplify, for an intermediate-N analysis containing 10 to 40 cases, from 4 to 6–7 conditions can be selected. (Berg-Schlosser and De Meur, 2009)

The initial selection of conditions with their thresholds for this QCA study looked like the following:

- The previous collaboration between the general contractor and client within the 10 years: if there is take 1; if not take 0
- Client type as private or public: for public clients take 1; for private take 0
- Construction delivery system: for design-build projects take 1; for the others take 0
- Project type: for residential projects take 1; for the others take 0.
- Contractor's case responsible: for number of years in the company 15 and more than 15 take 1; for less take 0
- Contractor's tender responsible: for number of years in the company 15 and more than 15 take 1; for less take 0

After building the initial above mentioned table it was noticed that the number of years in the company was not a good indicator as only in 28 cases out of 82 the number of years spent in the company were equal to 15 or more than 15. This contradicts the common sense notion that tender and project responsible are mostly grey haired, experienced professionals. The data was revisited to find out the actual number of years' experience in the field rather than the numbers years in the company. The corrected table for general contractor's tender professionals has now 47 persons with the same 15 years threshold.

The conditions mentioned below were not distinctive, and therefore were not used in the analysis. The first two derived from the literature presented in Table 1 and the third derived from case knowledge:

- Previous experience of a similar type of project: general contractor has wide range of experience in almost all different types of projects (originated from literature)
- Technical capacity of the general contractor: similarly the general contractor has both human resources and equipment to realize all the projects given a bid (originated from literature)
- Project type as residential, office, hospital, hotel vs. (originated from case knowledge)

After making these corrections the truth table based on binary codes was formed according to the thresholds given in table 3. Certain contradictions were observed for cases having the same conditions, but giving different results. This step is shown in Figure 02 as the "Internal validity test". In order to eliminate the contradictions in the truth table the methods given below offered by Rihoux and De Meur (2009) are addressed.

9. Add conditions to the model. This should be done cautiously and in a theoretically justifiable way.
10. Remove one or more condition(s) from the model and replace it/them with another condition(s).
11. Re-examine the cases in a more qualitative way to determine what differentiates the contradictory cases but has not been considered in the model.
12. Reconsider whether all cases are truly part of the same population.

The process is an iterative trial and error process and here the steps that have a positive effect will be mentioned only. First of all, two additional conditions were added to the analysis. They are relevant to the hypothesis claiming that organizational repetitions affect the project outcome. Similar to the previous collaboration between the general contractor and client, previous collaborations have been investigated between architect and consultants of the projects chosen as cases. In cases where the architectural works and consultancy services are provided by partnerships and consortiums, the general contractor's case responsible was asked about the qualitative differentiation of the data to identify previous collaboration between parties. The conditions added to the analysis are;

- The previous collaboration between the general contractor and architect within the 10 years: if there is take 1; if not take 0
- The previous collaboration between the general contractor and consultant within the 10 years: if there is take 1; if not take 0

Moreover, as a result of the deeper qualitative investigation of the data two cases were distinguished from the rest of the sample population. One of the contradictory cases was designed as public-private-partnership project that does not follow the ordinary tender processes. The other contradictory case was part of a bigger project executed in phases and thus it could not account for an independent project.

Finally, after trial and error the condition concerning the project type was found redundant as it did not have an effect in building the truth table without contradictions. For the sake of simplicity, the condition 'Project type: for residential projects take 1; for the others take 0', was taken out of the analysis. The final dichotomized table is presented in the appendix in order to give the reader an overview of the data set.

Phase 3 QCA Software analysis

For the software analysis, the instructions presented in the QCA users guide manual by Ragin (2008) were followed. Software runs very rapidly making it the simplest and fastest phase of the analysis once consistency is reached in the previous two phases. . As mentioned in the previous phases all the contradictions were eliminated. All cases observed are taken into consideration giving the frequency as 1.

In the next results and discussions section, only solutions with full consistency, based on the final contradiction free truth table given in the appendix will be presented.

RESULTS AND DISCUSSIONS

As a result of the QCA software analysis two different mechanisms in the form of two solution sets presented below are obtained. These are previous work experience between architect and general contractor in the last ten years for projects that are not planned to be delivered as design and build; or contractor's PM having more than 15 years of experience in the cases of design and build projects. Each of the solutions has 0.40 coverage with total 80% of coverage together making a satisfactory solution coverage according to the csQCA expectations that are above 0.750 (Jordan *et al.*, 2011, Thomas *et al.*, 2014). To reduce the complexity further, the two pathways were simplified into one single solution set in figure 3 given below.

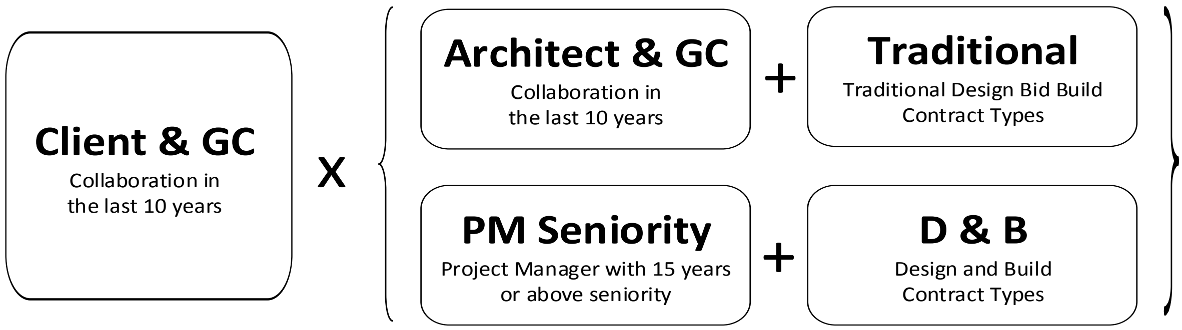

Figure 3 Simplified pathways leading to successful bidding using Boolean algebra

As seen in the Figure 3 the necessary condition, previous work experience between client and general contractor in the last ten years; should be supported by other factors in order to have successful bidding results. The solution set presented in Figure 3 is highly reliable as it has coverage of 80% which is above the QCA acceptable limit (0.75) and has a consistency of 1.0000. Moreover, the solution has a necessary (but not sufficient) condition: previous work experience between client and general contractor in the last ten years.

The frequency cut-off is 1.0000 meaning that all cases were taken into consideration even though the sample size was relatively large, 39 cases, to conduct QCA analysis. The following solution space was found as a result of the standard analysis with a solution consistency of 1.000 since all contradictory cases were eliminated.

In order to interpret the solution sets obtained and to get in-depth understanding of the research results, case knowledge and experiences in the field are revisited. To extract the solution sets seen in Figure 3, previous work experience between client and general contractor was a necessary but not sufficient factor, as it existed in both solutions together with other factors. One can conclude that it is the most important factor as it is present in both solution sets. Moreover, in the first solution path, the previous work experience between architect and general contractor is decisive in the cases that another project delivery system is chosen different from the design-build system such as the traditional design-bid-build. In the projects where the design-build delivery system is applied, the seniority level of the general contractor's PM assigned for the project plays a decisive role. As in the design-build delivery system, the design task is expected to be delivered or coordinated by the general contractor alongside the construction execution. Therefore, the experience of the PM plays a more important role.

The factors not presented in the solution are actually counter intuitive. The previous work experience between consultant and general contractor is expected to be an important factor as well; however, it is not present in the solution set. This might be because of the limited number of consultants undertaking such big projects included in the data-set. The same consultant groups in the country where this paper's case company operates mostly undertake the consultancy works of projects above a certain size.

Another factor absent in the solution set is client type, describing whether the client is public or private. Considering the size of the projects and recalling the project responsible interview responds it is concluded that similar competitive bidding process are run for both private and public client owned projects. Yet again according to the interviewees, due to the size of the projects client organizations are similar to each other in private and public owned projects in terms of hierarchy and structural complexity. Although some factors are not present in the solution set it is still important to note that all factors are considered together holistically in order to obtain a contradiction free data set leading to the end solution.

It makes full sense to have previous work experience with the architect in non-design-and-build cases, in other words in traditional delivery systems where tasks are separated, meaning simply that the architect designs and the contractor builds. Whereas, for design-and-build projects the general contractor's project responsible plays an important role as the design works are expected to be performed by the contractor as well together with the construction project execution. The performances of both design and build tasks under the same roof means more responsibility and risk for the general contractor. This special condition is therefore expected to be handled by the more senior project responsible.

Furthermore, in the design and build cases the decisions have to be taken at earlier project phases whereas in the traditional type of design bid build contracts many important decisions such as contractor chose can be postponed further in time. As seen in figure 1 in theory section postponing decisions will allow some more time for important decisions to be taken but it will add to the uncertainty. According to the solution paths the challenge to overcome uncertainty in the design and build type of project delivery system has to be handled by experienced project managers.

The results don't necessarily impose one project type against others as there might be project requirement forcing some decision to be taken in later stages in order to maintain the flexibility however; mechanisms leading to successful tendering should be known when project managers are allocated to the different type of projects.

Although the projects that contractors bid on depend on the current project portfolio, technical and financial ability to execute the project and the risk acceptance level, it might be beneficial for the bidder to be aware of the combinations of different factors that are more likely to result in particular outcomes. Finally, factors affecting the project outcomes are various and it is debatable to highlight particular ones, since projects are arguably unique. However, 39 projects with similar size and scope along a 5 years' time frame give an opportunity to describe a pathway of factors working together to lead to a particular tender result.

CONCLUSIONS

The paper set out to deliver a mechanism for enabling successful tenders by general contractors. The following combinations of factors that form pathways leading to particular project tender results, or more precisely, to win or to loose bids (seen from the bidder's perspective) are found. Translating the computerized language to verbal, previous work experience between client and general contractor together with either previous work experience between architect and general contractor for design-bid-build projects or senior project responsible involvement from the contractor's side in design-build projects are the paths leading to signing the contract for the general contractor.

As construction projects are typical examples of complex project-based work, companies operating in the construction sector have to deal with challenges of project-based organization. Due to the temporality of projects, the companies operating in the sector constantly need to get new projects in order to perform and survive.

The tender phase is the critical stage in the project life cycle where many important decisions such as contractors and subcontractors are chosen and uncertainty is the highest. Furthermore, this study adds the contractor's perspective to the picture instead of only the client's. Therefore, the factors affecting the qualifiers' decisions covered in literature, together with factors coming from case knowledge have been researched with the aim to identify the combination of conditions that affect the bid results.

The factors investigated were; previous work experience between client and general contractor, previous work experience between architect and general contractor, previous work experience between consultant and general contractor, the type of project delivery system, project type, seniority of general contractor's project manager, and the seniority of the general contractor's project tender responsible.

The QCA method was used for the given purpose as the method enables one to work with midsize data sets (in this case 39 projects), as well as to deepen the research qualitatively combining the benefits of top-down and bottom-up research strategies.

As a result of the QCA software analysis, two solution sets having both 0.4 solution coverage presented in Figure 3 given in the discussion of results were obtained and then they were minimized to one solution set having 0.8 solution coverage. The frequency cut-off was set as 1 meaning that all observed cases represented in the solution set have been considered.

In this particular case, working with a previously known customer appears to be important for contractors whose survival depends heavily on winning new contracts in order to keep performing in a project based work environment. It is important to note that previous work experience between client and general contractor appears to be a necessary condition that requires to be supported by other factors depending on the project attributes.

Finally, it is important to note that the obtained results are very much context dependent. Similar analysis done with a similar size of companies operating in different geographies and contexts may give different results. More case studies following the same steps in research design and data validation phases could be beneficial in order to draw more generalized conclusions.

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APPENDIX

The final dichotomized table prior to the analyses

Project Conditions Outcomes

case id	gccl	gcarch	gccon	cltyp	delsystem	pmsnrty	trsnrty	prwnls
1	1	1	1	0	1	1	1	1
2	1	1	1	0	1	1	0	1
3	1	1	1	0	1	1	0	1
4	1	1	1	0	0	0	1	1
5	1	1	1	1	1	1	1	1
6	1	1	1	0	1	1	0	1
7	0	0	1	1	1	1	0	1
8	1	0	1	0	1	1	1	1
9	1	1	0	0	0	1	0	1
10	1	1	1	0	0	1	1	1
11	1	1	1	1	0	1	1	1
12	1	1	1	1	0	1	1	1
13	1	1	1	0	0	1	0	1
14	1	0	1	0	1	1	0	1
15	1	1	1	1	1	1	1	1
16	0	0	1	0	1	0	0	1
17	0	0	1	1	0	0	0	1
18	1	1	1	1	0	1	1	1
19	1	0	0	1	1	0	0	1
20	1	1	1	1	0	1	1	1
21	1	0	0	0	0	1	1	0
22	0	0	1	0	1	1	0	0
23	1	0	1	0	1	0	1	0
24	0	0	1	0	1	1	0	0
25	1	1	0	0	1	0	1	0
26	0	0	0	0	1	0	0	0
27	1	1	0	0	1	0	0	0
28	0	1	1	0	1	1	1	0
29	0	1	0	0	0	0	1	0
30	1	0	0	0	1	0	1	0
31	0	0	0	0	0	0	0	0
32	1	1	1	0	1	0	0	0
33	0	0	0	0	1	1	0	0
34	1	0	1	0	0	1	0	0
35	1	0	1	1	0	1	1	0
36	0	0	1	0	1	1	1	0
37	1	0	1	0	1	0	0	0
38	0	0	0	0	1	0	1	0
39	1	1	1	1	1	0	0	0

8.5 Appendix E: Prescriptive Study ARCOM2015 Paper 5 (accepted-unpublished)

CAN ORGANISATIONAL MODULARITY HELP TO AVOID DISTPUTES IN CONSTRUCTION PROJECTS? - STUDYING THE EFFECTS OF ORGANIZATIONAL REPETITIONS USING QCA

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Construction industry hosts typical examples of project-based forms of working. Construction projects are usually defined with clear project goals such as budget, time, and quality requirements.

The project organization is normally formed temporarily in order to realize the project. After the project is commissioned to the owner, the construction project organization is typically abolished. The purpose of this study is to identify the organizational modularity of a general contractor operating in a highly complex sector in order to avoid disputes. Empirical material collected through data mining in previously completed project records are combined with the interview results with project managers and lawyers of a general contractor company. The Qualitative Comparative Analysis (QCA) method is applied to describe factors such as organizational repetitions together with project type and project delivery system, leading to disputes in the project execution. The QCA method is chosen deliberately for the analysis, as the data set is too large for qualitative study and too small to conduct a statistical analysis. Moreover, combinations of factors causing a dispute enable the reader to have an overview. The results will contribute to the development of more predictable project organizations and thereby it might be useful for both client and construction organizations in order to avoid disputes in construction projects.

Keywords: disputes, organizational modularity, project management, project success factors, QCA.

INTRODUCTION

Projects are unpredictable and non-linear and cannot be followed through specific linear phases (Koskela and Howell 2002). There exists a large body of literature about project success criteria (Hatush and Skitmore 1997; Müller and Turner 2007b; Belassi and Tukel 1996; King 1996), with emphasize on quality, time, budget, leadership.

Contractors operating in project-based industries work in many projects simultaneously all fighting against time with limited resources to remain within the agreed budget and provide the requested quality. When a conflict occurs, it causes loss of valuable working hours, delay, frustration in the project team, unsatisfied clients and finally financial losses. Moreover, future collaboration opportunities of parties and the reputation of the involved contractor are severally damaged (Li et al. 2013) Therefore, it is important to resolve conflicts in early stages before they turn out to be disputes.

Pulket and Arditi propose a method to predict the possible result of construction litigation using ant colony optimization. Their idea is straightforward such that if parties will know the outcome of the litigation they will eventually avoid the long time-consuming lawsuit (Pulket and Arditi, 2009).

Traditional statistical analysis would typically be interested in correlation between independent variables (factors) and dependent variable (the outcome). With a similar purpose to predict the disputes in construction projects, Diekmann and Girard undertake a statistical analysis with 159 divers construction projects. The projects used in the analysis include civil works such as highways and industrial and commercial purposes with dollar size of the contract varying from less than 1M to more than 100M. Although, they test many variables related to process and project environment, they conclude “the project variables do not affect the project disputes performance to a great extend” but people do (Diekmann, and Girard, 1995).

However, in construction projects different factors come together in certain combinations that are significant for the particular results. Qualitative comparative analysis (QCA) as a tool to describe the configurations of conditions causing particular project results makes it possible to embrace such holistic approach. The factors that could be observed across the projects leading to disputes have been investigated in this study.

The factors such as previous work experience between different parties like client, architect, contractor and general contractor as well as project attributes such as project type and system delivery chosen, and finally seniority levels of the contractor tender responsible and the project manager will be investigated in this study. QCA will be used as a tool to analyse the factors to describe a meaningful configuration of conditions leading to dispute in the construction projects.

The research question therefore is “what are the combinations of conditions leading to disputes in the execution of construction projects?”

RESEARCH DESIGN AND METHOD

A literature survey was conducted to get an overview of project success criteria and factors affecting project results. The factors (conditions) forming meaningful configurations having causal consequences on particular project outcomes were investigated by use of qualitative comparative analysis (QCA). These factors and cases were discussed through interviews with construction managers and lawyers. The QCA software introduced by Charles Ragin (Ragin 1987) was the chosen tool for the research, as it does not focus on statistical relations between independent variables. Rather, it targets to identify different combinations of parameters leading to the same results (Rihoux and Lobe 2011; Ragin 2008). Moreover, as described in Table 1 the method serves the need to process the data both qualitatively and quantitatively providing the ability to work with limited amount of cases.

Table 1: Advantages and Limitations of QCA (Jordan et. al 2011):

Advantages	Limitations

• Ability to work with smaller set of data compared to quantitative approaches • Ability to work with large number of cases compared to qualitative approaches • Easy to understand for the reader • Transparent • Replicable	• Dichotomization of data: Transformation of data into a binary notation • Difficulty in selecting conditions (independent variables) and cases • Lack of temporal dimension • Non-observed cases (combinations)

As there has been difficulties in understanding some papers using the QCA method, the research process illustrated in Figure 1 is presented to the reader to follow the way to the final solution. In the analysis section, the process will be described step-by-step in a detailed way for the reader to follow the QCA research method and for future researchers to duplicate the study with different cases with different datasets.

The results presented in this paper derive from a data set obtained through a data mining work conducted in the database of a general contractor company based in Denmark. Since a list of disputed cases was available from the juridical department of the case company, it was possible to apply purposive sampling techniques (Thomas et al. 2014). From this list it was possible to identify cases with positive outcome and negative outcome, that is cases with or without dispute. A test group of 23 construction projects which ended in dispute was compared with a control group of 23 projects with similar size and nature completed without having a dispute. For the sake of comparability, only the building projects realized in Denmark within the last 5 years' period were chosen. The data obtained from data sets was combined with 11 semi-structured interviews made with project responsible and lawyers of the company involved in dispute resolution processes. The head of juridical department and the section director of the construction group were among the interviewees. All the project names together with the responsible names have been fully anonymized. Further detailed information will be given about the case selection in the analysis section.

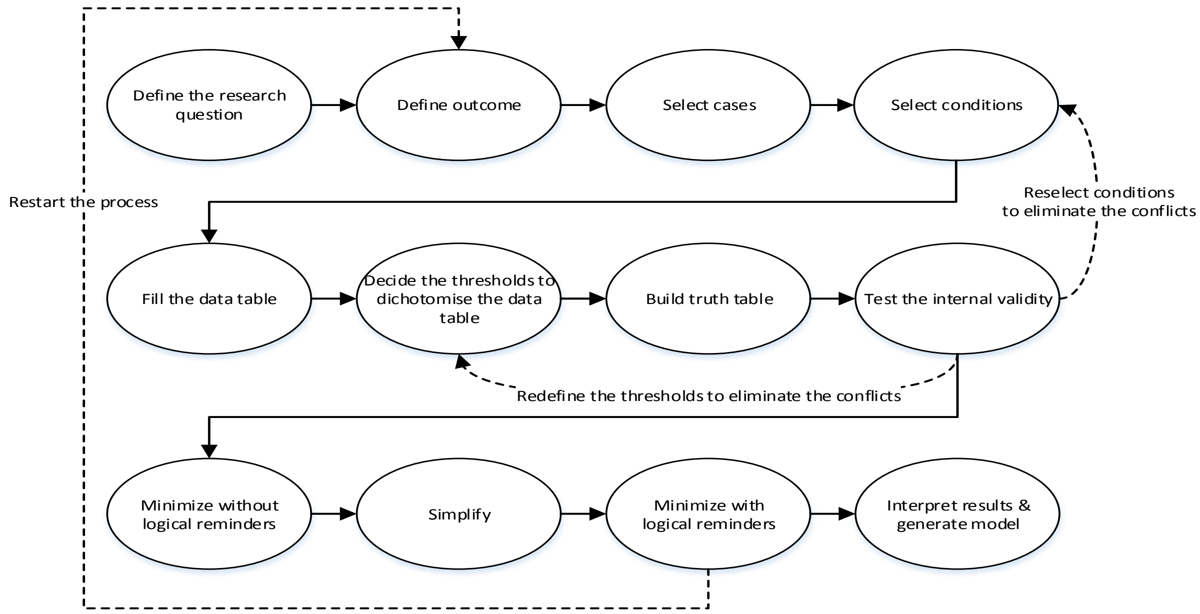


Figure 1 QCA Research Process

THEORETICAL BACKGROUND

King defines the factors on the way to achieve project success, as inter-dependent therefore holistic approach to investigate these factors is required. The interactions of success factors are of prime importance in determining a project's success or failure (King 1996). At this point, the necessity arises for QCA as a tool to describe the combinations of factors having a causal effect on particular project outcomes.
Moreover, Chan et al. (2010) select QCA over statistical methods because the study required a depth of case-based knowledge from archival research and qualitative interviews with senior managers. This approach of Chan et al. (2010) is particularly addressed in this study.
There has been a focus on describing project success in terms of certain different factors such as quality, time, budget, leadership, team motivation etc. (Freeman and Beale 1992; Belassi and Tukel 1996; Baker et al. 1988; Shao et al. 2012). However, *"the literature is very diverge and the only agreement seems to be the disagreement on what constitutes 'project success'"* (Prabhakar, 2008). In order to deal with diversity of factors fuzzy sets have been used in construction project management research such as Nieto-Morote and Ruz-Vila (2012), Nasirzadeh et al. (2008). Hatuslz and Skitmore (1997) select as project success factors time, cost and quality. These three factors are used as the only tangible factors in comparisons of projects.

Turner and Müller have been studying the importance of project leader and his/her leadership style on project success. (Turner and Müller 2005; Müller and Turner 2007a). They defend that the impact of the project manager, and his/her leadership abilities, on project success has not been researched. The authors published in two separate papers stating the leadership style and competence of the project manager is a success factor on projects and different styles are appropriate on different types of projects (Müller and Turner 2007; a and b).

Yet another effort has been made by Belassi and Tukel (1996) who group the success factors listed in the literature into four areas: Factors related to the project, factors related to the project managers and the team members, factors related to the organization, factors related to the external environment. In their research, they conclude that the impact of the factors related to the project managers and team members are more dominant compared to the other factors on project performance (Belassi and Tukel, 1996).

As it is very difficult to address the competency of the project managers and other project responsibles, in order to maintain comparability and measurability, in this study a combination of seniority levels and years spent in the company for the project manager and tender responsible was taken into consideration as factors to be investigated.

Project success differs noticeably with respect to the angle one looks at it. Freeman and Beale (1992) provide a very relevant example for the context of this paper from construction industry about the different points of views: *"An architect may consider success in terms of aesthetic appearance, an engineer in terms of technical competence, an accountant in terms of dollars spent under budget, a human resources manager in terms of employee satisfaction, and chief executive officers rate their success in the stock market"* (Freeman and Beale 1992).

Baker et al. (1983, 1988) conclude, *"in the long run, what really matters is whether the parties associated with, and affected by, a project are satisfied. Good schedule and cost performance means very little in the face of a poor performing end product."* They claim that perceived performance should be the measure, instead of using time, cost and performance as measures for project success (Baker et al. 1983).

Similarly, Latham's report (1994) states, *"In a rapidly changing environment, both clients and the supply side are increasingly looking to improve performance and reduce, and hopefully eliminate, conflict and disputes through a teamwork approach."*

Considering these contributions from Freeman and Beale, Baker et al. and Latham, dispute shows itself as a very significant factor of project success criteria. It was therefore chosen as the outcome to be investigated for this QCA analysis.

As Winch et al. (1998) describe in their study, uncertainty is high in the early stages of projects. As time goes and completion approaches certainty increases against uncertainty. Unfortunately, when a construction project is completed, teams are dissolved and knowledge and experiences gained collaboratively or individually during the project execution cannot be transferred to the next project. As a result, new project starts with the same uncertainty curve from bottom again.
To overcome this cycle, partnering of two or more parties across projects, is mentioned in Egan’s (1998) report as a way to resolve disputes as well as to improve the performance and sharing the gains. Therefore, Winch et al. and Egan’s arguments support “previous work experience between project participants” as an important condition to achieve successful projects. Thus, different constellations of previous work experience between the general contractor and parties such as clients, architects and consultants are chosen as conditions leading to disputes in this study. If there were no disagreement between clients, consultants and contractors, disputes would undoubtedly be fewer indeed (Kumaraswamy, 1997).
Similarly, Mitropoulos and Howell emphasize confidence between parties in order to avoid disputes and they suggest a dispute resolution being established in the beginning of the project, by the owner and contractor. (Mitropoulos and Howell, 2001).

ANALYSIS

A critic of artificial intelligence methods is that, application performs well when factors are already in numerical form such as for cost estimation. However, “there is no guarantee that it will perform as well in predicting the outcome of construction litigation where attributes are expressed in narrative form, are by and large incomplete and subject to interpretation, and where logic and traceability in the output are essential” (Pulket and Arditi, 2009). Therefore, to provide traceability, QCA analysis will be presented systematically in the analysis.

Define Outcome

To start with, it is important to give the definition of a dispute case. Dispute and conflicts are described in a taxonomy study in a way that conflicts require management and they can lead to disputes emerging resolution (Fenn et al., 1997). In the conducted interviews, the general contractor’s advocates argue that *“a project is classified as dispute case when claims by the parties are not discussed anymore one to one directly by conflicting parties”.* At that point, lawyers get involved to and communication is carried by law professionals only. Most of conflicts are settled without a case becoming a dispute, preventing lawyers to get involved. The company managers interviewed underline that there is benefit for all parties to come up with a solution before a case becomes a dispute case requiring a resolution. An interviewed project manager states, *“Disputes are time, energy and money consuming for the parties being involved”.*

Hoezen et al. (2012) describe in their study of contract processes how the relationship between contractor and other parties cannot be restored once solutions have been reached through tough negotiations and lawsuits. This surely supports the contractor’s incentive to achieve settlements to disagreements before a conflict becomes a dispute case. Managers interviewed for this study perceive a project without conflicts becoming dispute a major success. “*In litigation, business relationship often fractures because, at the end of trial, one party will emerge as ‘winner’ and the other as ‘loser*’ (Cheung and Suen, 2002). An interviewed division director underlines that “he would try all his best in order not to end up in court or arbitration with possible future clients”. It is therefore, among the 23 dispute cases studied only seven (30%) of them are the cases in which general contractor initiates the lawsuit, whereas in all the other cases, other parties sue the general contractor. Interestingly, when a party brings the conflict to arbitration or court the other party come up with their claims. Furthermore, the litigation or arbitration case durations are long, costly, difficult to foresee and in certain complicated cases court case durations are measured with years. These indicate how important for the parties to avoid disputes.

Select Cases

After selecting dispute as the outcome (dependent variable) to be analyzed, the following step of QCA is to select cases as presented in figure 1, in other words, sampling. Case selection is critical in QCA just like in other statistical or qualitative methods. The selected cases should be diverse enough to ensure explanatory strength in the QCA minimization, while still having comparability. (Jordan et al. 2011).

The cases used for the analysis originate from a general contractor company’s project database. Due to the commercial sensitivity of the data, all cases are anonymized. However it is necessary to inform the reader and future researchers who may like to duplicate the research about the data selection process.

Purposive sampling technique was used since a list of projects with disputes was already available. Dispute projects having a total amount of disputed money more than 2 million DKK were chosen as threshold since the data available for those projects was more detailed to conduct the analysis. In order to maintain comparability only building projects realized in Denmark were taken into consideration. As a result, 23 case projects with ongoing disputes were obtained. The 23 projects selected for the analysis had tender prices varying between about 700 million and 19 million and the average tender price of the projects was about 155 million DKK.

A control group of 23 completed projects during the last 5 years without any dispute from the completed projects archive of the company were chosen to drive the analysis. In order to maintain comparability these were projects of similar type, so to speak, all building projects; and similar size. The average tender price of the control group projects is 138 million DKK. Again, similar to the disputed projects, control group projects vary between 19 million and 432 million in tender prices.

The descriptive analysis presented an evenly distribution of the project properties such as project delivery system, building type and client type. Therefore, they are also suitable to conduct a comparative analysis.

46 Cases represent only a very small portion of the entire population considering the total number of cases about ten thousand. However the strength of QCA is based on its workability with relatively small amount of data sets compared to the other statistical tools (Jordan, et. al, 2011). Moreover, by the use of QCA, it is intended to draw patterns resulting particular outcomes rather than identifying correlations between independent variables (conditions) and the dependent variable (outcome) (Ragin, 1987).

Select Conditions and Create Contradiction Free Truth Table

Together with the organizational working history some project attributes like project delivery system, contract form, project type and size listed in table 2 are included in the analysis. Culture and different attitudes in construction conflicts are described as the potential root causes of disputes (Rooke, et al., 2003). However, it is difficult to convert culture and attitude into tangible factors. It is therefore chosen previous work collaboration between general contractor and other parties like client, architect and consultant within the last 10 years with the assumption that people and organizations that have worked together beforehand know each other’s manners and built a relation of trust. The threshold of 10 years is chosen with the assumption that after 10 years people tend to change places and organizations evolve making the work collaboration similar to a newly established one.

The threshold 15 years of experience for the construction manager and the tender responsible is chosen after the study made by Kog and Loh (2012). According to Kog and Loh (2012) the judgement with regard to of respondents with less than 15years of experience differs from that of the more experienced respondents and hence may not be good enough and views of respondents with less than 15years' experience in construction are likely to be biased and misleading.

Table 2: Conditions selected in the first iteration phase

Client & GC	The previous collaboration between the general contractor and client within the 10 years: if there exists take 1; if not take 0
Architect & GC	The previous collaboration between the general contractor and architect within the 10 years: if there exists take 1; if not take 0
Consultant & GC	The previous collaboration between the general contractor and consultant within the 10 years: if there exists take 1; if not take 0
Client Type	Client type as private or public: for public clients take 1; for private take 0
Project Delivery. Sytem	Construction delivery system: design and build projects (1), others (0)
Project Type	Project type if residential (1), others (office, hospital, hotel vs) (0)
Tender Responsible Seniority	A combination of contractor’s tender responsible seniority and number of years in the company: for number of years 15 and more than 15 take 1; for less take 0
Project Manager Seniority	A combination of contractor’s project manager seniority and number of years in the company : for number of years 15 and more than 15 take 1; for less take 0
Dispute as project outcome	Outcome, the project is : dispute (1); non-dispute (0)

After the above mentioned correction a truth table is formed. The contradictions are observed for cases having same conditions giving different results. In order to eliminate the contradictions the following methods offered by Rihoux and De Meur (2009) are addressed.

- Add conditions to the model. This should be done cautiously and in a theoretically justifiable way.
- Remove one or more condition(s) from the model and replace it/them with another condition(s).
- Re-examine the cases in a qualitative way to determine what differentiates the contradictory cases but has not been considered in the model.

- Reconsider whether all cases are truly part of the same population.

The process is a trial and error process with countless iteration. Luckily, the fsQCA software is dos based software and executes analysis with chosen conditions almost immediately. However, in order to make a judgement how to dichotomise each condition from verbal to binary system a considerable amount of time and energy is spent.

Finally, a truth table presented as table 3, without contradictory cases (cases with same combination of conditions giving two different outcomes) is obtained to conduct the analysis. In the next results and discussions section, only solutions with full consistency, based on the final contradiction free truth table will be presented.

QCA Software analysis

For the software analysis instructions presented in the QCA users guide manual by Ragin (2008) have been followed. Software runs very rapid making it possible to conduct several iterations including different data combinations. As mentioned in the previous phases all the contradictions are eliminated. All cases observed are taken into consideration giving the frequency as 1.

For the minimization process, following assumptions are made: Conditions expected to be absent in order to have dispute as an outcome are: The previous collaboration between the general contractor and client, general contractor and architect and general contractor and consultant within the 10 years, design and build project delivery system, Tender Responsible Seniority Project Manager Seniority being more than 15 years separately. Results obtained will be represented in the following section.

Table 3: The final dichotomized table used in the QCA analyses:

Projects Conditions Outcomes

CASE ID	GCCL	GCARCH	GCCON	DELSYS	PRJCTYPE	TRSNRTY	PMSNRTY	DISPUTE
1	1	1	0	0	0	0	1	1
2	1	0	1	0	0	0	0	1
3	0	0	1	1	1	0	0	1
4	0	0	1	0	0	1	0	1
5	0	0	0	1	0	0	0	1
6	0	0	0	0	1	1	1	1
7	0	0	0	1	1	0	0	1
8	0	0	0	0	1	0	0	1
9	0	0	0	0	1	0	1	1
10	1	0	1	1	1	0	0	1
11	1	0	1	1	1	0	0	1
12	0	0	1	0	1	0	1	1
13	0	0	0	0	0	0	0	1
14	0	1	1	1	1	0	1	1
15	1	1	1	1	0	0	0	1
16	0	1	0	1	1	0	1	1
17	0	0	0	0	0	1	0	1
18	1	1	1	1	0	1	0	1
19	0	0	1	1	0	1	0	1
20	1	1	1	0	1	0	1	1
21	0	1	0	0	1	1	1	1
22	1	1	1	0	1	1	1	1
23	1	1	1	0	0	0	1	1
24	1	1	1	1	1	0	1	0
25	1	1	1	1	0	1	1	0
26	0	1	0	1	1	1	1	0
27	0	0	1	0	0	0	1	0
28	0	0	0	1	0	0	1	0
29	1	0	0	1	0	1	0	0
30	0	1	1	1	0	1	1	0
31	0	0	0	1	0	0	1	0
32	1	0	0	0	1	0	1	0
33	1	1	0	0	0	1	1	0
34	0	1	1	1	0	0	1	0
35	0	1	1	1	0	1	1	0
36	0	1	1	1	0	0	1	0
37	0	0	0	1	0	1	1	0
38	0	0	1	1	0	0	1	0
39	1	1	0	1	0	0	0	0
40	1	1	1	1	0	0	1	0
41	1	1	1	1	1	0	1	0
42	1	1	1	1	0	0	1	0
43	0	1	1	0	0	0	0	0
44	1	0	1	1	0	1	0	0
45	1	1	1	1	1	0	1	0
46	1	0	1	1	1	0	1	0

RESULTS AND DISCUSSIONS

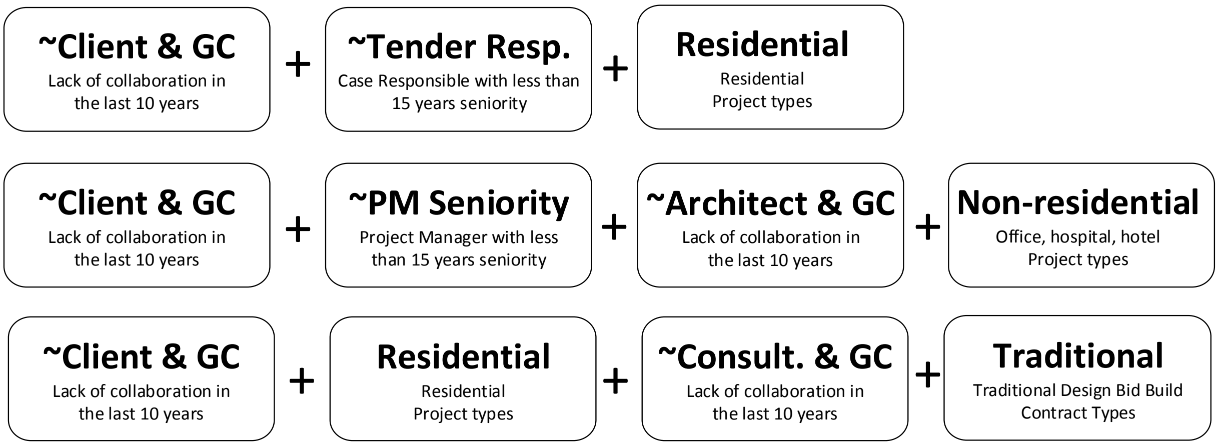
The following solution space was found as a result of the standard analysis for parsimonious solution. For the parsimonious solution there was observed with full (100%) solution coverage. The solution consistency is also fully covered as all contradictory cases were eliminated. The frequency cutoff is 1.0000, meaning that all cases were taken into consideration even though the sample size is relatively large, 46 cases, to conduct QCA analysis.

In some QCA analyses the investigating researcher choses to include in the analysis only cases observed more than once and in some analyses even more. For this analysis, as there exists no importance or significance difference between cases, all observed cases were taken into consideration, resulting with frequency cutoff: 1.000000. Consistency cutoff: 1.000000 implies that contradictory cases have been resolved. There exists no two cases with identical conditions leading to two different outcomes. This is the result of an iterative process by involving different conditions with trial and error method.

Because of working with 7 conditions describing a solution space=128 solutions (2^n with n being number of conditions), the final function is a complex one. Here 3 combinations of conditions obtained from intermediate solution are presented. As a result of Boolean algebra, they represent a more broad solution set compared to the parsimonious solution, and therefore they are more complex.

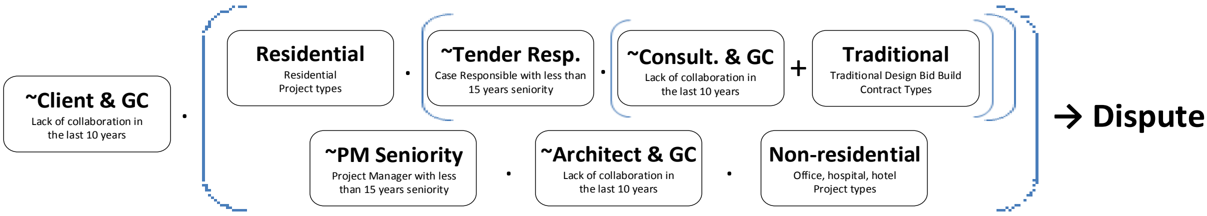
Model: dispute = f(gccl, gcarch, gccon, trsnrty, pmsnrty, delsys, prjctype)

3 Solution sets:



Sign: ~ represents absence of the condition in the solution set.

Obviously, this is still a parsimonious recipe; however, it is highly reliable as it explains 0.695652 solution coverage and it has a consistency of 1.0000. We can also minimize the formula by using Boolean algebra simplification shown as below and we can conclude that lack of previous work experience between the client and general contractor is a necessary condition for the dispute to occur.



Sign: ~ represents absence of the condition in the solution set.

Nevertheless, lack of previous work experience is not a sufficient condition alone. It should be followed by other conditions. In case of housing projects, the tender responsible of the general contractor with less than 15 years' experience in the field or lack of previous work experience between the clients' consultant in non-design and build projects lead to dispute. Another possible path leading to dispute is a combination of lack of previous work experience between the architect and the general contractor and the project manager having less than 15 years' experience in projects other than housing projects. All the above mentioned 3 solution paths lead to dispute when combined with lack of previous work experience between the client and the general contractor.

At last, a final interview is conducted with the department chief of the juridical department in order to get a final approval concerning the confidentiality of the data and his feedback about the findings. His acknowledgement of the conditions and solution paths is considered as a validation of the study.

CONCLUSION

Conflicts evolving to disputes and court cases in the execution of construction projects cause loss of valuable working hours, delay, frustration in the project team, unsatisfied clients and finally financial losses (Hoezen et al. (2012) and Li et al. (2013)). Therefore, it is the benefit of all parties to resolve conflicts in early stages before they turn out to be disputes. The aim of this study is to describe combinations of factors that can be observed across the projects leading to disputes.

QCA method is used to identify the factors working together, rather than correlations of individual independent variables, to a particular outcome. Moreover, QCA enables to work with a small data set both qualitatively and quantitatively. Interviewing the project responsible and the lawyers being involved in the process made it possible to go deeper in project investigation. Thus, based on 1) iterative analysis and 2) in depth interviews with project responsible and lawyers a set of combinations of conditions leading to disputes is pulled out.

Lack of previous work experience between the client and the general contractor appears to be the necessary condition for disputes to occur (solution coverage: 0.695652 and consistency: 1.0000). In case of housing projects, a tender responsible of the general contractor with less than 15 years' experience in the field or lack of previous work experience between the clients consultant in non-design and build projects lead to dispute. Another possible path leading to dispute is a combination of lack of previous work experience between the architect and the general contractor and project manager having less than 15 years' experience in projects other than housing projects. It can be concluded that the key to avoid disputes is to establish long-term professional contacts with the clients.

However, the solution set and the process leading to the simplified solution should be analysed carefully in order not to conclude misleading results. Furthermore, it may not be possible to apply the formula set given above in order to avoid conflict and dispute since other factors such as geography, interpersonal relations, and culture also might play a role in disputes. Nevertheless, it may be useful as a tool in case the critical project conditions fit well to the conditions described in this analysis. In that case, the QCA tool can help foreseeing a dispute before it appears.

Another important conclusion is the fact that for general contractors above a certain size it is beneficial to establish long-term relations with key clients. Such close focus in multiple project owners may open conflict free business ties, and construction projects that are much more effective. The results of this study are generated from one particular case company operating in Denmark. Further studies should be conducted with different data sets in different places and contexts in order to refine the solution set and to test the accountability of results obtained in the analysis.

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8.6 Appendix F: Descriptive II Study AEM Journal Paper 6 (submitted)

Architecture Engineering and Design Management

SPECIAL ISSUE ON OFFSITE CONSTRUCTION

Design Process of Facades through Application of Modularity: Divide and Conquer by use of Design Structure Matrix (DSM)

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Modularity has shown great potential in the manufactory industry, reducing order lead-time and creating variety with limited resources. In construction industry, the implementation of modularity has been limited with off-site production (OSP) only. The design process of construction incorporates a high amount of disciplines and stakeholders. In the application OSP the design phase appears to be critical as the necessity to freeze the design early is important. The purpose of this paper is to modularize the design process and investigate the potential of using modules describing organizational dependencies in the design process. The façade design is chosen for detailed analysis as façade modules has a high influence on the holistic design and the performances of the buildings. Thus design of façade requires an iterative and integral design approach which is representative for all design management activities. For the purpose of this study interviews with design professionals, contractors and suppliers, as well as a multidisciplinary workshop have been arranged. Thereby, the associated organisations, disciplines and activities entangled in the integral process of facades are revealed. By analysing the Design Structure Matrix (DSM) tool outputs with the Cambridge Advanced Modeller software, it becomes possible to identify highly iterative process modules, with a high amount of interfaces and dependencies being clustered together. The case study results have verified great potential since DSM and cluster analysis appear to be an applicable management tool in order to plan and schedule the complex design process.

Keywords: design process, design structure matrix (DSM), modularity in construction, off-site production (OSP), prefabricated façades

Introduction

A major issue in offsite building projects is design process enhancement in off-site production (OSP) as it is necessary to freeze design early in the most accurate way possible simply because changing the design after the production and assembly can overshadow the benefits of the OSP (Goulding, Rahimian, Arif, & Sharp, 2015). Therefore as a starting point, in this study we have taken as our research question: “how can we modularize the design process, in order to reveal organizational dependencies and decrease the uncertainties?”

OSP has well documented benefits in orde to reduce production time, to improve the quality of the finished product and to increase assembly speed (Gibb and Isack, 2003, Arif & Egbu, 2010, Nadim & Goulding, 2011).

The design process in OSP usually includes project- specific configuration of the standard building elements (i.e. routine activities), creative work (such as façades) and the development of technical solutions for project-specific aesthetics (Jansson et al., 2013). The whole design work is therefore treated as an integral process.

Iteration is necessary to deal with design requirements when solving complex design problems and undertaking aesthetic design work. One main reason for design quality and scheduling issues in building projects is unexpected iteration of sub-design processes (Pektas & Pultar, 2006).

On the other hand, constraints in applying OSP are investigated in many studies (Blismas, Pendlebury, Gibb, & Pasquire, 2005, Pan et al., 2007, Jaillon and Poon, 2008). Yet again in their survey Blismas et al., group the constraints of using OSP in three categories as process, supply chain and knowledge. They conclude that challenges related to knowledge appear to be the most essential ones (Blismas et al, 2005). However, two of the three top mentioned challanges in their survey are related to process. These are limitations relating to the necessity of freezing the design and specification very early in the process (top rated challenge) and key decisions early in process (the third most rated challenge). It goes without saying that the problems related to the process are affecting the rest of the construction planning and decision making, including material, method and contractor selection (Blismas et al., 2005).

In the study by Goulding at el., (2005) design process appears to be the major challenge in future offsite building projects requiring systematic enhancement and management both in short term (0 to 5 years) and in long term (6 to 10 years) (Goulding et al., 2015). In the short term (0-5 years), challenges all related to design such aspeople, construction process and design process, interface of OSP, design process integration and flexibility are raised as important areas to be further studied (Goulding et al., 2015).

In the analysis unit of this paper the design process of façade elements will be chosen as the object of investigation, since the risk factors applying to the design management (such as high amount of stakeholders, iteration of sub-design process, organizational dependencies, and information flow creating loops) are all present. Therefore, the more specific research question turns out to be: "how can we create efficient process modules describing organizational dependencies and work activity clusters in the case of façade design?"

In a study about off-site manufactured wood façade elements, Gasparri et al., conclude that "off-site prefabrication of façade elements allows a significant reduction in costs". This cost reduction becomes more significant when scaffolding cost savings are considered (Gasparri, Lucchini, Mantegazza & Mazzucchelli, 2015). Surely, some extra costs are added such as machinery to lift the façade elements and the workers to work in elevations but these expenses are remarkably low compared tothe time and money spent on scaffoldings. Finally, the cost savings included in the analysis by Gasparri et al., focus only on direct costs such as "material, man power and tools" (Gasparri et al., 2015). However, the use of prefabricated façade elements have much wider effects when issues such as better construction flow, better construction field space usage and improved safety at site are considered.

As a part of a survey study conducted in UK built and environment representatives from industry and academia were asked: 'Is OSP the future of the UK construction industry?'. The majority of industry respondents (73%) responded 'yes', whereas the majority of academia respondents (62.5%), either responded 'no' or 'do not know' (Nadim and Goulding, 2009). This significant difference is arguably the reason why academia fails to provide the tools and solutions that the industry requires to boost the OSP.

With this study we aim to contribute to the development of such tools through the method DSM (Design Structure Matrix-DSM). The DSM tool divides the design process into more manageable modules describing organisational dependencies in order to increase efficiency during the design phase.

Methodology

In this methodology section, a structure of the research design guiding this paper is provided. An abductive approach has been chosen for the research method. Contributions to modularity theory in different domains such as computer sciences and automotive industry are addressed in order to answer the research question "how can we modularize the design process?" The literature covering about modularity is presented in the theoretical background section.

A case company located in Denmark is chosen for the analysis. A set of exploratory interviews with 13 professional design managers, and project managers in case company were conducted. The interviews took place in the interviewees' workspaces so that authors had chance to observe the work environment. The semi-structured interviews took about 1 hour to 1 and half-an-hour. Moreover, all interviews were recorded and transcribed. The results of the exploratory interviews were grouped and analysed in order to narrow the research question into: "How can we create efficient process modules describing organizational dependencies and work activity clusters?".

Following the preliminary interviews the design process of the façade modules was chosen for analysis because it became apparent that façade sub-building elements are perfect representatives of complex building components in terms of design management difficulties.

Another set of semi structured interviews were made with 7 design and execution professionals related to the façade elements. The second set of interviews took longer in time, about 1 and half hours to 2 hours and yet again they were all recorded and transcribed. The purpose of the second round interviews was to get in-depth knowledge about the design phase of façade modules and different stakeholders involved in the process. The design professionals interviewed in the second round are employed by the case company and façade sub-contractors. All façade design work activities are identified as a result of second round interviews.

Finally, in order to identify the dependencies across the work activities in the design process, a 2 hour long workshop with a cross-functional design team was arranged at the head-quarter of the case company. Two process consultants, two project managers, two design managers, and one BIM manager participated in the workshop.As a result of the workshop, a Design

Structure Matrix (DSM) of the activities was co-created. Later, the results of the workshop were analysed with the Cambridge Advanced Modeller software (Wynn, Wyatt, Nair & Clarkson, 2010).

The theory that our research is based on is presented in the following theoretical background section followed by a description of Design Structure Matrix (DSM) tool. In the analysis section two interview rounds and the cross functional workshop are presented. In the results and discussion section the implementation of the DSM tool into design management will be discussed in depth.

Theoretical background

The design process can be categorised as a complex system. It involves a range of iterative processes between various professional disciplines that are highly dependent of each other's input and output. Disciplines work in parallel and with different interest and goals which adds significant to the degree of complexity. This aspect makes the design process fluctuate through time and thus become non-linear, difficult to predict and control.

However, Baldwin & Clark (2006) state that modularity from an engineering perspective will make complexity manageable, enable parallel work and accommodate future uncertainties (Baldwin & Clark, 2006). Campagnolo & Camuffo (2009) argue that the process modularity is strongly related to product modularity. Standardised interfaces and clearly defined design rules of the product module affect the success of the process modularity (Campagnolo & Camuffo, 2009).

According to Sako (2003), the outsourcing process is a modular approach and can pave the way towards modular product architecture. In terms of facades does this theory perspective apply with standard walls and its stock components, though customised wall is strongly dependent on the input from specialised suppliers with respect to the constructability?

The next section, analysis will lean on Ulrich´s & Tung´s (1991) definition of opportunities of modularity presented in Table1. Their definition relates to production methodology. Nevertheless, it can be used in the perspective of design management. As will be shown it justifies the use of modularity in the design process.

Table 01 – Key issues of the design process in connection with the opportunities of modularity (adapted from Ulrich and Tung, 1991)

	Key Issues	Opportunities of modularity
1	Limited time in the design process	Order Lead time
2	Insufficient planning tool	Order Lead time
3	Invisible multidisciplinary dependencies	Product Change, Product Variety, Decoupling of tasks, Design and Product focus

4	Vast coordination of information flow and decisions	Product Change, Product Variety, Decoupling of tasks, Design and Product Focus, Order Lead time
5	Difficult management of sub-contractors/suppliers	Component verification and testing, Component economies of scale, Order Lead time
6	Necessary of cross-functional collaboration	Design and Production focus, Facilitation of production (output)

Design Structure Matrix (DSM)

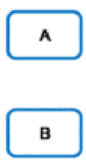
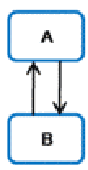
The intensive information flow and interdisciplinary iterative nature of construction design projects makes design process difficult to plan and schedule with traditional tools, which results in inevitable rework and time wasted(Oloufa, Hosni, Fayez & Axelsson, 2004).

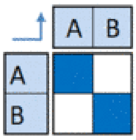
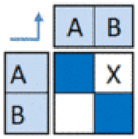
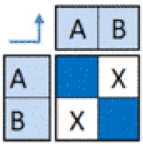
One of the tools that academia has developed in order to visualize the dependencies between parties or activities, is design structure matrix. DSM is described by its developer as a technique planning the design process information flow by visualizing the use of estimates, iteration and design reviews (Steward, 1981). The entities can be components of a product or tasks to complete a project and the matrix can be used to identify appropriate teams, workgroups and an ideal sequence of the tasks (Lindemann, 2009). A DSM is a square matrix with an equal number of rows and columns that shows relationships between elements/tasks in a system. In comparison to other system modelling methods DSM has two main advantages (Lindemann, 2009):

- It provides a simple and concise way to represent a complex system
- It is amenable to powerful analyses, such as clustering (to facilitate modularity) and sequencing (to minimise cost and schedule risk in processes)

Table 302 illustrates the graphical and matrix representation of parallel, sequential and coupled (iterative) activities.

Table 02 – Graphical and Matrix representation of task relation (DSM-Web)

Configuration of Relationships	Parallel	Sequential	Coupled
Graphical representation in a network diagram			

DSM representation in a matrix			

Since iteration is an indispensable part of the design process, controling the amount and making it manageable attracts the attention of many researchers. There are a lot of research projects within the DSM method in different areas. Cho and Eppinger (2005) apply DSM to an aerospace company for scheduling the engineering design process (Cho & Eppinger, 2005). Chen (2003) investigates in the product development in terms of project programming and framework reconstruction (C.H. Chen, 2003). Some applications of DSM in construction industry have been studied with different perspectives. Oloufa et al. (2004) take critical path method (CPM) and its extensive usage in construction as a starting point and they successfully combine DSM and CPM. They use DSM in order to support the shortcomings of CPM which occurs mainly in the design phase, since activities there require continuous estimation and iteration in order to reach an optimization in design (Oloufa et al., 2004).

In a recent study Haller et al., suggest an indicator, the sequence deviation quotient (SDQ), which reflects the amount of superfluous design iteration in a project. They define the superfluous iteration as “the iterations of design activities that will not contribute to quality improvement in standardized design processes and, thereby, [they seek to, red.] reduce the risk of time overruns and the risk of quality issues within the design phase of offsite projects” (Haller, Lu, Stehn & Jansson, 2015).

In our study, we undertake another approach based on modularity theory in order to make the design phase of façade elements manageable. In parallel with Simon´s (1962) definition of modularity, we aim to cluster the design activities into groups in order to identify modules having “high intra-component dependency and low inter-component dependency” (Simon, 1962). For that purpose, Cambridge Advanced Modeller software, which is developed by the Engineering Design Centre at Cambridge University Engineering Department and freely available online, is used (Wynn et al., 2010)

Analysis

Preliminary Interviews

The preliminary interviews show that design managers currently use CPM and Gaant Diagrams to plan and visualise the activities and the deliveries of the different design departments, where the indication of the dependencies across the different activities is marginal.

According to one of the senior design managers of the case company, “the time schedule becomes a black box, where you don’t know what is going to happen in the four weeks in front of you as a result of iterations”. The results of the interviews with design managers indicate that planning tools like MS Project are not sufficient to plan the iterative design process in detail.

The preliminary interviews imply that the design process of façade consists of three different sub-phases; tender, preliminary design and detailed design phase (see figure 01), which are among themselves highly integral, due to their iterative nature of the product development. The design process can be divided in different sub-deliveries from the involved trades which are working parallel. This perspective can give the design process a modular approach, but the information required for the sub-processes and deliveries are highly dependent on each other, and thus they become integral.

The project managers of the case company also stated that the selection of a modular façade system with predefined performance parameters can erase some of these dependencies and increase the modularity of these processes. The process of production includes the manufacturing of the façade components; glass, profiles, sealing/gasket, sunshades system and other matters. Furthermore, the process of assembly (unitized walls) and testing (customised walls) are also major processes in the production. The processes can be placed in the supply chain of the product, which is managed by the general contractor and the façade contractor. Hereby, we understand how integrated product, process and organization are.

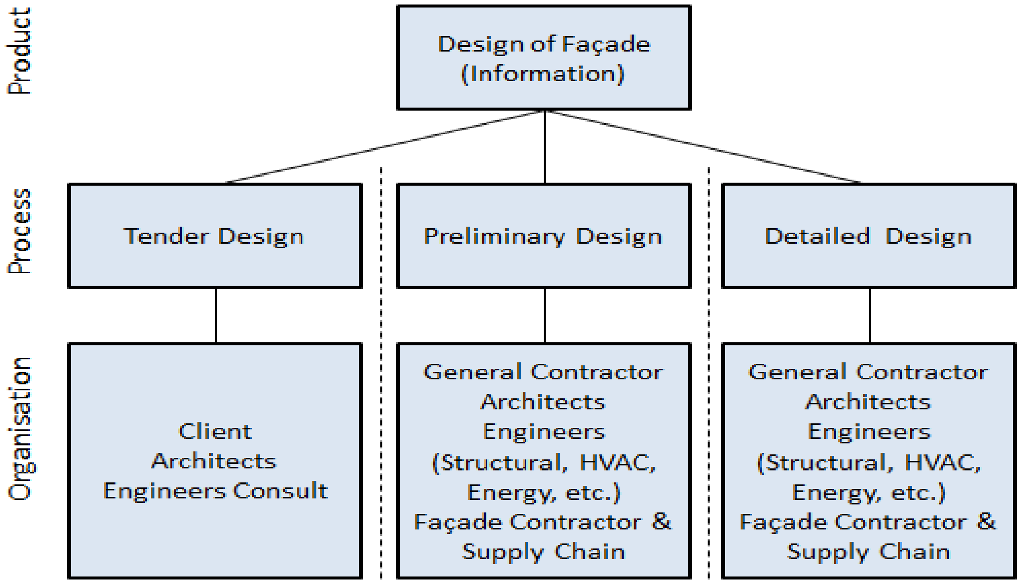


Figure *01* – Modularity perspective on the façade design (product), and the underlying processes and organisations

Following section describes the design process of the case company. The design process of facades can be aligned with the three phases of the general design process: tender, preliminary design and detailed design. In the tender phase, the architects were developing the first draft of the façade design in collaboration with the client and an engineering consultancy. In this phase, the first iteration defined the requirements in consideration of design and functional performance, which was the basis of the tender of the general contractor.

In the beginning of the preliminary design phase, the general contractor was optimising the overall design with their in-house engineering competences before they put the façade project out for tender. Yet according to design managers of the case company the preliminary design phase was a significant process for the design of the facades, the process in which most of the issues with the different structural components, building service systems and constructability had to be solved between the involved disciplines. After the design of the facade, the composition of components and the erection method of the façade systems is developed, and a mock-up for the visual approval (client, architect, engineer, contractor) and for a performance test (custom walls) was strictly recommended from the design manager of the Case Company, before the transition to the next phase.

According to the design managers of the case company the detailed design phase should be introduced after the design and functional performance of the composition of the façade system is approved and confirmed. The focus of the phase was solutions and details of the special components e.g. corners, balconies, windows etc. Furthermore, the detailed drawing is produced in a scrutiny process between the architects, engineers and façade contractor In addition to this the sub-suppliers production capabilities of components (glass, profiles), have a high influence on the output (façade wall), thus adding to the complexity of the process. Also, the general contractor has to develop the plan for the construction process in consideration of the logistics and safety, before the execution in the next phase can start. In conclusion, there are many layers, trades and factors to be taken into consideration in the design phase of the façade elements.

Cross-functional Workshop

In order to compile a DSM on the design process of façades, a cross functional workshop was facilitated in the case company, with the objective to identify the dependencies across the main activities. This process had the benefit of clustering the activities into much more manageable process modules by use of DSM.

According to the Society of Facades there must be appropriate dialogue and collaboration between the involved disciplines to achieve a high energy efficiency façade and to create a comfortable environment for occupants. Nevertheless, the boundaries are blurred between the disciplines involved in the process of design, supplies, installation, testing and operation of building façades (CIBSE , 2004).

The design process towards an architecturally accepted and functional façade of complex buildings is a simultaneous and cross functional cross disciplinary activity, which involves the following main disciplines (CIBSE , 2004) (Linde, 2012):

- Architects
- Façade Engineers

- Building Service Engineers
- Structural Engineers
- Contractors

Through desk research, interviews and the workshop at the case company following list of actors who were integrated in the façade design process was identified. Each actor has a description of their focus and influence, and the major objectives of each are presented in relation to a façade project in Table 03 below.

Table 03 – List of actors involved in design process

Actor	**Description**	**Objectives**
Client/ Investor	The client and/or the investor of the construction project have high expectations and requirements towards the façade and want to achieve the most for their investment. Clients commonly do not have the necessary knowledge and comprehension of construction or the design process, which can pose a range of challenges. Clients often introduce changes of the building design, without knowledge of the consequences.	Time & Cost Return of investment Functionality User friendliness Value for money
Architect	The architect company are focusing on the design performance, in order to concretise their concept and their big picture thoughts of building. The expertise and focus of architects firms can vary, where the technical quality is dependent on the in-house competencies, which reflect the technical quality of the design material.	Unique project Appearance Aesthetics before technical functionality
Municipality	The municipality is responsible to control the design according to the building regulations and give permission and license to the construction project. The façade have to be compliant with the local plan of the area.	Building regulation and restrictions Compliance of local plan Residents
Façade Contractor	The expertise and competences of façade contractors may vary and is dependent on their market focus (design/production/montage), the size of the company, experience (references) and their collaboration network	Production Time & Costs Functionality

	of subcontractor.	
Energy Engineer	Energy engineering is a broad field of engineering dealing with energy efficiency, energy services, facility management, plant engineering, environmental compliance and alternative energy technologies. The energy engineer is calculating the energy consumption of the building, which the performance of the façade plays a major role.	Sustainability Energy consumption Regulations and restrictions
Structural Engineer (Concrete & Steel)	The structural engineers are focusing on the primary structure of the building and needs the input of the loads, the structural function and stability of the façade project.	Stability Optimisation Costs
HVAC Engineer (Heating, Ventilation, Air Condition)	HVAC Engineers are in charge of dimensioning the ventilation system of the building, which is strong related to the performance specification of the façade, in order to achieve comfortable indoor climate. HVAC is part of Building Management System (BMS).	Functionality Indoor climate Optimisation - Cost
Electrical Engineer	The electrical engineers are responsible for the electrical installations and BMS system in the building. In relation to the facades are the automated sunscreens (internal and external) and/or automated windows within the field.	Functionality Optimisation - Cost
Fire Engineer	Fire Engineers are proving the fire safety of the building. The focus of the façade is the resistant of the components and the horisontal division that are separating the fire cells of the building.	Fire safety Building regulations
Acoustics Engineer	Acoustic is a specialised field of engineering and often an external consultant. The acoustic performance of the façade is important at has to be integrated in the design process.	Acoustic Functionality Indoor Climate Regulations
Construction Management	The construction management are handling the subcontractors and the process on site and are responsible to realise the design.	Constructability Process Time & Cost Safety
Montage/ Assembly	In some projects, the montage of the façade are put out for tender and performed by an independent company.	Process

contractor	Though, most of the time is the montage executed by the façade contractor.	Time & Costs Safety
Glass supplier	Glass is one of the main components of the façade and is most of the time delivered by a float glass fabric as con-trolled as a subcontractor from the façade contractor.	Production & Logistics Time & Costs
Solar screen supplier	Supplier of internal or external solar screens can be con-tracted out to a different company then the façade con-tractor. Outsourcing strategy of the system needs close monitoring of interfaces and design development.	Production & Logistics Time & Costs
QHSE – Quali-ty, Health, Safety & Envi-ronment	The department is represented in most companies and has a major role in construction projects; controlling the quality, health and safety issues of the design and the construction process. Furthermore, the sustainability factors influence this part of the project.	Quality Health Safety Environment Documentation
Operation and Maintenance	This body focus on the lifecycle of the building and are considering the operation and maintenance of the build-ing. In consideration of the façade this discipline is opti-mising the design regarding the cleaning operations and replacement of components etc. The integration of this discipline has gain focus due to the great potential of cost savings in the operation of the building through an improved design.	Functionality in Operation & Maintenance Usability

Figure 02 presents the output of the workshop, illustrating the dependencies across elements. The red fields in the matrix are indicating iterative processes – coupled activities, as described in the section above. The matrix from the workshop shows 35 iterative activities (shown with darker squares) in the design phase of facades, which gives an idea about the complex nature of this process.

Design Structure Matrix (DSM)

In order to cluster the activities identified as a result of the cross-functional workshop the DSM and its activity network the research software CAM – Cambridge Advanced Modeller is applied. (Wynn et al., 2010)

The Cambridge Advanced Modeller (CAM) software is a tool for modelling and analysing the dependencies and flows in complex systems - such as products, processes and organisations. It provides a DSM tool, a diagrammer and a simulation tool. (Wynn et al., 2010)

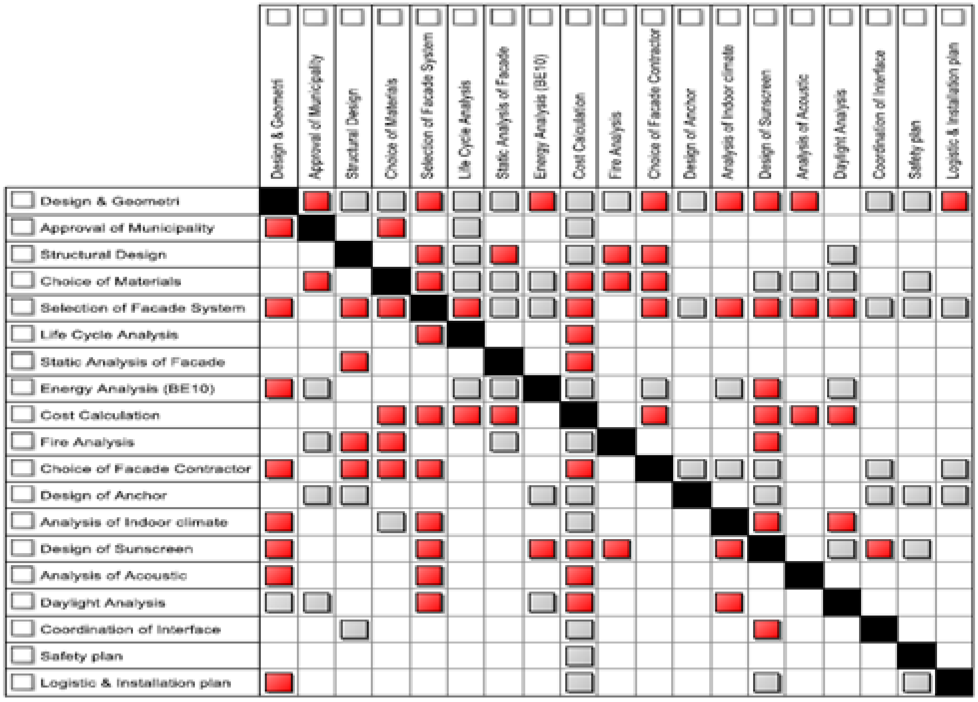


Figure *02* – Dependency Structure Matrix created during the Workshop (Wynn et al., 2010)

In

APPENDIX

Table 1– Description of activities which are represented in the design process of facades

Activity	**Description**
Development of Design & Geometry	The design and the geometry of the building is the input for the basis for the preliminary design phase, which is developed in the first iterative process by the architects and engineers consultancy. The design and geometry of the facade and geometry is then developed and optimised in the preliminary design phase by the cross functional design team.
Approval of Municipality	The task is including the exchange of designs and analysis of the building and façade with the state, in order to

	achieve the construction permission.
Structural Design of Building	The structural design of the building is concerning the design primary construction, which is concrete or steel shell construction.
Choice of Material and Surfaces	This activity is about the selection of materials, which are integrated in the façade system. The task has an iterative nature throughout the preliminary design phase, due to the optimisation and development of the façade system.
Selection of façade system	The activity "selection of the façade system" is about the development of the façade system its composition of components and erection method.
Life Cycle Analysis	The Life Cycle Analysis/Assessment (LCA) has become an important tool for determining the environmental impact of materials and products. LCA quantifies the materials, construction, use and demolition of building into embodied energy and carbon dioxide equivalents, along with the representation of resource consumption and released emission.
Static Analysis of Façade system	The activity of the static analysis is related to the structural function of the façade system, which elaborate on the section of façade performance parameters.
Energy Analysis (BE 10)	The energy analysis is about the energy consumption of the building where the façade performance is playing a major role, due to the heat/cooling contribution and the consumption effect of other building service systems.
Calculation of costs	The cost calculation is concerning the prediction of the expenses, which are effected through all changes in the project. The activity is a major task of the façade project because of its big effect on the budget and needs to be monitored throughout the design phase.
Fire Analysis	The task is calculating the fire loads and fire resistance of the components in order to fulfil the regulations and develop a safe building in situation of fire.
Choice of Façade contractor	The activity is a major task and consists of the tender process and selection of the subcontractor and the development of collaboration terms between the disciplines.
Design of Façade Anchor	The design of anchor is about the activities related to the concrete embeds, the anchor and the mounting log which are creating the physical interface components between the façade.
Design of Sunscreen/Sunshade	The activity consists of designing the interior and exterior sunshade system to control the sunlight in the building. The design activity is an important task and has a high degree of dependencies to other systems.

Analysis of Indoor climate	The indoor climate analysis is monitoring and balancing air quality, the thermal, audible and visual comfort in order to meet the regulations and requirements.
Analysis of Acoustics	The activity includes the noise assessment (traffic, Industrial, Recreational, Neighbours Construction) of the environment and the solution development to create a comfortable acoustics in the building according to the regulations.
Analysis of Daylight	The analysis of the daylight quantifies the amount and the distribution of sunlight in the project and improves the form of the building and room to get more natural light in order to get enough light for the tasks and minimise the use of artificial lighting.
Coordination of Interface	The coordination of interfaces is the necessary task to organise the different systems, components and structural element in order to develop a functional façade and minimise the impediments in the execution.
Development of safety plan	The development of the safety is inevitable and has to be considered in the design phase with the perspective on the façade system and its execution.
Logistic and Installation plan	The activity is about the assembly of the façade (on or off-site), the logistic and the plan of the installation, which is critical for the execution phase.

4 the results of the structural profiling analysis of the CAM software tool are represented. The table indicates the degree, the betweenness centrality, the closeness and the clustering coefficient of the activity elements, based on the DSM workshop output. These characteristics will be explained below.

The approach results in an *in-degree* and *out-degree*. The *In-degree* indicates the number of activity elements, which are depending/sub-sequentially. A high in-degree of an element can therefore be interpreted as an activity that has to be initiated on early in the process. The activity elements; design and geometry, selection of the façade system, choice of façade system and choice of façade system have a high number of in-degree.

Table 04 – Structural profiling on DSM (Wynn et al., 2010)

Model element	In-degree	Betweenness centrality	Out-degree	Active closeness	Passive closeness	Clustering coefficient
Analysis of Acoustic	3	0,668	4	5	11	0,833
Analysis of Indoor climate	6	1,086	6	5	14	0,786
Approval of Municipality	4	2,715	6	3	12	0,482
Choice of Facade Contractor	10	14,105	6	7	18	0,509
Choice of Materials	12	14,998	7	8	20	0,429
Coordination of Interface	3	0,25	5	4	8	0,714
Cost Calculation	8	53,829	18	19	16	0,353
Daylight Analysis	6	7,565	8	9	14	0,597
Design & Geometri	18	42,615	9	8	26	0,35
Design of Anchor	8	1,043	3	0	16	0,482
Design of Sunsrceen	9	24,174	11	12	17	0,442
Energy Analysis (BE10)	9	4,577	6	5	17	0,523
Fire Analysis	6	2,65	4	3	12	0,524
Life Cycle Analysis	2	0,393	7	8	8	0,595
Logistic & Installation plan	4	0,417	4	1	12	0,667
Safety plan	1	0	6	6	0	0,643
Selection of Facade System	16	45,058	10	11	24	0,371
Static Analysis of Facade	2	1,25	7	8	2	0,595
Structural Design	7	14,608	7	7	15	0,422

The *out-degree* is representing dependency of prior activity elements and indicates how many activities and the kind of output which the element is depending on. An element with a high out-degree value can therefore be interpreted as an activity which can be applied late in the process. However, this allowance cannot be taken for granted if the in-degree value is high as well. To exemplify the cost impact has the highest out-degree value, as all activities in the design or changes in the design are affecting the cost of the façade. Furthermore, the selection of the façade system has a high out-degree, because most design decisions are effecting the component composition of the facade system.

The *betweenness centrality* is an indicator of an element's centrality in a network. It is equal to the number of shortest paths from all vertices to all other elements that pass through that node. An element with high betweenness centrality has a large influence on the transfer of information through the network (Wassermann, 1994).

In relation to the DSM output based on the data from the workshop, the elements related to the cost calculation, the selection of the façade system, the design and geometry, and the design of sunscreen, have a high influence on the network, due to the indication of a high betweenness centrality. However, the choice of materials, the structural design and the choice of façade contractor are all playing a central role in the activity network.

The *closeness*, as the name implies, focus on how close the element is to all the other elements in the activity network. Closeness centrality describes the extent of influence of an element on a network (Wassermann, 1994). In consideration of the workshop results, the activities with a high betweenness centrality also have a high closeness, which underlines the tightness of the connected activities in the façade design process.

The *clustering coefficient* is a measure of the degree to which nodes in a graph tend to cluster together. A large number of networks show a tendency for link formation between neighbouring vertices, i.e., the network topology deviates from uncorrelated random networks in which triangles are sparse. The tendency is called *clustering* and it reflects the clustering of edges into tightly connected “neighbourhoods” (Saramäki, 2007). In consideration of the structural profiling data the clustering coefficient of all notes are quite high, which is grounded in the high degree of dependencies in-between. The analysis of acoustics and the calculation of indoor climate have the highest measurements of the clustering coefficients. It is assumed that the few but iterative dependencies are causing this coefficient.

According to Watts & Strogatz (1998) most real-world networks and in particular social networks tend to create tightly knit groups, characterised by a relatively high density of ties (D.J. Watts, 1998). This tendency is also represented in the network of the design process of facades since the activities are highly depended on each other and represent social ties at the same time

Creating Process Modules

The technique of clustering elements in relation to their dependencies enables modules to be created corresponding to products/components, processes and actors in an organisation. The goal is to find subsets of the DSM elements (i.e. clusters or modules) that are mutually exclusive and have a minimal interaction with other subsets. This implies that the activities in the module are significantly interconnected while the connection to the rest of the system is as little as possible. (Simon, 1962, Lindemann, 2009)

The manual approach of clustering the DSM has posed a challenge however, because of the strong interconnections within the work activities. Cambridge Advance Modeller was used in order to cluster elements and create modules within the façade design process, with a cluster algorithm.

After running the software, it has been found that the activity elements containing the acoustic and the static analysis of the façade are not integrated in the clusters, because of their low indegree values. Moreover, the activity elements which cause the most iterative processes are found to be the design & geometry, cost calculation and the selection of the façade elements.

The design and geometry of the building and the façade is one of the main architectural tasks and is forming the basis of the preliminary design phase, where the façade design is optimised. Because of its fundamental character this task is considered as a parallel running activity and it is therefore excluded from the DSM in the following analysis. Similarly, the cost calculation is also considered as a parallel activity, due to the fact that all changes have an effect on the budget and have to be monitored throughout the design process. Furthermore, the selection of the façade system is considered as a baseline activity and as the output of the iterative processes within the preliminary design, after which the components of the system are found. Following these considerations the three above mentioned activities are excluded in the second reconfigured clustering assessment.

In the second cluster iteration with the excluded activity of design and geometry, selection of façade system and cost calculations a new set of clusters have been created by the algorithm.

In this second round of iteration it has been observed that the structural activities of the primary structure and the façade have a strong relation and dependency underlining the importance of this process module. The lifecycle analysis activity on the other hand is maybe misplaced and should rather be merged with the first cluster due to the dependency towards the choice of materials and the approval by the municipality. The swapping operation additionally reduces the dependencies outside of the clusters and leads to the following final result of the clustering method as shown in Figure 44. Final DSM with clustered activity element from the workshop outputFigure 03.

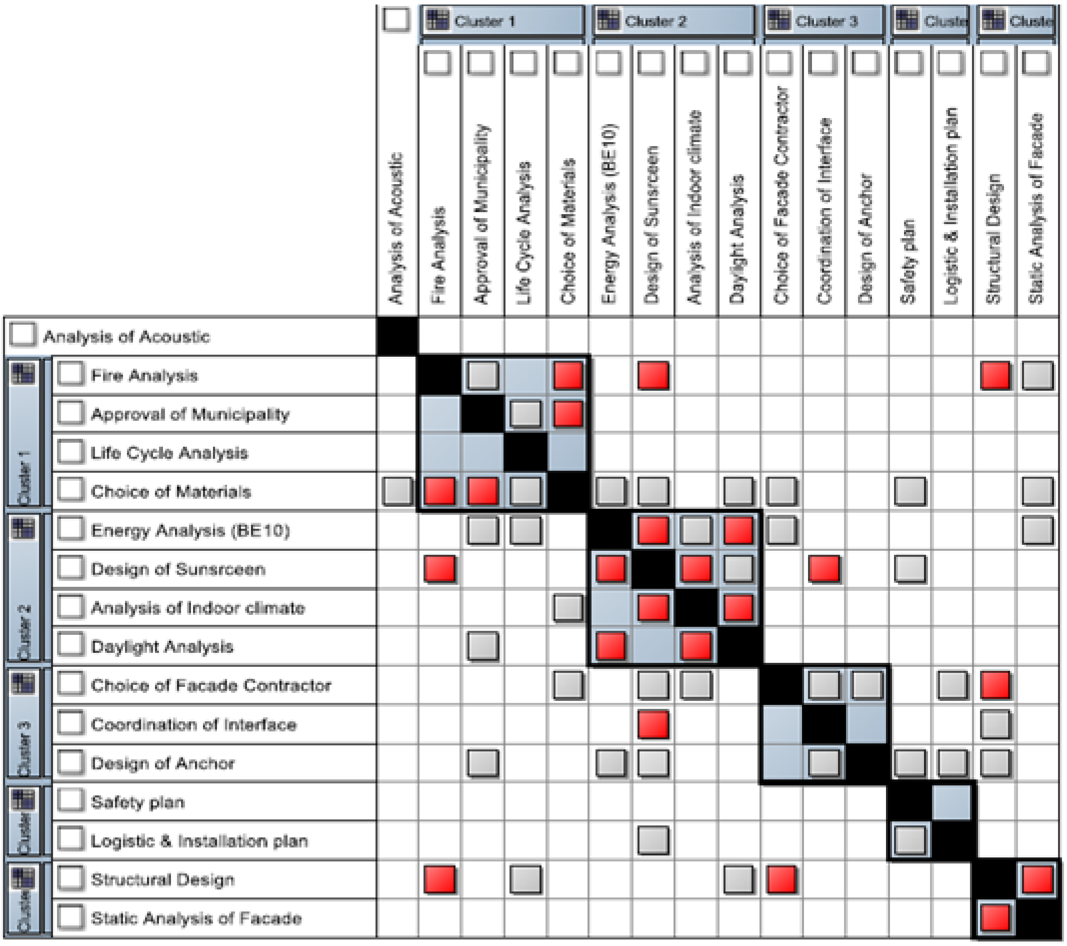


Figure *03* – Final DSM with clustered activity element from the workshop output (Wynn et al., 2010)

Results and discussions

Construction projects are typical examples of project based production as each project differs from the others, making it unique. However, despite variation in project sizes and types, the design process of building projects largely consists of the same activities (Austin et al., 2002).

Similarly, the results of the interviews and the cross-functional workshop states that the same design activities co-exist in different projects, however, the design process is redefined in each project individually.

The research has confirmed that the design process of facades has a high degree of complexity. This complexity comes mainly from a large number of independent actors who all are affiliated in the process, creating many interconnections and interfaces, with a high degree of dependency, thus resulting in integrity. Moreover, the actors are involved in an iterative process throughout the design phases and additional dependencies make the process fluctuating and difficult to manage.

Therefore, the results of this study focusing on façade design in detail can be generalised to other design management cases.

At the construction site, in the execution phase, OSP has obvious benefits and creates a more smooth execution phase, moving manufacturing away from the site and speeding up the mounting. The research implies that when prefabrication is used, the design has to be more thorough and precise. This aspect demands that sub-contractors are involved early in the process and that the decisions in relation to the façade are locked in an early stage, finally resulting in limited project changes and increased constructability.

Internal interview results show that the construction industry has not yet adapted to this concept, and furthermore the time frame in the design phase is limited. Also, decision and planning tools are not sufficient. As a result, decisions are often delayed, resulting in project changes and new sets of iterative processes, which further extend the design process. The authors believe that this transition needs to be handled more efficiently with stronger design management and better planning tools.

The finding is that the DSM tool appears to be an excellent tool for managers to use in the design process of facades, as it enables a mapping of dependencies. DSM clusters the work activities and actors into process modules make the design process more manageable and easy to digest. Moreover, to operationalize the modularity by applying DSM, design managers could plan the design process, structure meetings and gather the team of experts in respect to human and social values.

Through application of modularity, just like module façades can accelerate the execution phase, our proposed design modules will accelerate the design process, since the required geometric coordination of physical and functional performance parameters for each façade system will be managed within the clusters identified as a result of the DSM cluster analysis.

Conclusion

The results and the evaluation of the workshop conclude that the DSM, a tool from modularity theory, is a valid planning tool for design management. Furthermore, the DSM analysis reflected great potential to identify process modules in order to reveal invisible dependencies in the design phase of the façade systems.

The DSM method successfully enabled the identification of dependencies and interfaces between the crucial cross organisational design activities which are related to the façade design process. Furthermore, the method successfully established cross-functional process modules.

The application of the modular approach in design has the advantage of accelerating the execution process, as the workload and coordination are transferred to the design process, which in turn requires enhanced design management. Clustering work activities and thus creating process modules defining work activities and organizations involved in the design process is a way to operationalize the modularity theory. Process modules describing organizational dependencies in different stages of the design process are helpful in order to visualize and execute the process both for project participants and managers.

The façade project is a complex system, where activities are proceeding simultaneously and the involved organisations are working highly integrally. The main reasons for the integral nature of this process are that the design needs to be considered in the unique construction project and its environment, and that the façade performance is highly synchronised with other building system designs. Fragmented organisations, high quality expectations, project changes, insufficient planning and slow decision-making, adds significantly to the challenges within the design process of façade projects.

Although design of façade is complex and therefore representative for other design management cases, future research could investigate and use the DSM on other design processes. It would be beneficial to test it on a smaller and less complicated system than the façade system first and then apply it to unique more complex design processes.

It would be interesting to discover the dependencies and information flow within each cluster discovered in the analysis of the DSM, mapping them in detail and revealing the next level of complexity. The same cluster analysis can be applied to another tool which is MDM (Multiple Domain Matrix), similar to DSM, but in addition adds people responsible for activities.

Visualising internal dependencies within the general contractor company itself as well as dependencies between the company and the external organisations surrounding it, will eventually influence the understanding of and respect for one another's work. In relation to the research question, project-based processes challenge the concept of modularity. However, this study shows that modularity can still be applied and resolve some of the major problems existing in the highly integral and iterative design process.

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APPENDIX

Table 1– Description of activities which are represented in the design process of facades

Activity	Description
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Approval of Municipality	The task is including the exchange of designs and analysis of the building and façade with the state, in order to achieve the construction permission.
Structural Design of Building	The structural design of the building is concerning the design primary construction, which is concrete or steel shell construction.
Choice of Material and Surfaces	This activity is about the selection of materials, which are integrated in the façade system. The task has an iterative nature throughout the preliminary design phase, due to the optimisation and development of the façade system.
Selection of façade system	The activity "selection of the façade system" is about the development of the façade system its composition of components and erection method.
Life Cycle Analysis	The Life Cycle Analysis/Assessment (LCA) has become an important tool for determining the environmental impact of materials and products. LCA quantifies the materials, construction, use and demolition of building into embodied energy and carbon dioxide equivalents, along with the representation of resource consumption and released emission.
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Energy Analysis (BE 10)	The energy analysis is about the energy consumption of the building where the façade performance is playing a major role, due to the heat/cooling contribution and the consumption effect of other building service systems.
Calculation of costs	The cost calculation is concerning the prediction of the expenses, which are effected through all changes in the project. The activity is a major task of the façade project because of its big effect on the budget and needs to be monitored throughout the design phase.
Fire Analysis	The task is calculating the fire loads and fire resistance of the components in order to fulfil the regulations and develop a safe building in situation of fire.
Choice of Façade contractor	The activity is a major task and consists of the tender process and selection of the subcontractor and the devel-

	opment of collaboration terms between the disciplines.
Design of Façade Anchor	The design of anchor is about the activities related to the concrete embeds, the anchor and the mounting log which are creating the physical interface components between the façade.
Design of Sunscreen/Sunshade	The activity consists of designing the interior and exterior sunshade system to control the sunlight in the building. The design activity is an important task and has a high degree of dependencies to other systems.
Analysis of Indoor climate	The indoor climate analysis is monitoring and balancing air quality, the thermal, audible and visual comfort in order to meet the regulations and requirements.
Analysis of Acoustics	The activity includes the noise assessment (traffic, Industrial, Recreational, Neighbours Construction) of the environment and the solution development to create a comfortable acoustics in the building according to the regulations.
Analysis of Daylight	The analysis of the daylight quantifies the amount and the distribution of sunlight in the project and improves the form of the building and room to get more natural light in order to get enough light for the tasks and minimise the use of artificial lighting.
Coordination of Interface	The coordination of interfaces is the necessary task to organise the different systems, components and structural element in order to develop a functional façade and minimise the impediments in the execution.
Development of safety plan	The development of the safety is inevitable and has to be considered in the design phase with the perspective on the façade system and its execution.
Logistic and Installation plan	The activity is about the assembly of the façade (on or off-site), the logistic and the plan of the installation, which is critical for the execution phase.

8.7 Appendix G: Descriptive II Study IGLC 2016 Paper 7 (published)

OFF-SITE PREFABRICATION: WHAT DOES IT REQUIRE FROM THE TRADE CONTRACTOR?

Baris Bekdik[1], Daniel Hall[2], and Sigmund Aslesen[3]

Abstract

The purpose of the paper is to show what is required to industrialize a building process from the standpoint of the trade contractor. Rationalization of building processes has, over the years, caught the attention of numerous IGLC papers. Although significant contributions have been made to further understand and improve existing construction processes, relatively few contributions have focused on the opportunities for industrialization from the trade contractor's perspective. This paper uses an in-depth case study to address the deployment strategy for off-site fabrication techniques and processes used for modular plumbing fixture carriers deployed on two large-scale hospital projects in the United States. Findings include the organizational and technological arrangement for prefabrication. The paper applies value stream mapping to visualize the process and improve it. Because this work looks at only one case study, the conclusions are limited in generalizability to other prefabrication operations. However, it represents an important in-depth case from the trade contractors' perspective and will contribute to the growing body of research focused on industrialization and prefabrication in lean construction.

Keywords

Lean construction, modularity, prefabrication, standardization, value stream mapping (VSM).

INTRODUCTION

Industrialization includes the process by which a traditionally non-industrial sector of the economy becomes increasingly similar to the manufacturing industry. The process implies variations of greater use of prefabrication, preassembly, modularization and off-site fabrication techniques and processes (National Research Council 2009). By definition, the production performed outside of the construction area in a temporary or more permanent workshop off site, is named as prefabrication (Gibb 1999, Ballard and Arbulu 2004). Among the benefits attributed are improved production control due to reduced variance in the material and information flow (Lennartsson et al. 2009), decreased complexity of the on-site construction process (Larsson and Simonsson 2012), improved quality and productivity in construction

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(Viana et al. 2013), schedule savings and reduced on-site labor (Antillón et al.2014), just-in-time delivery, zero defects and customized products (Bildsten et al. 2010), and reduced lead times (Ballard and Arbulu 2004).

All the potential benefits considered, one might expect the construction industry to embrace industrialization. The majority of works on building sites are, however, still performed manually. “The primary categories of work involved in construction are the handling and transport of materials, the fabrication of elements or modules, fittings and connections, the positioning and fixing in the corresponding place, and the prior and subsequent processing steps using special tools” (Girmscheid 2005). These work steps are not very different from other areas of industrial production. Nevertheless, the challenges or constraints facing construction industrialization seem to be substantial and diverse, amongst others including the low degree of standardization in products and processes (Hermes 2015); the lack of design-production interface (Tillmann et al. 2015, Larsson and Simonsson 2012); the low IT integration in the industry (Blismas 2007); the multiple project environments creating a high level of uncertainty (Bertrand and Muntslag 1993); the market-driven, short term buyer-supplier relationships (Bildsten et al. 2010); the lack of trust between contractors and suppliers (Melo & Alves 2010); the reluctance among suppliers to adopt new standards (Lennartsson et al. 2009); the lack of holistic thinking in the product design (Björnfot and Stehn 2005); and the demand variability from the contractor, the late receipt of design information, the frequent design changes and frequent changes in installation timing and sequence (Ballard and Arbulu 2004).

Furthermore, there are some repeatedly mentioned ideas about realizing prefabrication in construction in the literature. One group claims that a high production volume is a prerequisite in order to apply prefabrication (Pan et al. 2007, Jaillon and Poon 2008 and Jonsson and Rudberg 2014). Some others add that large investments and sophisticated production is necessary for different trades to work on prefab modules. “A module is almost never the output of a single trade but must be seen as a product designed and manufactured by a number of different trade experts and most often installed at the site by the manufactures’ own, specially trained crews” (Bertelsen 2005).

This paper takes the above mentioned challenges into consideration and it focuses on off-site prefabrication from the perspective of the single trade contractor. The case company is one of the largest mechanical, electrical, and plumbing (MEP) building system experts in US. The company has proven to be successful in its strategy to industrialize part products and provide services related to their installing. The paper’s particular interest is on what is required for this strategy to become economically viable. In an attempt to answer this question, we emphasize the industrial fabrication including the use of standardized working methods and tools as well as new information technology; the logistical planning related to production facilities, storage of materials and the transportation and installation of modules on site, and; the use of contract models to support the industrialization.

CASE STUDY

The case company, Southland Industries is one of the largest mechanical, electrical, and plumbing (MEP) building system experts in US. The case company is currently engaged in delivering two large-scale new hospitals for Sutter Health located in San Francisco, California. St. Luke’s Replacement Hospital is a 20,900 m2 (215,000 square foot), 120 bed project and Van Ness and Geary Hospital is a 68,750 m2 (740,000 square foot), 274-bed project (CPMC 2020). The case company has signed an Integrated Form of Agreement (IFOA) to deliver these two hospitals. This IFOA approach requires pain and gain sharing, where all team members share in the risk and reward for delivering the hospital on time and on budget.

To maximize production efficiency for the two hospitals, the two projects are leasing a large warehouse on Treasure Island in the San Francisco bay. A part of that warehouse is dedicated for the case company's prefabrication of modular plumbing fixture carriers. This is in addition to more typical prefabrication of the mechanical ductwork produced for other projects as well in the case company's main factory. At the time of the study, the case company had begun work on both the St. Luke's Replacement Hospital (STL) and the Van Ness and Geary Hospital (VNGC). Most of the work done so far is VNGC but work at STL is beginning now.

METHODOLOGY

Our case study proposes a map to visualize the flow of resource usage, including time, labor, and inventory through implementation of Value Stream Mapping (VSM) (Rother and Shook 1998). For this research, we conducted as a group and individually a number of visits to the final construction site and temporary workshop where the manufacturing takes place. Our observations are based on our participation in big room meetings, interviews with contractor and trade project managers, architects and owner representatives. Moreover, we have had the privilege to observe and take time records of the manufacturing work performed by the use of jig modules in the temporary workshop. The current and suggested future state Value Stream Maps will be shared in the analysis section and finally improvement suggestions at macro and micro level will be given in the discussion and conclusion section.

ANALYSIS

In analysis section we will present the value stream map (VSM) of operations for the case company, followed by a description of several of the areas. Furthermore, areas of improvement suggestions presented on the same figure 1 with circles on the VSM then are discussed in detail in the discussion section.

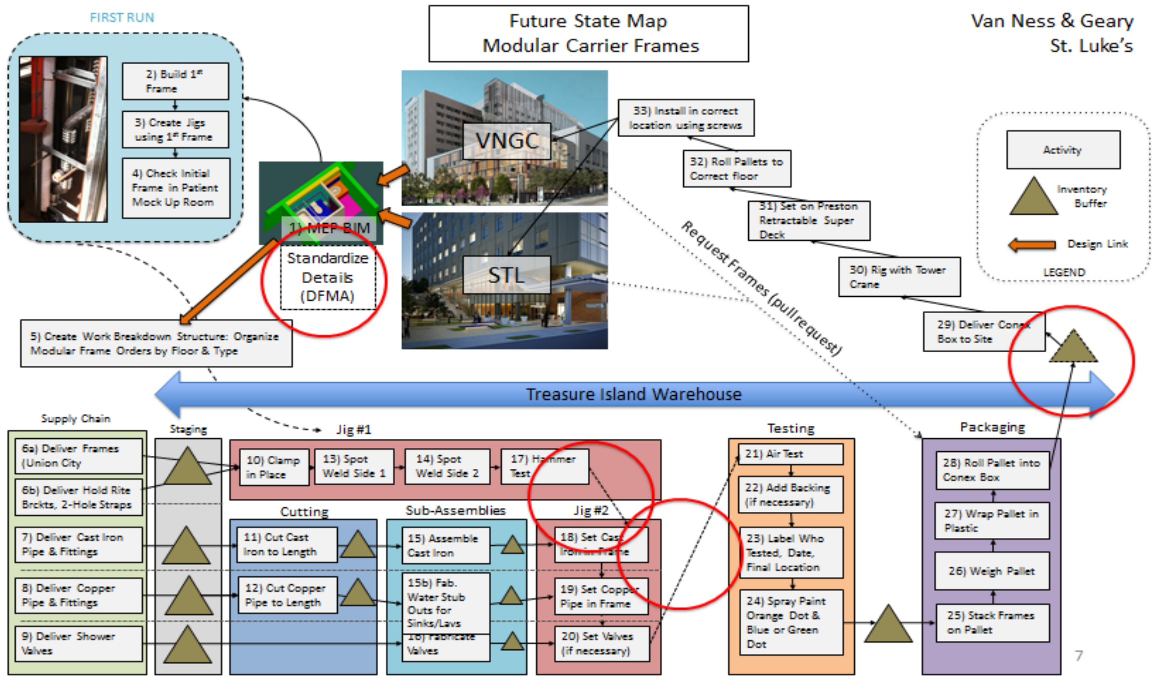

Figure 1 Value stream map of the modular frames

Value stream map (VSM)

First Run

The process begins with a fixture carrier design created using Building Information Modeling (BIM). As the creator of the modules states “it wouldn’t really be possible without the BIM.” BIM allows the practitioners to see the overall picture and therefore catch the similarities in design in different parts of the structure. Therefore, it becomes possible to identify each repeating module with number or repetitions and then create a jig in order to build it if it is feasible. From cut sheets that come from the BIM, a “first run” to create an initial set of jigs for a carrier frame is made. Then the first frame is built without a jig, and then that frame is used to create the initial set of jigs. Jigs are checked continuously for both accuracy to the BIM and easy to use for the workers. Altogether, twenty jigs have been made. Some of the jigs have adaptors so they can have additional configurations. It is difficult to estimate how long it takes the creator of the jigs to make one. However, after the experience gained during the process it takes now only couple of hours to build a jig.

In addition, there are many common elements between the two projects. Therefore an economy of scale is possible by using the same jigs with some little modifications in order to build for two projects. A few of the first VNGC carrier frames are mounted in the patient mock-up room to make sure that they fit. Birch and seven-layer plywood are used to make all parts of the jigs. This is easy to work with and reconfigure as necessary. There is no leveling or measuring required. Everything is set by stops and jigs, and locations can be calculated and fixed. This not only avoids the risk of making measurement mistakes, but also saves considerable time for the worker who does not have to bother with placement, leveling and tolerances during operation.

Supply Chain

The supplies for the modular carrier frames are delivered to the warehouse and brought in with a forklift. The frames for the carriers are made in the main factory and are delivered. Because the main factory has many competing project needs, occasionally those frames are not delivered before the previous set runs out, causing the team to work on something else for a short while. The cast iron pipe and copper pipe is delivered in long stock lengths and staged in large stock quantities in the warehouse.

Cutting & Sub-Assemblies

Separate cutting stations are set up to cut the cast iron and the copper pipe to length. Special consideration has been given to ensure cuts can be made using blocks and a stop, to reduce the need for workers to measure. Once pipe is cut to length, it is pre-assembled and readied for placement in Jig #2.

Jig #1 & Jig #2

At Jig #1, rhe strut is spot-welded to the metal frame for the fixture. The following work activities that occur on the current state map: 10) Clamp in Place; 13) Spot Weld Side ; 14) Spot Weld Side 2; and 17) Hammer Test. The purpose of the activity is to spot-weld square strut across the metal frame as shown in Figure 2 on the left hand side, which serves as strength for the frame and provides the attachment points for the cast iron and copper assemblies. Before the activity can take place, the frame material must be assembled and delivered by Southland's sheet metal shop in Union City. Jig #2 is the location where the completed frame is set in place and the cast iron and copper pipe assemblies are installed in the correct location. Jig #2 also uses a wheel to rotate and flip the frame around, so that the worker is always able to perform the work most efficiently.

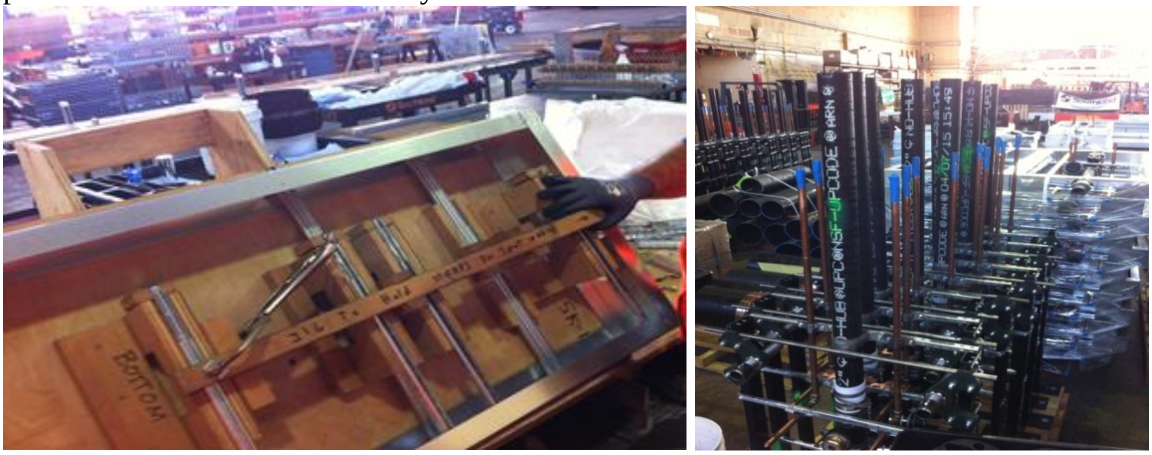

Figure 2 Welding jig on the left and stock of prefabricated modules on the right

Testing

An air test is completed on all finished assemblies, which are now considered rough-in modules. Once passed, a label is fixed to the module stating who did the testing, at what time the testing occurred, and where the final location (site, level and room) of the fixture is. A green paint dot is sprayed on the rough-in module to indicate that it has passed the test. The case company also uses different colored paints for a second dot, to distinguish between the two jobs. VNGC is painted with a blue dot and St Luke's with a red dot. Each finished item has a code written in black permanent marker pen on the bottom of the frame. For example, we saw LV-1 for the lavatory frame type 1.

Packaging and Storage

The completed rough-in modules are stacked together on a pallet and weighed. The frames are grouped by their floor location. Each shipping container can hold with 7,25 tons (16,000 lbs.) and the case company is very careful not to go over this weight. Currently they are storing completed and wrapped pallets on the Treasure Island floor and then moving them into the completed Conex Box. It would be preferable not to move the pallets twice but because the fabrication is far ahead of installation, it is necessary at this point. Right now the first and second floors of VNGC are completely fabricated and in storage as some of the prefabricated modules can be seen in Figure 2 on the right hand side, while installation of these items is not until mid-2016 at the earliest. Temporary shop will accumulate a very large inventory buffer on site before it is time to begin delivering the rough-in modules.

Delivery

The delivery plan is the part of the current state map that has not occurred yet because the construction sites are not ready for the rough-in modules. The current plan is for each site (VNGC or STL) to call temporary shop when they are nearing the point when rough-in modules are required on a certain floor. At that point, Treasure Island will deliver the container to the site. The entire container will be rigged using a tower crane, and the pallets will be rolled onto the retractable Super Deck at the correct floor for their installation. However, one of our hosts mentioned that the site has changed delivery projections almost on a weekly basis. This current delivery process has not begun and is likely the most uncertain part of the process to date.

DISCUSSION

By employing lean construction concepts, the case company has set up a successful prefabrication operation for rough-in modular frames. The current state of operations represents a commitment to the lean construction philosophy. The decision to use prefabrication is a long-term philosophy, the use of the production line will greatly reduce (material and time) waste, and the tasks have been standardized and "mistake-proofed."

The work is exceeding expectations already. Although the delivery and installation of the rough-in modular carriers has not started yet, there is reason to believe the team will continue to successfully meet the new challenges as they arise for the overall benefit of the project. We tried to investigate the improvement possibilities by applying lean approach defending the optimization of value stream in a manufacturing process. The case we have chosen is a an example of a large scale hospital building construction in the context of California that can be taken as an example by worldwide construction professional building large scale facilities.

This case study is a clear example of what a single trade contractor can do to boost product modularity. The improvement suggestions studied for this case serve to the purpose to achieve standardized work for the future projects to come. As the off-site production observed is the very first attempt, neither we nor the host company had the previous project records to compare the work done. According to the company professionals, the man-hour estimates in the planning phase were made based on the similar type of work performed at site. They had foreseen six employees working for both St. Luke's Replacement and Van Ness and Geary Hospital projects but during the execution of the manufacturing the project team realized that three full time employees were sufficient to serve the project pace on site. Even this man-hour reduction alone proves the benefit of batching different construction project works together in a workshop. Moreover, the project team all agreed that hospital construction required far more sophisticated prefabrication operation than a typical project would normally do. Therefore, we believe that the current successful prefabrication operations can provide a standard to be improved for the future projects.

The improvement suggestions for the off-site manufacturing are parallel with the lean spirit of continuous improvement. Although, the suggestions are very much case specific and the starting point can generically be applied to other off-site manufacturing operations as well.

An overall analysis of the current value stream map shows three opportunities to improve. First, the case company could look to reduce inventory buffers and attempt to achieve more of a continuous flow. The current state map reveals that the process uses many inventory buffers (shown with a triangle). These inventory buffers act as a decoupling mechanism to separate tasks with different cycle times. Inventory is identified as one of the seven types of waste in a production system (Ohno 1988). While some decoupling buffers are necessary, future work could look to reduce inventory between tasks and achieve a more single-piece (e.g. continuous) flow (Viana et al. 2013). To exemplify, a typical inventory buffer between the production lines can be mentioned: When a batch of frames is done at Jig #1, they are stored out of the way in groups around ten to twenty as they await the availability of Jig #2. By setting activity at Jig #1 and Jig #2 to a similar takt time, frames could move directly from the Jig #1 station to the Jig #2 station (with a small inventory buffer of 1-3 frames in between). This would reduce the need for additional storage and the motion of carrying and stacking the frames after each batch.

Packages waiting in the inventory for the shipment to the site are again other great sources of the waste. It is very understandable that managers want to have a buffer between the site work and the workshop. However, missing communication and plan changes at the construction site cause the workshop to work with a greater contingency than required.

Second, the case company could use the success at workshop to cross-train others in the company. This includes management through the lean “go and see for yourself” philosophy and the workforce through the principle of creating challenging and meaningful work to develop the skills of all employees.

This would give management insights and vision should they want to replicate this operation for future projects. In addition, the workshop staff could seek opportunities to challenge their workforce through additional cross training of employees. The operations at the workshop are somewhat specialized at this point. By switching in additional employees or rotating the tasks for current workers, case company can continue to develop the skills of all employees. This would ensure that existing workers have challenging and meaningful work and that new workers have confidence in the tasks if the same prefabrication is attempted on future projects. Moreover, such a close relation between site and workshop management will increase the efficiency in communication and help to solve the extra inventory buffer problem described above.

Third, case company has the opportunity through BIM to standardize the design of future plumbing carriers so that many of the same jigs can be reused. While this may not always be within trade contractor’s control (for example, a project might employ a different MEP engineer who requires different details), it would be a great benefit to continue this prefabrication on future projects. Future BIM designs could use the existing jig setups. Furthermore, case company team have gained valuable insight into what type of fixture design is easy to assemble and which is more challenging. If this feedback can be communicated to the design team, future BIM designs could make assembly even more productive. This concept is referred to as design for manufacturing and assembly (DFMA) and could give case company the opportunity to leverage the gains at the workshop and increase productivity on the next project.

This will also allow for continuous improvement of the current process using DFMA principles. Furthermore, more reliable manufacturing and installation schedules will be planned based on the data from previously completed projects.

The three above mentioned improvements support each other. More efficient results can be achieved by the implementation of all of them simultaneously.

Finally, with the repetitive work and the production volume the productivity will increase and the improvements will become more visible. In order to make best use of the present modules created (jigs) for the manufacturing in the future, the design of the projects to come should be developed according to the design for manufacturing and assembly (DFMA) principles. The project team has already very valuable experience in different types of modules. Some modules are easier to adopt and to work with while some others are difficult and more time consuming. Why not to make the most favorite modules best practice for the next projects?

CONCLUSION

Our case study focusing on the prefabrication process of the mechanical works is a clear example of the achievements that can be made even as a single trade contractor in a large scale hospital construction. Moreover, contrary to the barriers mentioned in the literature the modules created during the prefabrication process do not require high volume production or high capital investments. Although, those modules are created to serve the current project design, they represent proven solution for the future projects to come.

Furthermore, an implementation of standard modules not only facilitates the manufacturing in a controlled off-site location and assembly on construction site but also help the design phase to be more consolidated. Moreover, the applied modules increase the cost and scheduling predictability both during the manufacturing and assembly.

Once the work is performed by implementation of standard modules reducing the product variety (Mohamad et al. 2013), the next level of improvements will be the main topic. We believe by standardization of the manufacturing operations a level of dexterity will be attained and improvements will require more radical changes such as involving other trades into the manufacturing operations.

The involvement of different trades in order to execute offsite production of modules has many product design and organizational challenges. Therefore, the early involvement of the pain and gain sharing philosophy of Integrated Form of Agreement (IFOA) will make the next level of modularization possible. Although, the observed projects are executed with IFOA, there is a missed opportunity to modularize the production units such as entire bathrooms or patient rooms requiring the cooperation of multi-trades. Observed off-site manufacturing case study can be baseline for future case studies in order to move from one-a-kind type of production to standard work. And then modules having multi-trade functions finally can be realized.

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Productivity in construction is a trend topic both in the academia and in the industry. The aim of this research is to enhance the conditions for improving productivity in the fragmented building industry, by exploring the repetitions occurring within and across projects.

The thesis advocates that modular thinking of products, processes and organisations can be reapplied on new building construction projects.The academic contribution of the thesis is the adoption of the complexity framework in the construction industry, specifically to inform the development of modularisation approaches.

The thesis includes a case study of hospital design and construction, highlighting missed opportunities for modularity and reuse across organisational boundaries. The application of a range of analysis tools, such as QCA, DSM and VSM, are presented to the question of modularisation opportunities and success factors in the construction industry.

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