Digitalization as Driver for Standardized Specification and Design of Buildings

- In Search of an Efficient Building Design Management Methodology

Niels Treldal

PhD Thesis

Department of Civil Engineering

2017

DTU Civil Engineering Report R-367
April 2017

DTU Civil Engineering
Department of Civil Engineering

Digitalization as Driver for Standardized Specification and Design of Buildings
In Search of an Efficient Building Design Management Methodology

Report: BYG R-367
2017

PhD Thesis
Niels Treldal

Cover photo: Figures and photos by author along with Ramboll BIM models
Published by: DTU, Department of Civil Engineering,
Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark
Request report from: www.byg.dtu.dk

ISBN 978-87-7877-461-3
ISSN: 1601-2917

This page is intentionally left blank.

Preface

This thesis is submitted to the Department of Civil Engineering at the Technical University of Denmark in partial fulfilment of the requirements for the degree of doctor of philosophy. The dissertation is paper-based and consists of the present thesis and six scientific papers prepared during the study.

The research was conducted as an Industrial PhD project[1] between September 2013 and April 2017 (including 6 month parental leave and work on other obligations). The principal supervisor was Head of Section and Associate Professor Jan Karlshøj, Department of Civil Engineering, DTU, and company supervisor was Senior Director Ronni Holm Dam, Buildings Unit, Rambøll Denmark A/S. It was a great pleasure to be able to combine the worlds of academia and business for the last three years, and I would like to thank all of my supervisors for their great enthusiasm and many hours of inspiring discussions. I would also like to specifically thank Senior Director Bjarne Rasmussen, Rambøll Denmark A/S, for taking ownership of my work and promoting implementation in the company.

As part of the research, I spent four months at the Centre for Integrated Facility Engineering (CIFE) at Stanford University under the supervision of Professor Martin Fischer. I would like to express my gratitude to Professor Fischer, his research unit and students at CIFE for a very inspiring stay.

The research was funded by Rambøll Denmark A/S and the Innovation Fund Denmark to whom I am grateful. The research would not have been possible without the help from my many skilful colleagues in Ramboll, and I would like to thank all who spend time on my research. From academia, I would like to express a special gratitude to the following former and current PhD students which I had the pleasure to co-author papers with: Ergo Pikas, Erik Falck Jørgensen and Thomas Fænø Mondrup. I also had several rewarding visits to universities around Europe, and I would like to thank all who was so kind to spend time on discussing my research.

Finally, but definitely not least, I would like to thank my family, friends, and colleagues for their support and patience during the last three and a half years. Most of all, I want to thank Marie, Laura, Clara and Sofie, my wonderful wife and daughters, for their endurance, support and love.

Copenhagen, April 2017

Niels Treldal

[1] 1 An Industrial PhD project is a three-year industrially focused PhD project in which the student is hired by a company while being enrolled at a university at the same time. For more information, see https://innovationsfonden.dk/en/application/erhvervsphd.

This page is intentionally left blank.

Foreword

Over the latest years, there has been a fast-paced development in the complexity of buildings driven by the desire for new and exciting architecture with more complicated geometry but also the need for more intelligent buildings with advanced mechanical and electrical installations. At the same time, the design process has been compressed and often the construction on site is started before the design is completed.

This development is increasing the need for good design and change management in order to have an efficient and errorless design process. Changes and decisions from clients or end users' often have large impact on the design and many interdependencies between disciplines makes it difficult to have the fully overview of the size of the impact.

With the intensive use of BIM in design, we now have better tools for more efficient production of models and drawings but also a good basis for the many simulations of daylight, energy etc. However, the building industry is still lacking behind other industries when it comes to efficient processes regarding information flow, interfaces and standardization of design data. This makes it very difficult to take fully advantage of automation.

The present PhD project's attempt to standardize design data and improving processes of design management is a vital and important step towards a better and more efficient design process that will provide major benefits to Ramboll and the building industry.

Therefore, the relevance of the project cannot be overestimated. Over the past three years, we have participated in a very exciting and challenging creation process and we have already seen positive results in our test projects. We are eager to implement the results and continue the development of this important area.

Ronni Holm Dam,

Senior Director in Buildings and company advisor

Rambøll Denmark A/S

This page is intentionally left blank.

Abstract

The architectural, engineering and construction industry is suffering from low productivity and the integration of project information, design solutions, design processes and project organization is believed to be a solution to produce high performing buildings more efficiently. Utilization of contractual frameworks to support such integration is still relatively new to the industry, but when successfully implemented it can foster collaboration and considerably increase possibilities for achieving project success related to buildings which are buildable, operable, usable, and sustainable. Digitalization is a driver in such a framework to support an efficient way of working, but multiple barriers exist for its expansion. This thesis focuses on solutions to improve digitalization and integration in the building design process.

The often unique, fragmented and interdependent nature of building design makes it difficult to adopt methodologies from other industries – such as manufacturing – where digitalization and integration seems better established. Solutions to integrate the different elements in building design processes into a coherent methodology are far less explored, and the goal of this research is, therefore, to increase the understanding of the relation between information needs, standardisation and efficient design management. The research draws on findings from previous research on information management, design management and socio-technical science and focuses in particular on an improved foundation for efficient planning and decision making processes.

The research concludes that high variability exists in current building design processes. This could be acceptable if the goal is to increase the understanding of the design problems to solve, but there is a risk that non-value adding design iterations will occur too frequently if the variability is not carefully managed. Building a strong community within the design team is found to be critical to reduce variability as it allows project managers to entrust the team to find solutions and coordinate activities more efficiently. Based on several case studies it is identified that applying an agile project management method adds a needed structure to the design development process and increase collaboration and shared understanding. Only when such applicable management practices are in place, digitalization can add proper value. For digitalization to add value, efficient information management is also found to be critical, which requires that information can be captured, structured and exchanges in a standardized way.

To achieve efficient standardization, proposals for modularisation and expansion of current industry information exchange standards were developed in the current research. An IDM package framework is proposed to make the current IDM methodology from buildingSMART more modular and easier to reuse and utilize on projects. A generic LOD framework is proposed to make the agreement on geometry information exchange more pragmatic. Furthermore, an expanded schema architecture is proposed for the BCF format from buildingSMART to support an increased use of process information exchange within task management. The proposals were evaluated in several different ways and found to match a range of industry needs, making the proposals of interest for further research and development.

Based on the findings, operational principles of how building design can be produced efficiently are described with specific considerations to information flow and value generation. The operational principles are, furthermore, combined with socio-technical and reflective theory to propose a methodology of how information in building design can be managed to also support a collaborative and learning building design process. A methodology is proposed and contains information models for the mission, function, product, and process (MFPP) for building projects to summarize the findings in this research in a combined contribution to further research and development. The methodology is a pragmatic approach to more extensive PLM systems used in the manufacturing industry and incorporates an agile design development process. The modular yet structured approach in the MFPP methodology allows for automation of information requirements, flow optimization and automatic identification of relations between information models, which is believed to lower the barriers for implementation of digitalization and integration in the AEC industry.

The research makes use of a range of different theories and methods which have previously been evaluated individually in the AEC industry and found useful. Based on the findings in this thesis it seems clear that these theories and methods should not be considered as alternatives to each other but as elements in an integrated approach. A key challenge ahead for the AEC industry is to find ways to integrate these theories and methods as opposed to executing them in parallel and thereby not achieving the required level of improvement. The MFPP methodology can serve as contribution to how several perspectives can be integrated in a common approach for efficient building design management.

Danish Abstract

Byggesektoren lider af lav produktivitet, og integration af projektinformation, designløsninger, projekteringsprocesser og projektorganisation anses for at være en løsning til mere effektivt at skabe højtydende bygninger. Brug af aftalemæssige rammevilkår til at understøtte en sådan integration er stadig forholdsvis nyt i byggesektoren, men når sådanne rammevilkår indføres korrekt, kan det fremme samarbejde og øge mulighederne for at opnå succes på projekter ved at skabe bygninger, der er bygbare, driftsbare, bæredygtige og funktionelle. Digitalisering er en forudsætning i en sådan omstilling for at understøtte en effektiv måde at arbejde på, men der eksisterer en række barrierer for en sådan implementering. Denne afhandling fokuserer derfor på løsninger til forbedring af digitalisering og integration i projekteringsprocessen af byggeri.

Byggeprojekter er karakteriseret ved ofte at være unikke, fragmenterede og med mange indbyrdes afhængigheder, hvilket gør det vanskeligt at anvende metoder fra andre industrier - såsom produktionsindustrien - hvor digitalisering og integration synes bedre implementeret. Løsninger til at integrere de forskellige elementer i en sammenhængende metode inden for projektering af byggeri er langt mindre udforsket, og målet med denne afhandling er derfor at øge forståelsen for sammenhængen mellem informationsbehov, standardisering og effektiv styring af projekteringsforløbet. Projektet bygger på resultater fra tidligere forskning inden for informationshåndtering, projekteringsledelse og socio-teknisk videnskab og fokuserer især på at skabe et bedre grundlag for effektive planlægnings- og beslutningsprocesser.

Projektet konkluderer, at der findes høj variabilitet i den nuværende projekteringsproces. Dette kunne være acceptabelt, hvis målet er at øge forståelsen af de projekteringsproblemer, der skal løses, men der er risiko for, at ikke-værdiskabende iterationer vil forekomme for ofte, hvis variabiliteten ikke håndteres omhyggeligt. At opbygge et stærkt fælleskab inden for projekteringsteamet viste sig at være afgørende for at reducere variabiliteten, da det tillader projektlederen at overlade det til teamet at finde løsninger og koordinere aktiviteter mere effektivt. På baggrund af flere casestudier er det fundet, at anvendelse af en agil projektledelsesmetode tilføjer manglende struktur i projekteringsproces samt øger samarbejdet og den fælles forståelse. Først når sådanne ledelsesmetoder er på plads, kan digitalisering tilføje reel værdi. I forbindelse med digitalisering er effektiv informationshåndtering også fundet afgørende, hvilket kræver, at informationer kan registreres, struktureres og udveksles på en standardiseret måde.

For at opnå en effektiv standardisering er der i denne afhandling udviklet forslag til modularisering og udvidelse af nuværende informationsudvekslingsstandarder til byggesektoren. En løsning med IDM-pakker foreslås for at gøre den nuværende IDM-metode fra buildingSMART mere modulær og dermed lettere at genanvende og anvende på projekter. En generel løsning for informationsniveauer foreslås for at gøre aftaler om geometrisk informationsudveksling mere pragmatisk. Desuden foreslås en udvidet arkitektur for BCF-formatet fra buildingSMART for at understøtte en øget anvendelse af informationsudveksling inden for opgavestyring. Forslagene er blevet evalueret på forskellig vis i afhandlingen og det kunne konstateres, at de matcher en række af byggesektorens behov, hvilket gør forslagene interessante i relation til videre forskning.

På baggrund af resultaterne beskrives principper for, hvordan projektering kan udføres mere effektivt med specifikt fokus på flow af information og generering af værdi. De operationelle principper er desuden kombineret med socio-teknisk og reflekterende teori for at foreslå en metode til, hvordan information i projektering kan håndteres for at understøtte en effektiv proces. En metodik indeholdende informationsmodeller for byggeprojekters mission, funktion, produkt og proces (MFPP) foreslås for at opsummere resultaterne i projektet i et fælles bidrag til videre forskning og udvikling. Metodikken er en pragmatisk tilgang til mere omfattende PLM-systemer, der anvendes i produktionsindustrien, og omfatter en fleksibel projekteringsproces. Den modulære, men også strukturerede tilgang i MFPP-metodikken giver mulighed for automatisering af krav til informationer, flowoptimering og automatisk identifikation af relationer mellem informationsmodeller. Dette vurderes at reducere barriererne for implementering af digitalisering of integration i byggesektoren.

Projektet gør brug af en række forskellige teorier og metoder, der tidligere er blevet evalueret individuelt i byggesektoren og fundet anvendelige. På baggrund af resultaterne i denne afhandling synes det klart, at disse teorier og metoder ikke bør betragtes som alternativer til hinanden, men som elementer i en integreret tilgang. En vigtig udfordring for byggesektoren er at finde måder at integrere disse teorier og metoder i modsætning til at udføre disse parallelt og derved ikke opnå det nødvendige forbedringspotentiale. MFPP-metodikken kan tjene som bidrag til, hvordan flere perspektiver kan integreres i en fælles tilgang til effektiv projekteringsledelse.

List of Abbreviations

AEC – Architecture, Engineering, and Construction

APM – Agile Project Management

BCF – BIM Collaboration Format

BIM – Building Information Modelling

CDM – Collaborative Design Management

DSR – Design Science Research

IDM – Information Delivery Manual

ICE – Integrated Concurrent Engineering

ICT – Information and Communication Technology

IFC – Industry Foundation Classes

IPD – Integrated Project Delivery

LOC – Level of Completeness

LOD – Level of Development

LOI – Level of Information

LOR – Level of Reliability

MVD – Model View Definition

MFPP – Mission, Function, Process and Product

PLM – Project Life-cycle Management

PPC – Percent Plan Complete

TFV – Transformation, Flow and Value

This page is intentionally left blank.

Content

List of Scientific Papers

Paper A - Introducing A New Framework for Using Generic Information Delivery Manuals
Thomas Fænø Mondrup, Niels Treldal, Jan Karlshøj, Flemming Vestergaard
Proceedings of 10th European Conferences On Product And Process Modeling In The Building Industry (ECPPM), Vienna, Austria, pg. 295-301, 2014

Paper B - Information Flow Management in Building Design based on IDM packages
Niels Treldal, Jan Karlshøj
Journal of Computing in Civil Engineering, 2017
In review

Paper C - Pragmatic Use of LOD – a Modular Approach
Niels Treldal, Flemming Vestergaard, Jan Karlshøj
Proceedings of 11h European Conferences On Product And Process Modeling In The Building Industry (ECPPM), Limassol, Cyprus, pg. 129-136, 2016

Paper D - Resource Utilization in Building Design: Reducing Variability
Erik Falck Jørgensen, Niels Treldal
Special issue of Construction Management and Economics, 2017
Shortpaper accepted – final paper in review

Paper E - Agile Approach to Building Design Management
Niels Treldal, Jan Karlshøj
Journal of Construction Engineering and Management, 2017
In review

Paper F - Using BCF as a Mediator for Task Management in Building Design
Niels Treldal, Hussain Parsianfar, Jan Karlshøj
Proceedings of International RILEM Conference on Materials, Systems and Structures in Civil Engineering, Kgs. Lyngby, Denmark, pg. 48-59, 2016

This page is intentionally left blank.

Structure of the Thesis

This thesis is divided into four parts and six scientific papers. The four parts introduce the practical and theoretical point of departure, describe the research design, summarize the scientific papers, and finalize by discussions, conclusions and evaluation of the entire dissertation. The research questions are answered based on findings described in details in the scientific papers. Together, the four parts and the scientific papers constitute this PhD thesis. The overall structure is as follows:

Part I – Practical Point of Departure
The first part introduces the topic, describe the problems observed in practice, and the context of these problems in an industry facing considerable barriers to improve digitalization and integration within the design processes. This part also describes what needs to be improved to achieve successful projects, and the perspectives for the industry if barriers are reduced. The research scope is defined which leads to the selection of literature to explore in the next part.

Part II – Theoretical Point of Departure
The second part places this thesis in the context of the body of knowledge. Focus on information and knowledge management, socio-technical implications and design management is selected to frame the research in its search for an efficient building design management methodology. The review of literature is balanced between two views on design: related to either efficiency of information exchanging, or the social and cultural views on developing common understanding and learning. This section is concluded by summarizing the findings in literature in a combined theoretical information model for building design.

Part III – Research Design and Findings
Based on the practical and theoretical point of departure, research questions are formulated in the third section, which motivate this research. The selected research methodology is accounted for and key findings from each of the six scientific papers are described. Along with findings, the research method in each paper is discussed and an evaluation of the research quality of findings is included. This evaluation is used to justify the conclusions made in the final section.

Part IV – Discussion and Conclusion
The final part starts by summarizing the findings in the scientific papers in a proposed methodology for building design. Based on this methodology and additional findings, research questions are answered. The relation to practice is of great importance to this research, and for this reason the usefulness of the results is evaluated. The contributions to the knowledge base are listed, and the predicted barriers and impacts on practice are described. Finally, suggestions for further research are provided.

This page is intentionally left blank.

Part I – Practical Point of Departure

1 Introduction

‘We have a well-functioning common data environment, but it is not a living collaboration platform. It also does not manage all the flows of information, but how to make the cut between what information to put where? I think we are in some sort of idle position, waiting for new people and new technology.’

[Project Manager ‘Ellinor’ interviewed for Paper D]

Ever since the Danish government initiative ‘Det Digitale Byggeri’ [Digital Construction] was initiated in 2003, digitalization has been a key driver for change in Ramboll in Denmark and in the architecture, engineering, and construction (AEC) industry in general. The design of a Concert and Conference Centre in Reykjavik, Iceland, and Ramboll’s own Head Office in Copenhagen started soon after and were some of the first buildings being designed in full 3D in Denmark. Ramboll provided all engineering services in both projects and the degree of innovation happening was very high in the following years. Similar development has been experienced in the other Scandinavian countries, in the US and UK along with many other countries, and the key digitalization driver has been the process of using object-oriented 3D models, most often described as Building Information Modeling (BIM), along with other information and communication technologies (ICT).

The expectations for what BIM can do to the industry were and are still very high and have often been described as a paradigm shift for the entire AEC industry (Anumba et al. 2007). The digitalization of e.g. the car, airplane and banking industry has been a source of inspiration of how fundamentally also the AEC industry can be changed to the better. This radical change in the AEC industry is, however, still to come. The productivity in the industry is in general just as low as it was 20 years ago, paper is still a key source for communication in most construction sites, and the utilization of data in information systems to provide better value to projects is moving slowly. Many exciting innovative initiatives continue to come forward, but the pace of development and adoption is much slower than what many, including this author, had hoped for.

The idle position referred to by the project manager in the statement above essentially seems to have lasted for too long. Five years ago, this author was in a meeting with a leading thermal simulation tool vendor discussing possible improvements to reuse data from the BIM models in this simulation tool. The response to our request was:

> ‘If you can tell us what object attributes (properties) we need to look for in the BIM model – and promise us that our other clients will ask for the same attributes – we will be happy to include these in our next BIM interface release.’
>
> [Director, leading thermal simulation tool vendor]

A quick query around the office indicated that no one were able to provide a consistent list and five years later, still only limited support for import of attributes in the this software is implemented. It seems as the rest of the industry is similar challenged and points to the observation this author has made over the years of a ‘chicken or the egg’ challenge for improving digitalization. No one seems clearly interested in defining unambiguous information needs if no software can support the exchange of information anyway, and software vendors seem reluctant in implementing requirements which are not widely accepted by their users.

At least in Ramboll, it seems quite clear that the right tools are available to support the range of services requested by clients in relation to advanced simulations, life-cycle assessments, visualizations etc. The tools are there, but to integrate and utilize them intensively is more costly than what clients are willing to pay because of too much work in collecting and modifying the information required for each tool to provide valid results.

Based on these observations, the motivation for this thesis was to identify how utilization of digital information can be increased to further boost the digital transformation of the AEC industry. Standardisation seemed as a key solution to this quest. Three years later, this author also learned that careful consideration to the context in which information is used plays a highly important role if digitalization is to improve productivity and likelihood of project success.

1.1 Current State of the AEC Industry

The productivity has for decades remained low in the global AEC industry when compared to the general economy and the manufacturing industry in particular. The productivity in the manufacturing industry has almost doubled in the last 20 years whereas productivity in the construction industry has experienced less than a 20 % improvement (Barbosa et al. 2017). The total economy (data included 96% of the global GDP) has experienced an average annual growth rate of 2,7 % per year compared to 1 % in the AEC industry. The study by Barbosa et al. concludes that if the AEC industry could catch up with the rest of the economy, a potential of $1.6 trillion a year could be saved. Barbosa et al. identifies seven areas where the AEC industry needs to improve to catch up with the development. Reaching parallel conclusions on low productivity, Teicholz (2013) identifies four similar areas requiring improvements to increase productivity. In table Table 1, the identified areas are listed and similar areas are aligned. The focus areas of this thesis are highlighted in bold.

Table 1. Areas identified which needs to improve to increase productivity in the AEC industry.

No.	(Barbosa et al. 2017)	(Teicholz 2013)
1.	Reshape regulation and raise transparency	
2.	Rewire the contractual framework	Better Use of IPD framework
3.	**Rethink design and engineering processes**	**An improved Business Model that Supports Owner Life-Cycle Requirements**
4.	Improve procurement and supply-chain management	
5.	Improve on-site execution	Greater Use of Off-Site Fabrication and Modular Construction
6.	**Infuse digital technology**, new materials, and advanced automation	**Better Use of Data with BIM**
7.	Reskill the workforce	

In general, areas for improvements can be grouped into design processes, construction processes, digitalization, workforce competences and framework conditions such as regulation, contracts and supply-chain management. While the remaining areas are acknowledged, this thesis focuses on how to improve design processes and digitalization.

1.1.1 Fragmented, Unique and Complex

The reasons for the low productivity are multiplex, but in relation to design processes and digitalization three challenging characteristics of the AEC industry are identified. Firstly, the AEC industry is highly fragmented. Projects include architects, engineers and contractors most often from different companies, and in particular in construction the industry is split in multiple companies with more than 52 % of the total work completed globally being provided by companies providing only a single specialized trade (Barbosa et al. 2017). Due to competitive procurement strategies where the lowest offers are often selected in each case, the organisation in each project is likely to be unique, which significantly limits abilities for knowledge transfer from project to project. The fragmented industry is believed to be a key reason for slow utilization of ICT where ICT innovation most often rely on individual stakeholder benefits rather than project or industry-wide benefits (Eastman et al. 2002).

Secondly, the AEC industry is challenged by mostly producing unique 'one-off' facilities compared to mass production in manufacturing (Kamara et al. 2007). The optimization potential from repeatable operations is for this reason limited. Kamara et al. argue that the differences to manufacturing is mostly related to the product and that re-engineering of the processes in the AEC industry similar to what has increased productivity in manufacturing is still achievable.

Thirdly, the AEC industry is considered a complex system in relation to both the product, the processes and the organization (Bertelsen 2003a; Pikas et al. 2015). The design process are described as having a 'wicked nature' caused by the fact that there is often no optimal solution to the problems faced and, furthermore, preconditions are defined in parallel with the solutions (Bertelsen 2003b; Lawson 2005). Irrational behaviour must be expected from such complex systems and this makes the mapping and management of information flow more challenging than in other relatively stable and repetitive industries like manufacturing (Emmitt and Ruikar 2013). In such a fragmented and dynamic environment the integration and exchange of information between information systems is crucial for efficient management of design process (Soibelman and Kim 2002). The AEC industry is for this reason facing considerable barriers because the abilities for improvement requires extensive efforts that are to be invested in unique and temporal organisations which reduce motivation.

1.1.2 Siloed Knowledge and Information in Design

For a 55.000 m2 science park in Copenhagen, the Niels Bohr Building, currently being constructed with Ramboll as lead designer, the aggregated BIM model contains more than 510.000 objects. Beside geometry definitions, each object includes an average of around 10 attributes of relevance to the design, resulting in approximately 5 million design attributes which needs to be managed. The BIM model is illustrated in Figure 1 and has been widely used for design coordination, visualisations, drawing production and quantity take-offs for various purposes. The way attributes are organised does not follow any particular structure and are defined by disciplines individually. Only a high-level object type classification structure according to Danish standards is used.

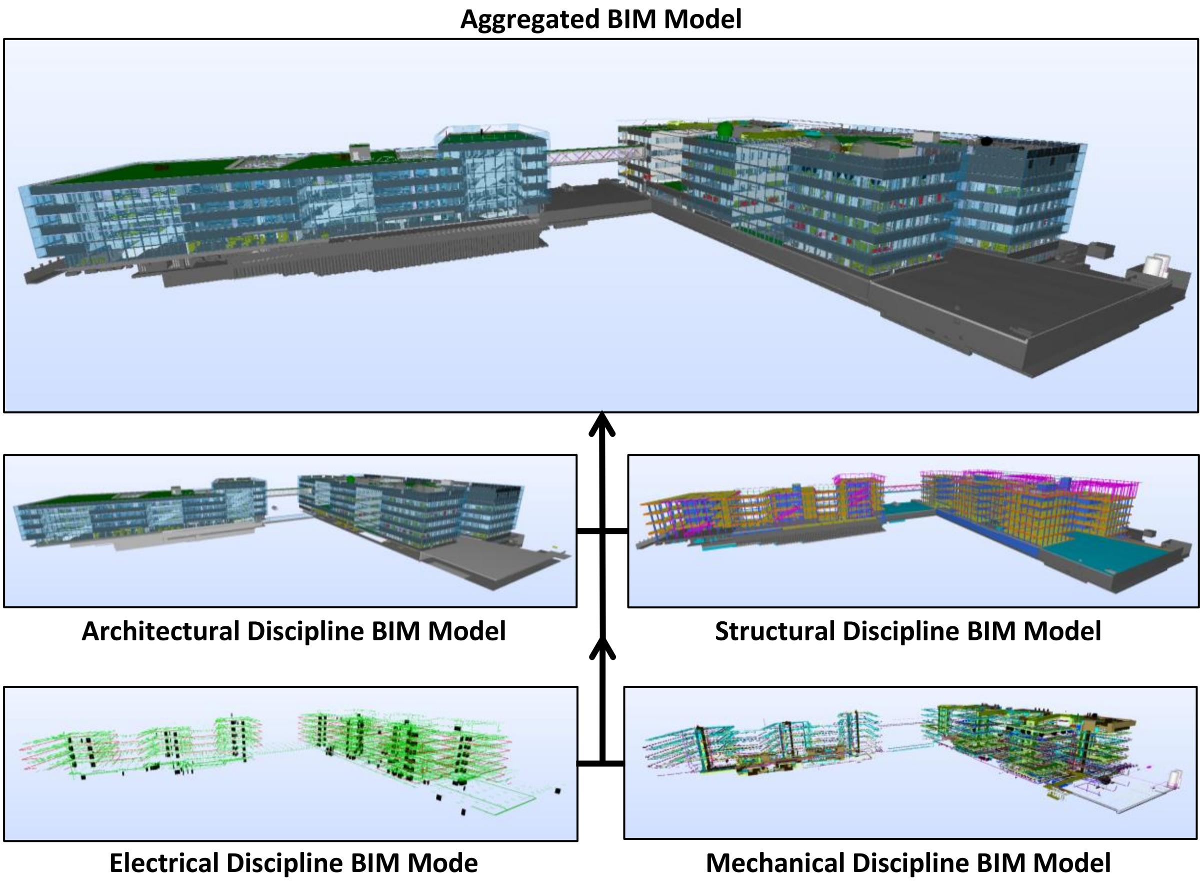


Figure 1. BIM model of the Niels Bohr Building designed by Ramboll, Vilhelm Lauritzen, Christensen & Co, GHB and Colin Gordon & Associates

The e-mail archive in this project contains more than 41.000 inbound emails and 82.000 outbound emails. The project has 108 internal design meeting memos and 125 client meeting memos with typically 10-20 follow-up actions plus at least a similar amount of decisions taken within each meeting. This adds to 4.500-9.000 project-related tasks and decisions which need to be managed on top of the numerous amounts of tasks and decisions defined in e-mails. The project folder for the engineering work of the project contains 2.900 Excel sheets and 4.300 Word documents and a range of schedules in MS Project. The client brief (Universitets- og Bygningsstyrelsen 2010) was a 96 page document plus 24 appendixes including a range of requirements for both the project mission and vision; functional requirements such as energy and space requirements; product specific requirements such as specific materials for components; requirements for work processes in relation to e.g. energy calculations; and requirements for the procurement strategy in relation to construction. Several client consultants were responsible for ensuring that all these requirements were appropriate and monitored that these were sufficiently met in the design proposals, however, no structured link between the range of requirements and the design was created. As the design progressed, several changes were introduced in the project, e.g. from considerable changes in user needs (Andersen 2017) and the brief documents were for this reason not an accurate description of the final building. Such a project is always a remarkable accomplishment, but from an information management point of view there seems to be nothing out of the ordinary in this project. This is the way information is captured and managed in most current design processes. Sometimes a database is used to capture user requirements as opposed to using Excel sheets and a quantity database is sometimes used to manage quantities for tender, but in general information is what Yalcinkaya and Singh (2016) describe as 'siloed' because information is unstructured and scattered in many platforms with limited interaction between them. With such amounts of information to manage, previous studies have indicated that the design teams spend up to 40 % of their time searching for information (Gallaher et al. 2004). Yalcinkaya and Singh conclude that building design projects are challenged in managing knowledge – in particular the large range of tacit knowledge which is also essential for successful project – and information management processes are quite often ad-hoc at best.

In manufacturing, such amounts of information would often be managed in a Project Life-cycle Management (PLM) system. The intention with a PLM system is to capture and manage product-related information within an enterprise also including functionalities for requirement management, data vaults for file access control, formal workflow support, and processes for executing engineering changes (Bruun et al. 2014). The unique and fragmented nature of AEC projects seems to be a key limitation in this regard, as such PLM systems will have to be set up individually for each project often making the effort far too costly. Yalcinkaya and Singh (2016) suggest to use linked-data technology to manage and link data to provide an improved insight to the required design knowledge in a more automated way. It is out of scope of this thesis to identify technologies to link information. Instead this thesis will focus on identifying what information needs to be captured in relation to how information can be applied to achieve successful projects in a more pragmatic way.

1.2 Evaluating Project Success

Evaluating whether a project is successful or not have long been acknowledged to have more implications than the traditional triple constraints of time, cost and quality as judgement from key stakeholders are as or even more important (Serrador and Turner 2005). There is also a time-dependency on project success: *'As time goes by, it matters less whether the project has met its resource constraints; in most cases, after about one year it is completely irrelevant. In contrast, after project completion, the second dimension, impact on the customer and customer satisfaction, becomes more relevant.'* (Shenhar et al. 1997 p. 12). Shenhar and Dvir (2007) propose five dimensions to base general project success on and define evaluation criteria as described in Table 2.

Table 2. Five dimensions of project success (Shenhar and Dvir 2007)

Success Dimension	Evaluation Criteria
Project efficiency	Meeting schedule goal Meeting budget goal
Team satisfaction	Team morale Skill development Team member growth Team member retention
Impact on the customer	Meeting functional performance Meeting technical specifications Fulfilling customer's needs Solving a customer's problem The customer is using the product Customer satisfaction
Business success	Commercial success Creating a large market share
Preparing for the future	Creating a new market Creating a new product line Developing a new technology

Project efficiency is one dimension, linked closely to productivity, whereas the other dimensions have a broader perspective on value generation.

Focusing on the AEC industry, generating value is ultimately to create high-performing buildings which achieve their purpose throughout their lifetime (Fischer et al. 2017). To do so, Fischer et al. define four criteria for success for such buildings: buildable, operable, usable, and sustainable. Buildable refers to how easy the building is to assemble. Operable means that the structural, mechanical, electrical, and other systems in the building work together and are easily maintained and fixed. Usable refers to whether the building supports the purpose of the people who work, live, or in other ways interrelate to activities within the building. Finally, sustainable refers to whether the building works in harmony with the natural, social, and economic context. Fischer et al. conclude that integration within design processes and the use of metric to continuously monitor and evaluate on stated performance criteria in all the four aspects above are of vital importance to ensure project success.

1.3 Improving BIM processes

By increasing the use of BIM processes more information could be captured within object-oriented BIM models and exchanged directly between object-oriented software to increase integration of knowledge (Eastman et al. 2011). BIM is a process to manage and facilitate the exchange of building information and can support collaboration and allow for automation of processes (Aram et al. 2010; Moon et al. 2015; Zhang and El-Gohary 2015). As such, design information structured using BIM methods constitutes an information system to support design and construction processes (Berard and Karlshoej 2012). The use of BIM has increased rapidly and the value achieved in areas such as visualization, reducing errors and improving collaboration is well documented (Malleson 2016; McGraw-Hill Construction 2014; Pikas et al. 2011). The current unstructured approach of managing information is, however, limiting abilities for achieving value generation from the use of information systems (Martínez-Rojas et al. 2015). To improve this, a need for further standardization of information is required (Malleson 2016).

To capture building related information, buildingSMART has developed the open model framework schema IFC, which allows for generating semantic rich data models specifically targeting the exchange of BIM related information (ISO 2013). Although interoperability issues related to software implementation of IFC import and export functionalities are still a barrier to seamless IFC exchange (Oh et al. 2015), the use of IFC has increased significantly in the industry along with the implementation of BIM (Malleson 2016). In order to add further structure to the information exchange, buildingSMART has also developed Information Delivery Manual (IDM) and Model View Definitions (MVD). IDM is a solution to capture the process model of selected use cases and generate information exchange requirements for the product model on this basis (ISO 2016). MVD allows for defining a data structure and the semantics required to exchange information using a specific data format in an unambiguous way (ISO 2016). To capture process related information, buildingSMART has, furthermore, adopted two additional open exchange standards. The first standard is called BCF and allows for task-related information and task linkage to IFC models to be captured in a standardized data structure (BuildingSMART 2016). The second standard is called IDM Part 2 and allows for defining and managing tasks in relation to contractual agreements with support for workflow specifications (ISO 2012a). Based on the range of open standards available it would seem that the basis to improve structuring of information in the AEC industry is in place. The use of open standards is of interest in this thesis because it allows for a consistent approach to information management throughout unique and fragmented AEC projects by limiting dependencies for requirements of particular software. For this reason, the above standards will form a basis for the research presented here.

1.4 Improving Design Processes

Integration within design processes is required to address many of the areas for improvement in Table 1 and Fischer et al. (2017) argue that the multi-party contractual arrangement in Integrated Project Delivery (IPD) is a highly successful approach to achieve this. Fischer et al. define a 'Magic Formula' of what it takes to operate within an IPD framework as shown in Table 3.

Table 3. The Magic Formula for integrated project delivery (Fischer et al. 2017)

Value Definition	Framework	Environment	Interactions	Network of Knowledge
• Enterprise Needs & Constraints • Stakeholder Values • Performance Goals • Objectives & Metrics	• Relational Contract • Delivery to Target Cost • Integrated Organization • Information Infrastructure	• Right People • Virtual World • Proximity • Transparency	• Quantity • Quality	• Connections Across Boundaries • Clarity of Customer Supplier Relationships

Increasing integration within design processes requires that values needs to be identified, managed and monitored; a framework which motivate for collaboration needs to be in place and the right team needs to be assembled, collaborate and sit closely together; intensive interaction needs to be promoted; and understanding of the network of knowledge needs to be in place. Only in doing so, Fisher et al. conclude that high performing buildings can be designed which are buildable, operable, usable, and sustainable. Other types of multi-party contractual arrangement exist such as partnering or project alliance, and they all share similar goals of motivating integration and collaboration (Lahdenperä 2012). In relation to building projects, Lahdenperä concludes that IPD is of interest as the sharing of risk is very explicit. Explicit sharing of risk is important in building projects as the value-chain is often complex and utilization of e.g. BIM often provide more value further down in the value-chain. Lahdenperä concludes, however, that differences between the contractual arrangement types are not that clear to describe because the development of each approach regularly adopts what seems successful in the other approaches.

Although it is difficult to separate a framework like IPD from design planning and management methodologies, it is argued here that within the framework of IPD different planning and management methodologies can be used. Multiple planning and management methodologies aiming at increasing intense collaboration has been proposed in recent years – most based on lean principles. As with the contractual frameworks, there are considerable overlaps in the development and implementation of planning and management methodologies as they also seem to continuously adopt what is successful in other methodologies. In Table 4, five selected methodologies are described which have been promoted to provide value in building design processes.

Table 4. List of selected planning and management methodologies suggested for building design

Methodology	Key Characteristics
Integrated Concurrent Engineering (ICE) (Fischer et al. 2017; Kunz 2013)	Using intensive and well-planned ICE sessions, design teams meet and rapidly develop incremental steps of the design. There is an emphasis on a well-integrated technical infrastructure, formal objective metrics and informal processes and culture.
Lean Design Management (El Reifi et al. 2013; El Reifi and Emmitt 2013; Tilley 2005)	Emphasis on reducing waste based on lean principles by focusing on briefing and client interaction, value and value stream mapping, lean culture, team assembling and information flow. Makes use of methods like the Last Planner System, Set-based Design, Target Value Design etc.
Collaborative Design Management (CDM) (Bølviken et al. 2010; Fundli and Drevland 2014)	Assumes design to consist of three elements and focus primarily on design production and decision-making processes, and only secondarily on the design creation process. Includes a variation of the Last Planner System focusing more on decision-making and design related constraints analysis.
Integrative Design (Reed 2009)	Promotes an incremental design process where far more analyses are completed in a collaborative manner in the beginning of design to ensure that the right solutions are selected. Emphasis on ensuring that no solutions are developed in silos.
Agile Project Management (APM) (Cobb 2011; Owen et al. 2006)	Focus on managing a changing environment by incremental design development rather than a plan-driven development and by promoting self-managed teams. By use of methods like Scrum, the approach is supplemented with tools to prioritize activities and monitor design development performance in a highly collaborative manner.

From the above table it is clear that the methodologies overlap and share conclusions that the building design process must be based on clear values definitions, develop incrementally, ensure efficient flow of information and avoid development in silos. This should be seen in contrast to the traditional waterfall design process, which is common today, and are aligned to the phase-model in design describing a step-wise design development approach starting with the brief and conceptual design and ending with a fully detailed and technical design. In complex and turbulent project environments, such as building design, such conventional planning principles based on a waterfall approach seems, however, more and more limited in their ability to achieve project success (Cobb 2011; Riedel et al. 2013). For this reason, the goal of this thesis is to explore how such new incremental planning and management methodologies can contribute to project success and in particular how information can be managed to support such methodologies by increased use of BIM and digitalization in general.

1.5 Perspectives

Although there has been an increase in the number of AEC projects that use multi-party contractual arrangement, it is still relatively modest compared to the more traditional approaches that rely on competitive tendering (Emmitt and Ruikar 2013). Based on 60 interviews with teams using IPD contracts, Cheng et al. (2016) identify a high degree of success in all analysed projects in relation to both time, cost and client satisfaction. Furthermore the study concludes that IPD contracts along with lean processes and tools seem to have the ability to foster collaboration as opposed to this happening more spontaneously in traditional projects. The study also finds that BIM, co-location, and lean tools are not the most essential elements to achieve project success. Instead monitoring and evaluation of metrics, project development, and commitment are essential along with a strong team oriented project culture.

This study is backed up by a more generic study of manufacturing companies concluding that the combination of new management procedures along with digitalization is of great interest as this is seen to increase productivity far beyond what digitalization can achieve alone (Appel et al. 2005). Based on an analysis of 100 manufacturing companies in Europa and the United States, Apple et al. concludes that single minded roll-out of new IT only increased productivity by an average of 2 % whereas a combination of new management practices and IT in general increased productivity with 20 % as shown in Figure 2.

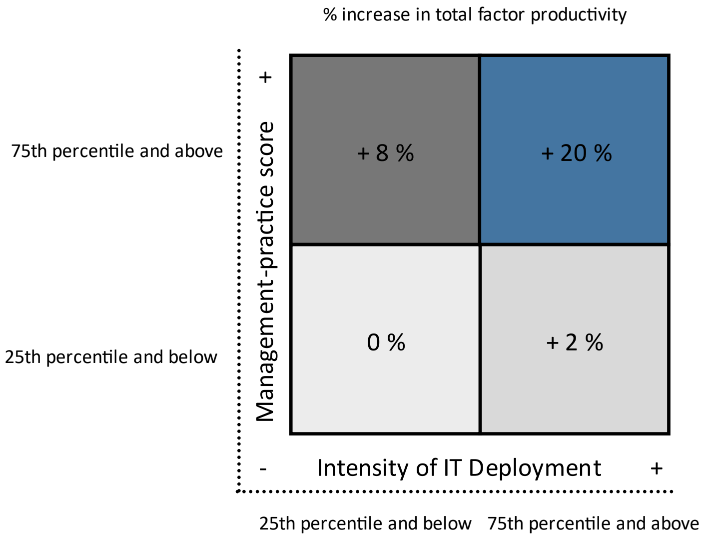


Figure 2. Increase in total factor productivity based on IT deployment and use of new management practices (Dorgan and Dowdy 2004)

Despite a well-documented potential, the AEC industry often find it difficult to implement ICT tools and related management methods (Miettinen and Paavola 2014). In addition to new contractual frameworks, there also seems to be a need to change tools and methods to make implementation simpler, more flexible and better match abilities to avoid silos in both knowledge management and design development.

2 Research Scope

The primary goal of this thesis is to explore ways to use digitalization to improve building design processes. The thesis focuses on improving both design processes and digitalization as they need to be viewed in relation to each other as described in the previous section.

Being one of the largest industries in the world, the AEC industry spans over a range of project types and services. The focus for the thesis is the design phase in the life-cycle of buildings. As processes in this phase are closely related to the previous brief phase and the subsequent construction phase, implications on these phases are considered as well as the remaining life-cycle. Furthermore, the thesis focuses primarily on the engineering design of building services although work in other disciplines are addressed in most scientific papers. The research scope is illustrated in Figure 3.

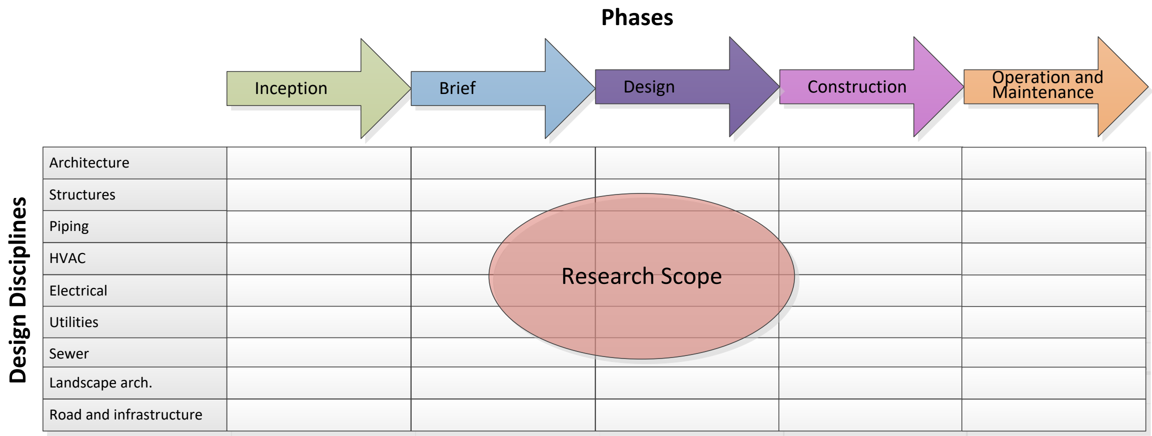


Figure 3. Research Scope in relation to AEC phases and design disciplines

The way, in particular, architects work can be somewhat different from building services design and Coates et al. (2010) indicates that architects could have more barriers to use BIM and lean tools compared to engineering disciplines. When analysing the design process, both views are addressed, but the research data collected is limited in relation to architectural design as compared to engineering design.

As described in the previous sections, the potentials of both multi-party contractual arrangement and BIM is well-established and it is not a goal of this research to assess the value potential of proposed solutions. Instead this thesis aims to identify barriers for digitalization related specifically to standardization and design management and propose solutions to remove these barriers. How individual design tasks are completed and the skills required to do so is of less interest to the research and instead focus is put on how to ensure that the right information is available when needed and as needed.

This page is intentionally left blank.

Part II – Theoretical Point of Departure

3 Theoretical Point of Departure

The previous section described the current state of the AEC industry and identified design processes and digitalization as some of the key areas for improvement. To improve design processes, increased integration and collaboration are identified as potential solutions. The development process, the organisation and the mind-set of the design team need to change in order to achieve such improvements. To increase the level of digitalization, there is a need to improve the structuring of information and the abilities to easily exchange information. The unique nature of AEC projects makes standardisation and methods for information management more difficult compared to other industries, and abilities to incorporate flexible and pragmatic approaches to information management is required. The need for intense interaction in design teams requires more skills from the team and increase pressure on their performance. If the improvement initiatives are to generate value within such integrated design teams, the socio-technical aspects is, therefore, also important in relation to how design teams interact with each other and the information available.

Pikas et al. (2016) find that two well established, but competing views on design collaboration exist. The first view is a constructivist approach which acknowledges design as a social process with dynamic intersection of social and cultural views for developing a common understanding (Bucciarelli 2003). The second view is related to communication theory originating from information theory and mathematics, focused on the efficiency of exchanging information and meaning between two points (Carlile 2004). As illustrated in the following sections, both views are required to achieve project success and the two views will for this reason need to be balanced when evaluating solutions.

Compared to project management, limited research exists specifically targeting design management in building design (Knotten et al. 2015) and Kroll and Koskela (2015) further argue that there is a general lack of theory on building design. For this reason, the following sections will identify relevant theories developed for the AEC industry and supplement these with theories from other domains to describe the topics addressed above. The theories addressed will focus on:

- Information and knowledge management - to understand what information is and how it can be structured, stored and exchanged efficiently.
- Socio-technical systems – to understand how social behaviour impacts interaction with technology and how integration of teams and knowledge can be achieved.
- Design management – to understand how processes and designers are to be managed to ensure that the right decisions are made at the right time and at the right cost.

This section will end by summarizing how the described theories can be used to sketch a framework for a potential methodology to support information structuring in design management. The theories will also be used to further justify the findings in the scientific papers included in this thesis.

4 Information and Knowledge Management

Achieving successful AEC projects is highly dependent on having access to the right information and having abilities to share the right information when required (Martínez-Rojas et al. 2015; Tribelsky and Sacks 2011). Information relevant when managing building design can be divided into product information and process information (Shafiq et al. 2013; Wang and Leite 2016). A product model and a process model can be used to capture and structure such information (Lee et al. 2007). A product model is defined as a standard medium for sharing and exchanging information electronically among heterogeneous systems and could be the BIM model. A process model describes how activities within a process are connected, ordered, and structured. Working with both product and process models requires a level of standardization in both concepts, routines, processes and data formats (Hooper 2015; Martínez-Rojas et al. 2015).

When considering information, six connected terms are often entangled with each other: data, information, knowledge, communication, knowledge base and document (Otter and Prins 2011). In Table 5, the different terms are described.

Table 5. Terms used in relation to information and their characteristics
– based on (Davenport 1997; Hjelseth 2015; Otter and Prins 2011)

Term	Key Characteristics
Data	Abstract, formal, sometimes symbolic entities like elementary facts, letters and binary numbers. Often quantified and easy to capture, structure and transfer using ICT.
Information	A string of data endowed with relevance and purpose. Human mediation is necessary and needs consensus on meaning. Requires ontologies to be captured, structured and transferred using ICT.
Knowledge	Specific data and information in the human mind related to intelligence, experience skills and attitude, which can be the subject of manipulation in terms of navigating, combining, reflecting, synthesizing or even redefining the meaning of data strings. Often tacit and difficult to capture, structure and transfer using ICT.
Communication	A process for exchange of information to equalize the information on both sides. Three steps are involved: 1) information gathering and transmission, 2) information receiving and interpreting and 3) information storage and retrieval. The meaning of the information can be distorted or partly lost during all these steps.
Knowledge base	Total collection of information, which exists within a person, organization or system. Can consist of tacit knowledge (implicit meaning and understanding) and/or explicit knowledge (formal structured knowledge).
Document	A collection of generated information, which is stored physically in some way and is able to be transferred as part of a communication process. A database can be considered as a special kind of digital document where data is placed in a formal structure. The structure allows for meaningfully retrieval and updating of data in a variety of ways.

From the descriptions it is clear that it is not data which is difficult to exchange; it is the meaning of data which is far more complicated to exchange. Ontologies can add meaning to data and turn this into information. The IFC and BCF standards from buildingSMART are examples of such ontologies adding meaning to product and process data respectively. The focus in the AEC industry has been primarily on standardization of product information and far less on process information which can add to make processes tedious and inefficient (Wang and Leite 2016). For this reason an equal balance on the two should be required.

4.1 Managing Product Information

For quite some time an idea existed in the AEC community that one common shared BIM data model should be generated in each project and used collaboratively for defining and sharing product information. This should be seen in contrast to the traditional point-to-point exchange of documents, which is believed to increase the complexity level for data retrieval, lead to poor interoperability between different management systems, and make information reuse harder (Martínez-Rojas et al. 2015). The AEC community has now learned that handling a totally shared data model is not the ideal solution either, because it becomes too complex if several participants working in different disciplines are to be involved. The asynchronous processes in design lead to insurmountable deadlock situations, which are limiting the overall process (Linhard and Steinmann 2014) and abilities to ensure consistent interoperability between software tools using IFC are still suffering which make round-tripping of IFC data error-prone (Oh et al. 2015). Some believe that using only one proprietary platform could solve interoperability issues, however, the span of activities to be supported in the AEC life-cycle does not exist in one platform, making such solutions less attractive for the industry (Berlo et al. 2012). Instead the idea of reference models are now used most commonly where each discipline share only an extraction of their individual discipline model, which can be combined into an aggregated model when needed as previously illustrated in Figure 1 (Section 1.1.2). Using such an approach with IFC has been found to create a stable and usable collaboration environment for the AEC industry when combined with smart process workflows (Berlo et al. 2012). Exchanging too much information can lead to lack of high value information, difficult decision-making, and limited opportunities to reuse design, and for this reason there is also a need to consider how the flow of information can be reduced to target actual information needs only (Tang et al. 2008). The three scenarios for information management and exchange are illustrated in Figure 4.

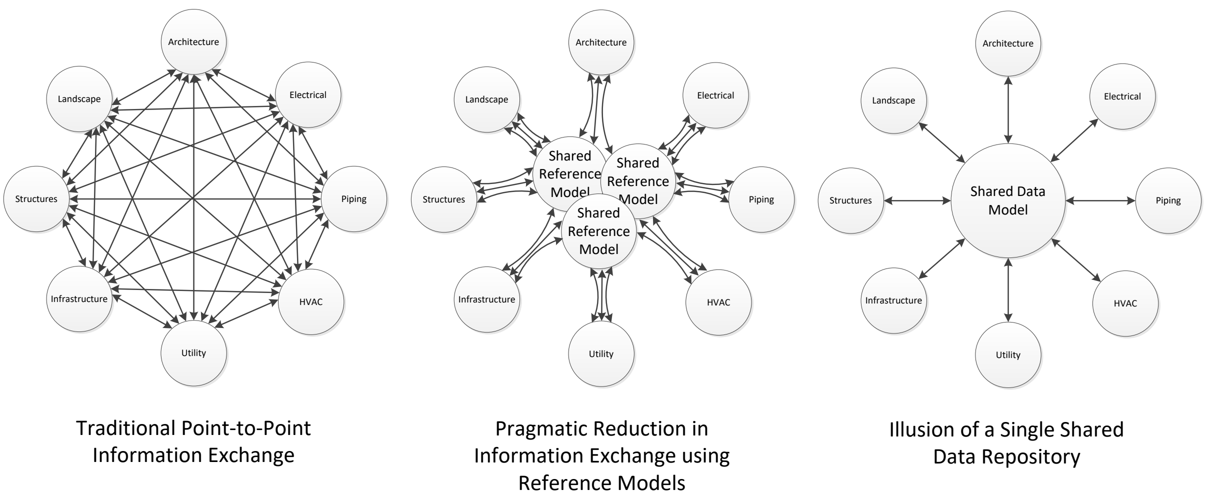


Figure 4. Three scenarios for information management and exchange - based on (Berlo 2015; Berlo et al. 2012)

Essential to the approach described by Berlo et al. (2012) & Berlo (2015) is a pragmatic and decentralised approach where data is exchanged via reference models using one or more data repositories (such as model servers) to tailor the flow of information as required. The approach is illustrated in Figure 4 (middle). Improved abilities to create links between the data repositories and the desired design software tools and abilities to easily and unambiguous ensure that the right information is available when needed are, however, still remaining issues (Berlo 2015; Berlo et al. 2012).

Based on information theory, Lee et al. (2007) develop a range of process semantic and syntactic rules for information flow modelling to define the required information content for a product model based on a process model hereby linking product information requirements to design processes. Using such information flow logics can be used to integrate the development of IDM and MVD requirements with design processes, improving abilities to define unambiguous information exchange requirements (Lee et al. 2013).

4.2 Managing Process Information

As noted in the beginning of this chapter, abilities in the AEC industry to properly manage process information are far less elaborated than abilities to manage product information. Hartmann et al. (2009) concludes that it is a key barrier to the development of information systems if the duality of product and process management is not addressed equally. Several open BCF platforms have been proposed to link the product model with process information primarily focusing on design coordination issues to improve abilities to monitor coordination performance (Berlo and Krijnen 2014; Linhard and Steinmann 2014). Essentially they consist of an open database with linkage to a model server and are as such a repository for design tasks. Numerous commercial platforms have also been introduced with similar purposes, but they all share a relatively narrow focus on design coordination and limited abilities to relate tasks to design processes in general. The PLM systems used in manufacturing include far more capabilities to capture and link design process information to the development of the product. Capturing and structuring process information allow other industries to support the management of the overall product development processes much more efficiently (Hartmann et al. 2009) and should be of inspiration to the AEC industry.

The fragmented nature of AEC projects can be a barrier in sharing process information as some information will be considered commercially sensitive, which individual firms might not want to share with collaborators. A more decentralized approach to manage process information is for this reason proposed by Berlo and Krijnen (2014), as it will allow stakeholders to isolate internal communication and only share what is considered to add value to the collaborative development process. The idea of decentralised information repositories is similar to the proposal for management of product information as described in the previous section, and the combined information system for building design, therefore, seems complex in its structure.

The unique nature of building design projects, furthermore, makes it complicated to create stable information systems which can support such shifting needs, and for this reason Hartmann et al.

(2009) propose an ethnographic–action research cycle for the development of information systems in AEC projects. The essential idea is to tailor information systems to observed challenges in each project which calls for a modular approach in the development of such information systems. The need for a framework to base such development upon seems important as the efforts to define and build such information systems for individual AEC project are otherwise far too comprehensive.

4.3 Collaboration and Knowledge Management

Sharing information is often not sufficient to ensure project success in design projects. Instead knowledge creation and integration should be the goal in a collaborative design process. If actors are not able to create and integrate knowledge, they will not achieve a common understanding of the problems at hand and thereby not be able to achieve desired design results (Kleinsmann and Valkenburg 2008).

The decomposition of work in AEC projects into distinct disciplines helps reduce product complexity and exploit opportunities for parallel execution, however, one vital problem of decomposing the design process is that knowledge is scattered within sub-teams and knowledge management becomes more complex (Yassine and Braha 2003). Each discipline team operate within their own object world with different paradigms, languages and activity systems which require design team members to share knowledge with other sub-teams (Bucciarelli 2003). Various techniques and technologies for knowledge capturing exist, but the considerable range of tacit knowledge in the AEC industry along with the temporal nature of each project complicates and reduces the incentives for structured knowledge capturing. Yalcinkaya and Singh (2016) points to systems based on the theory of transactive memory system by (Wegner 1987) to capture, support and visualise the knowledge network. Transactive memory is meta-knowledge of the memory structure in an organization or group (Wegner 1987). It can also be defined as the group's shared awareness of who knows what, which is based on attributions of responsibility, skills, and/or expertise in different domains (Wegner et al. 1991). Yalcinkaya and Singh (2016) point to the need for linking knowledge matrixes to the organisation, process and product information to create such systems for the AEC industry. So far this is still in development.

Despite efforts like Yalcinkaya and Singh, there is a long standing challenge of technology being difficult for leveraging knowledge in design teams (McDermott 1999). All teams need to build a relationship – often through face-to-face meetings – before they can effectively collaborate electronically: *'If a group of people don't already share knowledge, don't already have plenty of contact, don't already understand what insights and information will be useful to each other, information technology is not likely to create it'* (McDermott 1999). McDermott concludes that most knowledge management efforts treat these cultural issues as secondary implementation issues and instead focus too much on the information systems and what information to capture. Pemberton-Billing et al. (2003) also conclude that in projects where knowledge is lacking in the beginning, face-to-face communication is essential until a strong community is created based on common understanding.

Essentially, intense collaboration is needed to share knowledge and reach common ground in design projects (Koskela et al. 2016) and instead of the fundamental strategy of decomposing a project into smaller parts, a switch to the fundamental strategy of integration should be made (Fischer et al. 2012). This emphasises findings in previous studies that technology implementation in the AEC industry should be split, addressing people and process issues over technology (Dave et al. 2008).

To improve information and knowledge integration when implementing new technologies such as BIM, there has to be a balance between how people skills, processes and technology are aligned as illustrated in Figure 5. If innovations happen too fast in one area, adoption of technology may not produce desirable outcomes which can instead be a setback for innovation and limit knowledge integration and collaboration (Gu et al. 2014).

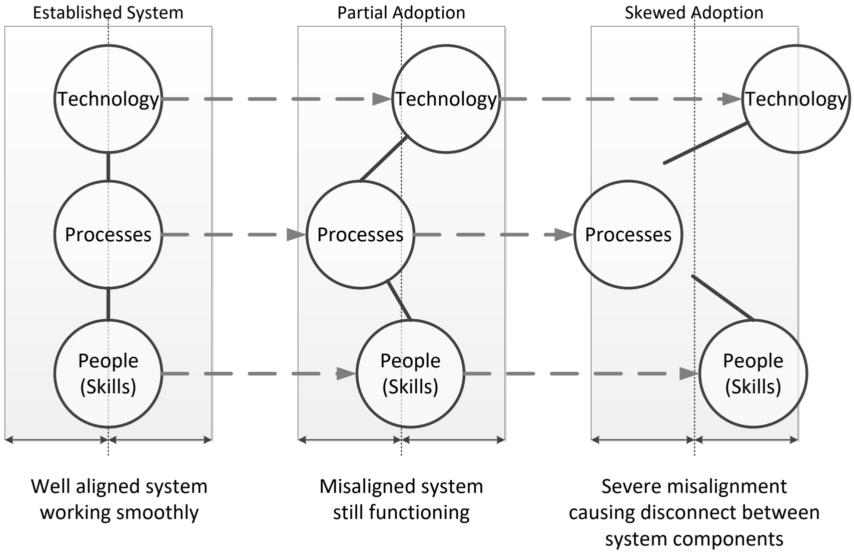


Figure 5. Potential co-evolution stages across technology, processes, and people in a BIM ecosystem (Gu et al. 2014)

Gu et al. develop a BIM ecosystem framework to identify business needs before defining technical requirements for the implementation of new BIM technology. This again leads to modular requirements for the ICT tools to be implemented because the information system needs to be tailored to each project.

Similar conclusions are reached by Miettinen & Paavola (2014) who argue, however, that two separate views on technology implementation – in particular in relation to BIM – is required:

- A normative framework – as proposed by Gu et al. which relies on guidelines defining the best or mature state of technology development as well as training and descriptions of BIM use cases in which savings, efficiency and rewards have been achieved.
- An activity theoretical approach – which regards the technology implementation as an open-ended process directed by ideals of integration with no well-defined final stage. It is an expansive learning process which can be adopted and further developed in other organizations and contexts sharing similar challenges if well-documented.

In the activity theoretical approach, the social context needs to be carefully identified and understood for successful implementation to be achievable. For this reason, the next section will describe such social implications.

5 Socio-technical Implications

An information system where technology interacts with people is referred to as a socio-technical system. Design information structured using BIM methods constitute an information system (Berard 2012) and for this reason, research on BIM should acknowledge both technology and the social situation within which the technology is placed.

Design teams can interact using coordination, cooperation or collaboration. The three levels of interactions are summarised by Pikas et al. (2016) as:

- Cooperation – an activity by which individuals, groups, and organizations come together, interact and form relationships for the mutual gain and benefit. Mission and goals of the different organizations are not aligned. Control is centralized, but interaction and information sharing only happens on an ad-hoc basis and authority and resources rest within individual organizations.
- Coordination – an activity to more specifically manage dependencies among tasks and/or resources and a more formal focus than cooperation on the alignment of goals, resources, and rewards along with sharing of some risks, control, and leadership.
- Collaboration – an activity where common goals and interests are developed and authority, responsibility, risks, control, leadership, resources, and rewards are shared.

Collaboration is required to increase project success within building design projects and there is a need to change the social context in which design teams are organised to a more integrated approach to achieve this (cf. Section 1.4). Team formation and performance can be viewed within the practice theoretical framework (Nicolini 2012). Within this framework, two distinct concepts for shaping of groups and human activities and interaction are described as either a *communities of practice* (Lave and Wenger 1991; Wenger 1998) or a *network of practice* (Brown and Duguid 1991). A community of practice is a group of people who share a common practice or interest whereas a network of practice is a group of people who have a common goal, but do not share the same interdependence of a common practice. Comparing to the above descriptions for design team interaction, it would seem that coordination is the expected form of interaction in a network of practice whereas collaboration is more likely to be achieved in a communities of practice.

A design team is normally not considered as a community of practice as legitimation is drawn from the formal hierarchy imposed by some form of management (Pemberton-Billing et al. 2003). In a community of practice legitimation is more informal as members have to earn their status in the community which comes from their contributions. Pemberton-Billing et al. finds that it is possible for a team to evolve into a community of practice, but such a community cannot be simply imposed on a group. Only through individual trajectories, communities can be shaped to provide a position for each individual through legitimacy (Wenger 1998). This is likely why many design teams today only achieve coordinating interaction between design disciplines while essentially desiring a more collaborative interaction. Each design discipline naturally belongs in individual communities of practice, but it is far more difficult to create an ‘intermediate’ community of practice consisting of different disciplines unless shared goals and values can be embodied in the actions by each team member.

5.1 Boundaries and Objects

To describe how different communities interact, the idea of boundaries and objects were introduced which can engage in a boundary infrastructure linking different communities together (Star 2010; Star and Griesemer 1989; Star and Ruhleder 1996). Carlile (2004) proposed three categories for sharing and assessing knowledge across boundaries:

- Syntactic – Differences and dependencies between actors are known. A common lexicon (syntax) is developed that is sufficient to share and assess knowledge at a boundary.
- Semantic – Novelty generates some differences and dependencies that are unclear - different interpretations exist. Common meanings are developed to create shared understanding and provide an adequate means of sharing and assessing knowledge at a boundary.
- Pragmatic – Novelty generates different interests between actors that impede their ability to share and assess knowledge. Common interests are developed to transform knowledge and provide an adequate means of sharing and assessing knowledge at a boundary.

From the above description, it can be concluded that engagement in a collaborative interaction is an ability to achieve pragmatic knowledge sharing whereas interaction based on coordination is likely to only achieve a semantic level of knowledge sharing. Wenger (1998) introduce boundary objects as artefacts, documents, terms, concepts, and other forms of reification around which communities of practice can organize their interconnections. Boundary objects are not intended to form consensus, but in a boundary infrastructure some boundary objects will form more mutually dependent relationship than others (Star 2010). Knorr Cetina (2001) introduce epistemic objects as another type of mediating object of knowledge with an open structure as this ensures the necessity of mutual commitment and shared understanding in an epistemic culture. Objects becomes epistemic when they embody what one does not yet know and they create social bonds either because their complexity requires joining forces or because the drive and desire toward the same object constitutes the basis for mutual recognition and sense of belonging (Nicolini et al. 2012).

Nicolini et al. (2012) describe how objects may serve different objectives in different phases of the life cycle. Boundary objects can be used to transfer knowledge in a syntactic or semantic way. They may in this state serve a purpose if interfaces between communities are well-defined and leave limited need for interpretation. However, as a starting point they will not motivate collaboration. The open structure of epistemic objects will require a dense and more mutually committed collaboration in communities, but such object will also allow for transfer of knowledge in a pragmatic way where shared understanding of a complex problem is required.

5.2 Implications for the AEC Industry

What should be required in complex AEC projects is for this reason an intermediate community of practice where knowledge is shared via epistemic objects. Only then it seems possible to achieve efficient collaboration. In a traditional design team organized in a network of practice, disciplines will be coordinating via boundary objects limiting abilities to reach a shared understanding. Some external stakeholders such as clients or authorities might not need to be involved in the intermediate community and could interact with the design team via boundary objects. However, difficulties for e.g. clients to formulate well-defined problems require close interaction to achieve shared understanding (Pemberton-Billing et al. 2003) and in such cases it should be considered if the client needs to be part of the community as well. The desire for a community of practice as opposed to a network of practice is illustrated in Figure 6.

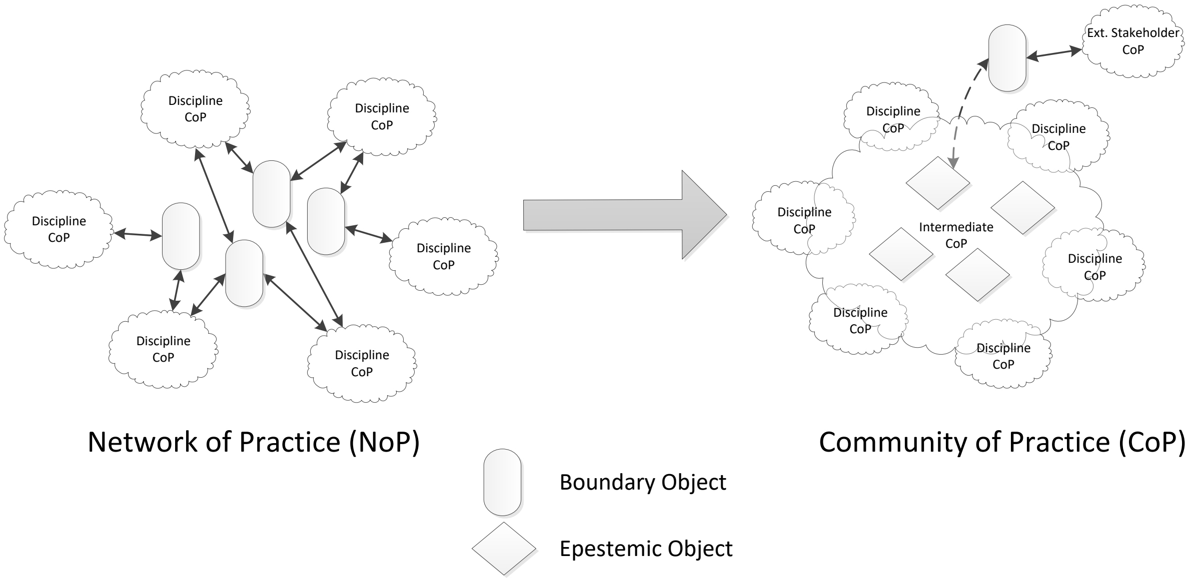


Figure 6. Interaction via mediating objects in networks and communities of practice

The above conclusion is of interest also in relation to the utilization of BIM processes. Kerosuo et al. (2015) identify in several case studies that design teams find it difficult to make good use of the integrated or aggregated BIM model. The process of solving design coordination issues retrospectively after first creating individual discipline models does not seem to match the needs of the design teams. Such discipline models could be considered as boundary objects and the aggregated BIM model should then somehow convert to an epistemic object and allow for collaboration. According to the theories above, this is highly unlikely to happen. Kerosuo et al. (2015) conclude that the understanding of well-bounded and defined entities between design disciplines is challenging to describe useful interaction in BIM processes. Instead it would seem that each discipline model should be developed jointly in an intermediate community as epistemic objects from the outset. In this case the aggregated BIM model should act purely as a platform for discussion in an integrated and collaborative environment.

6 Design Management

Design management is the convergence of two cultures: the culture of design and the culture of management. Once design is understood, one is better able to manage the design process and the designers (Emmitt and Ruikar 2013). Parallel to the two competing views of collaboration (cf. Section 3), two different schools of thought exist in understanding what design is. Emmitt and Ruikar (2013) describe the two schools of design based on original definitions by (Schön 1983) and his reflective theory:

- A rational activity – Assuming that work in design can be approached as a rational, systematic, problem-solving activity and in some cases an information processing activity.
- An interactive inquiry – The second school of thought is that design is a creative, artistic and interactive inquiry, strongly grounded in social, cultural and psychological thinking – referred to by Schön as the *reflective practitioner*.

Emmitt and Ruikar argue that the rational activity view is over simplistic or 'technocratic' as it does not reflect the reality of how designers behave and makes very little attempt to recognise the 'messiness' of a highly creative and complex environment. On the other hand Emmitt and Ruikar acknowledge that viewing design as a purely interactive inquiry can make the design process appear to be rather chaotic and muddled and hence difficult to comprehend and manage.
To be able to operate in this design environment, Emmitt and Ruikar conclude that most AEC designers acknowledge the need for some structure – e.g. concur to the phase-model in current practice – however, such structure is often considered a guideline more than a precise framework to follow.

Acknowledging the above, design management can be considered as the task of managing information handling between participants in a design team (Otter and Prins 2011). Bølviken et al. (2010) furthermore describes that a key difference between manufacturing and design is that where completion of manufacturing processes requires physical actions, design tasks and processes are completed by means of decisions. For this reason, the primary concern within design management should be to ensuring that the right information is available to the design team when needed to make the best possible decisions.

6.1 Decision Making in Design

To make the best possible decisions requires a proper understanding of the design problem to solve (Lawson 2005). Rowe (1987) describe three different types of design problems which are elaborated by (Emmitt and Ruikar 2013):

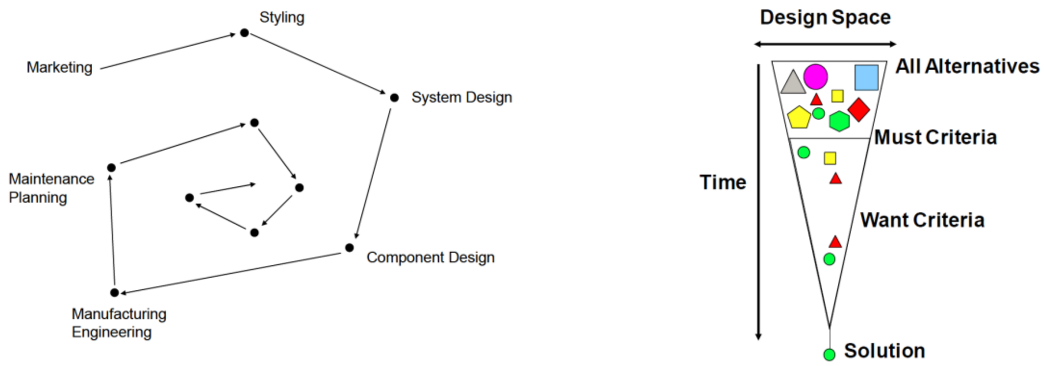
- Well-defined problems – where the goals are clearly prescribed, an example could be a repeat building type, where the building design is already known such as standard retail units (e.g. supermarkets), speculative office buildings and 'standard' house designs as employed by speculative housing developers.
- Ill-defined problems – where the goals are not clear at the outset. The client knows that they want to commission a building project, but there is little clarity about exactly what is required at the outset. Here the designer's role is to establish the nature of the problem and clarify the goals of the client and the building users

- Wicked problems – where the goals are extremely difficult to define. In this situation, the problem defies easy formulation and definition, requiring constant reformulation and definition. Here it is common to have a very vague brief and to start designing to try and establish the nature of the problem. In such situations, it would be possible to carry on designing for an indefinite period, but usually the constraints of time and finance force a decision to be made.

The increasing level of technical complexity, social and business expectations and multifaceted regulations makes it difficult to describe well-defined problems for even 'standard' buildings (Fischer et al. 2017) and with a constant push for improved energy performance of buildings in most countries it seems that few AEC projects today can be described by well-defined problems.

Arroyo (2014) describe a range of multiple-criteria decision-making methods to base decisions on a mathematical decision from assessing alternatives in various ways. Arroyo concludes that *Choosing By Advantages* is the best approach for the AEC industry to make decisions as judgement is here based on differences between alternatives as opposed to more arbitrary scales used in other selection methods. Arroyo also refers to more simple A3 reports presenting a problem, its background and possible solutions for fast and transparent decision making. Depending on the importance of each decision, different yet structured methods can therefore be applied.

Parrish (2009) argues that the entire design development process should be based on assessments of alternatives in a set-based design approach as opposed to what is described as a traditional point-based design process – as illustrated in Figure 7.



Point-based design process
(Ward et al. 1995)

Set-based design process
(Parrish 2009)

Figure 7. Different type of design development approaches

In set-based design, several design alternatives are developed equally for a period of time before narrowing the number of alternatives based on first 'must' criteria and then 'want' criteria. The method is found to identify more optimal solutions to design problems as the best from each design alternative can be incorporated in the final design (Parrish 2009). In point-based design it is likely that sub-optimal solutions are selected. How the design development process is completed is for this reason of considerable importance to the potential value generation and project success.

6.2 Design Task Dependencies

The organisation of design teams and tasks is also of great importance to the value generation and in order to understand the difficulties of design management, the dependencies in design must be understood (Knotten et al. 2015). Three main dependencies exist in design which are described as parallel/pooled (independent), sequential (dependent), and coupled/reciprocal (interdependent). Bell and Kozolowski (2002) furthermore introduce a fourth dimension called intensive interdependence as illustrated in Figure 8.

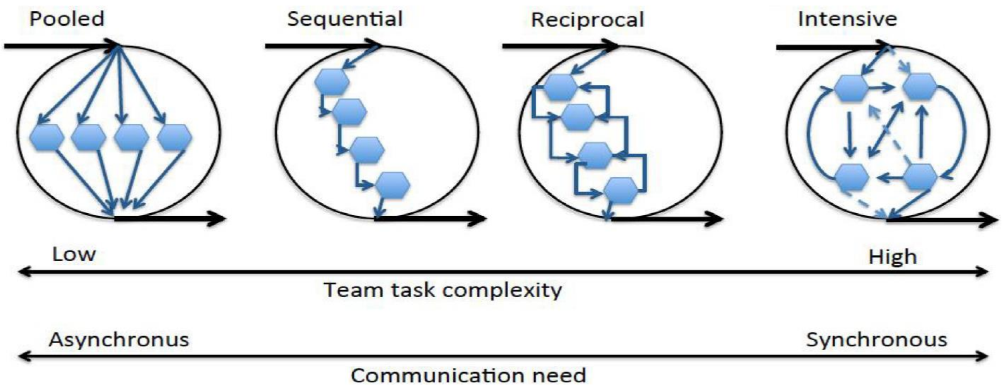


Figure 8. Task dependency and complexity (Bell and Kozolowski 2002; Knotten et al. 2015)

When design can be completed based on well-defined problems, a sequential logic can be in place and result in pooled and sequential dependencies (Knotten et al. 2014). Similarly Knotten et al. concludes that if design is based on problems which are wicked or ill-defined, a reflective logic is needed and results in reciprocal or intensive dependencies. A standard project management approach (Pinto 2016; PMI 2013) can help manage pooled and sequential processes, but it is not an effective tool to manage reciprocal or intensive processes (Knotten et al. 2015).

The planning and management methodologies described in Table 4 (Section 1.4) are all responses to the management of interdependent tasks and wicked or ill-defined problems. Management of design should for this reason depend clearly on how well design problems can be described, but it should also be a clear aim in design management to reduce the amount of wicked and ill-defined problems to reduce complexity.

Pikas et al. (2015) conclude that complexity exists within the product, the processes and the organisation but also that the interdependencies between the three makes building design complex to manage. Avoiding complexity seems for this reason unlikely, but Pikas et al. concludes that methods related to BIM and lean can add considerable value in design management by improving the understanding of these interdependencies. To elaborate this further, fundamentals for improving management of design complexity is described in the following sections.

6.3 Managing Design as Output

Koskela (2000) argues that it is a needed theoretical shift to principles of concurrent engineering (Anumba et al. 2007) which is required in design management. This step is similar to what the construction industry has experienced with the implementation of lean philosophies most often framed as Lean Construction. Viewing design as a production system, Koskela (2007) concludes that the weakness of standard management approaches is that they view design only from a transformation viewpoint and therefore do not address the actual complexity in design. Instead he argues that consideration to management of the information flow and value generation should be of equal importance. The three concepts for design management are described in Table 6 and constitute Koskela's proposal for a TFV-theory of design.

Table 6. Transformation, flow and value generation concepts of design – TFV-theory (Koskela and Huovila 1997)

	Transformation Concept	Flow Concept	Value Generation Concept
Conceptualization of Design	As a transformation of requirements and other input information into product design	As a flow of information, composed of transformation, inspection, moving and waiting	As a process where value for the customer is created through fulfilment of his requirements
Main principles	Hierarchical decomposition; control of decomposed activities	Elimination of waste (unnecessary activities); time reduction, rapid reduction of uncertainty	Elimination of value loss, rigorous requirement analysis, systematized management of flow-down of requirements, optimization
Methods and practices	Work Breakdown Structure, Critical Path Method, Organizational Responsibility Chart	Design structure matrix, team approach, tool integration, partnering	Quality Function Deployment, requirements management, value engineering, Taguchi Methods
Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name for practical application	Task management	Flow management	Value management

6.3.1 Task Management in Design

In the transformation concept, design is seen purely as a process of transforming client requirements to design in the most efficient manner and promotes decomposition of design work using e.g. a work breakdown structure. The 'standard' management methods mentioned in the left side of the table above fits this need and are also promoted in traditional management literature for project success (Pinto 2016; PMI 2013). Substantial problems in the current practice and limited costumer focus are addressed by Koskela as limitations of this view. Furthermore, such single-minded view on design can lead to sub-optimization as focus is on efficiency of individual tasks as opposed to the entire design process.

6.3.2 Flow Management in Design

For this reason, transformation should be optimized also in relation to the flow of information in the design process. Ensuring focus also on the flow concept will decrease uncertainty as more information should be available in time. Koskela describes that information can be either in a transformation, waiting, moving or inspection stage and that only the transformation stages adds value to the project. The other stages are wasteful and should be limited. The transformation stage can include either design or rework, and rework is also considered as wasteful. The major general cause for rework is argued by Koskela to be variability associated with uncertainty (missing or unstable information) and focusing on including methods mentioned in the middle of Table 6 is for this reason important.

Pikas et al. (2015) concludes that the current building design practice is still based on the transformation concept and that applying a tool like the Design Structure Matrix adds clear value in understanding and optimizing design task dependencies. *Pull planning* is another method to ensure efficient flow in design and a key reason why principles from the Last Planner System (LPS) is also found to be attractive to design. LPS allows for a structured approach to pull planning and is found to add clear value in improving and adjusting building design task execution (Hamzeh et al. 2009).

6.3.3 Value Management in Design

Additionally to flow management, Koskela argues that meeting customer requirements in the best possible manner is also a missing concept in current design practice. Requirements needs to be identified, captured and optimized and a range of methods to support this are listed in Table 6 in the right side. Most methods originate in manufacturing and Kiviniemi (2005) concludes that most have shortcomings in relation to the AEC industry as the decision making process is not as well defined compared to manufacturing. Most solutions will for this reason be too difficult to utilize at the outset of AEC projects or not be able to reach the level of detail required in AEC projects. Instead Kiviniemi proposes to define requirements in a structure similar to the product model so that requirements can be linked more closely to the final solution and alignment can be ensured at all times. This proposal is shown in Figure 9.

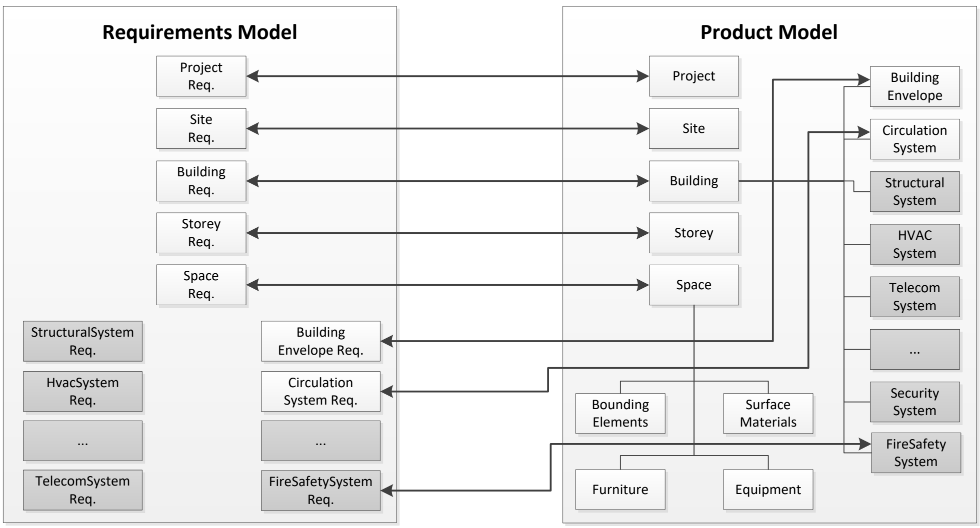


Figure 9. Relation between requirements model and product model (Kiviniemi 2005) - grey systems are out of scope of Kiviniemi's work

By creating this relation, Kiviniemi finds that the challenge of requirements being abandoned as design progresses can be reduced and instead the development of design can be completed synchronized to related requirements. The scope of the underlying requirement model specification is currently limited to architectural design requirements, but Kiviniemi believes that the model can be expanded to include requirements for building systems as well. Kim et al. (2015) finds that commercial solutions now exist which support the concept of requirement models but concludes that there is still considerable barriers in keeping the requirements updated as changes are introduced in design. Kim et al. finds that automated updating of requirements can be achieved by mapping requirements to user activities, but this will require additional work to build such relations. The work by Kiviniemi does not address in details how requirements are to be developed and El. Reifi and Emmitt (2013) find that issues related to the design brief are responsible for almost 30% of the rework in design.

Systems engineering is an generic approach to address requirement identification, capturing and optimization by a step-wise systematic decomposition of requirements from overall system level to lowest element level (INCOSE 2015). Design synthesis and system validation is completed in a similar step-wise approach from component level and up to ensure consistency between requirements and design. In an iterative approach to systems engineering, Lightsey (2001) propose a three step development cycle of: 1) *Requirements Analysis* where the mission and design problem are identified and converted to functional requirements, 2) *Functional Analysis* where functional requirements are decomposed and where interfaces are identified and 3) *Synthesis* where design solutions are developed based on functional requirements and validated. This process is shown in Figure 10.

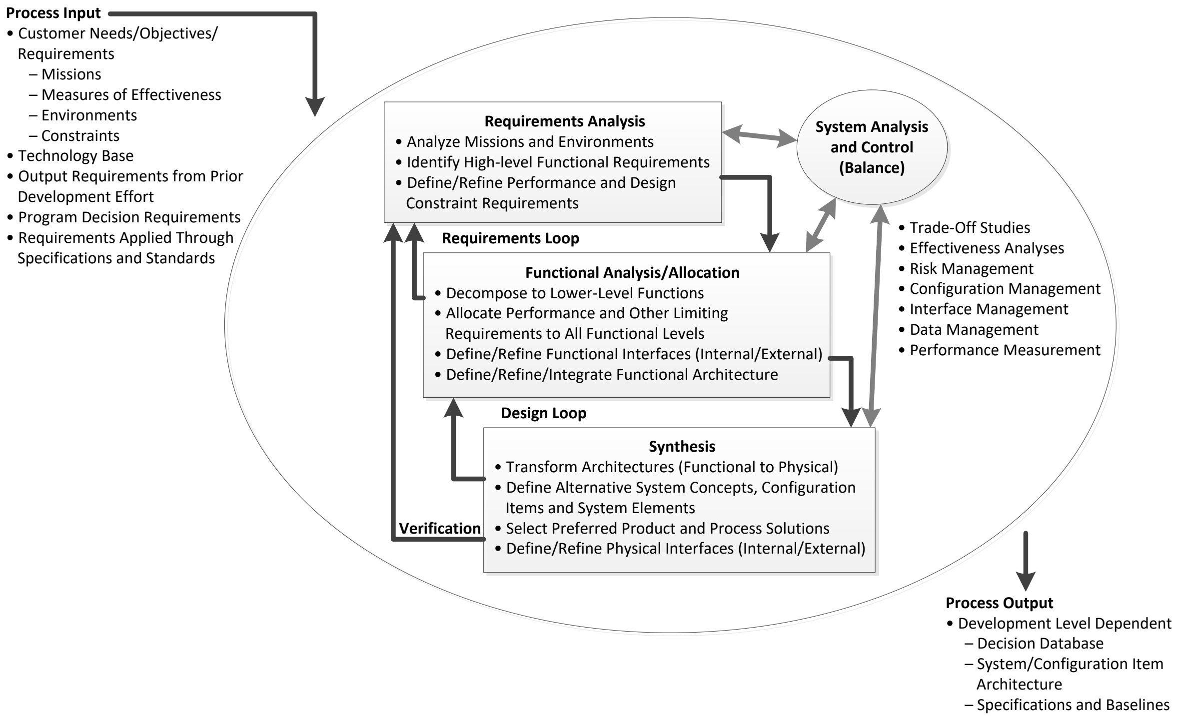


Figure 10. Proposed steps in systems engineering (Lightsey 2001)

Lightsey (2001) does not propose a structure to organise information within, but the requirement model proposed by Kiviniemi (2005) could support requirement capturing in the functional analysis step in the systems engineering approach. This would also act as a useful platform for the synthesis step where the product model needs to be developed in close relation to the functional requirements.

Andersen et al. (2009) propose a concept for a mission breakdown structure to capture the granularity in what contribution the project will make to the development of the client organization and its environment. Riis (2013) details the structure to consist of a project mission (long term value), sub-missions (short-term value) and project objectives (deliverables to the organization). The structure is illustrated in Figure 11.

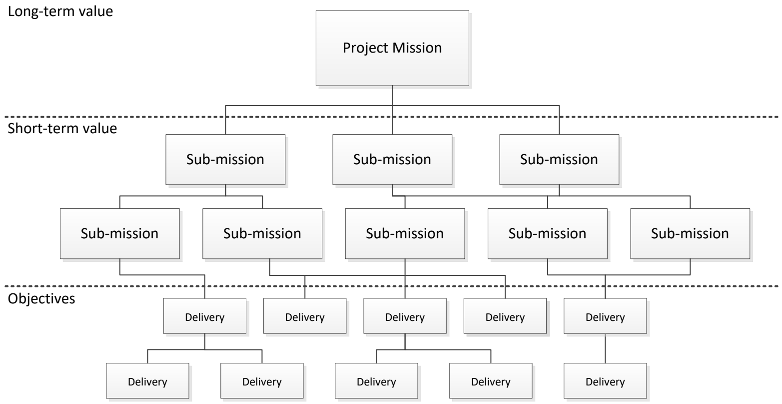


Figure 11. Mission Breakdown Structure – based on (Riis 2013)

Using a mission breakdown structure could capture information from the requirement analysis step in the systems engineering approach from Lightsey (2001) and act as a structured link to the functional requirement to be developed on this basis. From initial use of systems engineering in infrastructure projects, Hoeber et al. (2015) find systems engineering to provide clear value in linking a requirement breakdown to product model content in BIM models and although the model structure is slightly different in the case study, the concept in general seems applicable also in building design.

The above approach is a more pragmatic method to value management in building design. It can be iterative and the close link between requirements and design can allow for both requirements and design to develop as the design progresses. This addresses the limitation of previous value management methods identified by Kiviniemi (2005) and therefore seems more applicable to building design.

6.3.4 Limitations of the Transformation, Flow, Value Theory

Without ambitions and tools to model and manage the flow and value generation processes, design team collaboration degenerates into interaction for interaction's sake which does not correlate with performance (Koskela 2007) and a need for lean based concepts as the TFV-theory presented by Koskela for this reason seems highly important to design management.

Currently the implementation of lean based methods in building design is limited (El Reifi and Emmitt 2013). This seems related to both a lack of applicable methods in building design but also a misalignment between the focus on waste reduction and the required iterative nature of design (Bølviken et al. 2010).

From the above it seems that lean methods promotes a rational view on design and somewhat ignores the interactive inquiry which design can also constitute (cf. Section 6). This is argued to be why especially architects often find themselves limited in their use of lean and BIM (Coates et al. 2010). The learning perspective of design should for this reason not be ignored and will be discussed in the next section.

6.4 Managing Design as Learning

In response to the often wicked and hence complex challenges in design, the idea of *design thinking* has gained increasing attention in order to understand and propose solutions to approach the design process in a learning perspective (Johansson-Sköldberg et al. 2013). Johansson-Sköldberg et al. describe five different views on design thinking:

1. As the creation of artefacts (Simon 1996)
2. As a reflective practice (Schön 1983)
3. As a problem-solving activity (Buchanan 1992)
4. As a way of reasoning/making sense of things (Cross 2011; Lawson 2005)
5. As creation of meaning (Krippendorff 2006)

Although the different views share similar ideas of design as a learning process, they serve different intentions in explaining how design evolves. In relation to decision making, the approach by Cross (2011) and Lawson (2005) is of interest as it builds on Schön's reflective theory as a way of reasoning but based in a practical context. Related directly to the AEC industry, Lawson (2005) argues that the design process should include three steps repeated in an iterative development process: 1) analysis, 2) synthesis and 3) evaluation. The analysis and synthesis steps are similar to principles from systems engineering, but where systems engineering focuses primarily on verifying that solutions meet requirements, Lawson adds an evaluation step to ensure that learning and improvements on this basis can be incorporated into the design. Combining the different perspectives of design development can result in a design process map as illustrated in Figure 12.

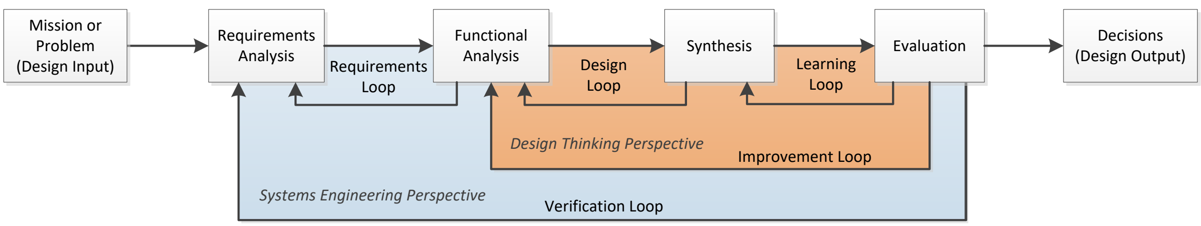


Figure 12. Map of the design process from both a systems and a design thinking perspective – illustration from Paper E

The concept is in line with the iterative problem-solving approach of Plan-Do-Check-Act described by Deming (1982). This idea of continuous improvement is what ultimately lead to the development of lean principles (Liker 2004) and is also the fundamental part of agile principles (Owen and Koskela 2006). As described in Paper E, the map in Figure 12 is also an accurate representation for the Agile Project Management methodology used in this paper and agile principles should for this reason also be of interest in building design management.

Agile Project Management is discussed in details in Paper E and will for this reason not be elaborated further in this section, however, the following statement from one of the founders of the Agile Manifesto (Beck et al. 2001) is of interest:

> When we reduce the cost of experimentation enough, the entire economics of how we develop products changes—it switches from a process based on anticipation (define, design, and build) to one based on adaptation (envision, explore, and refine).
>
> (Highsmith 2009)

Analysis of multiple design alternatives using set-based design (cf. Section 6.1) is a solution based on adaptation for building design. Such a design development approach is highly resource intensive to execute, but the better information can be structured and integrated, the faster it is to develop design alternatives using BIM processes (Wallaert and Knudsen 2017). According to Highsmith such possibilities are not only important to support the desired learning process in design, but also likely to be a competitive advantage in the AEC industry. Building design management methodologies should for this reason motivate for such abilities.

7 Managing Building Design

Summarizing the findings in the previous sections it is concluded that design management methods should address production, socio-technical and learning elements to ensure project success, and a methodology to support such needs is required. The IPD framework (cf. Section 1.4) addresses all three elements. The framework can be described as a series of integration steps of information, organization, process and product as illustrated in Figure 13.

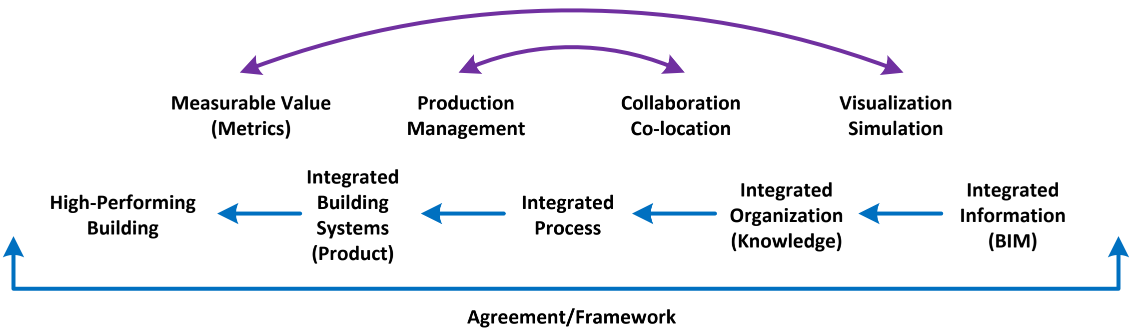


Figure 13. Integration of product, process, organization and information to support creation of high-performance buildings (Fischer et al. 2012)

Fischer et al. (2017) concludes that so far no practical examples of integrating all elements in one project have been achieved, but each step has been applied individually in different projects with success which is believed to validate the approach. The framework provides only limited guidance on how the different elements are to be linked together. The quality of the process and the quality of the resulting building are affected by the way in which organisations and individuals interface (Emmitt and Ruikar 2013). In relation to the IPD framework, the interfacing between different elements is for this reason important. In particular there seems to be a need to understand how information is ordered and connected to achieve integration between the different elements.

For the manufacturing industry, the product life cycle support standard (ISO 2012b) provides a standard for connecting requirements to product and processes as required above. The Eurostep PLM system, Share-A-Space, is supporting this standard and implementation of this system in the AEC industry is being attempted (Tarandi 2011). The challenges of implanting such PLM system has been discussed previously (cf. Section 1.1.2) and it would seem that the AEC industry is in need of a more pragmatic system, lowering the entry barrier for unique and fragmented building projects.

7.1 Information Models in Building Design Management

For this reason, the four information models identified in the previous sections can be combined to demonstrate how information, organization, process and product can be integrated in a more pragmatic solution as illustrated in Figure 14. The four models include:

- A Mission model – structured in accordance with the mission breakdown structure described in Section 6.3.3 to capture client and other stakeholder value in a hierarchical order.
- A Function model – structured in accordance with the requirements model described also in Section 6.3.3. *Requirements model* is rephrased to *Function Model* to emphasise that this model should be expanded to include both client requirements, performance metrics, and other functional or logical requirements developed during the design phase which needs to be matched in the final design product (cf. Figure 12).
- A Product model – structured based on an object breakdown structure following preferably the IFC specification as described in Section 4.1.
- A Process model – considered as a repository for tasks based preferably on BCF as described in Section 4.2, but should be structured based on both work breakdown structuring as described in Section 6.3.1 and based on task sequencing order as described in Section 6.3.2 to support both task and flow management respectively.

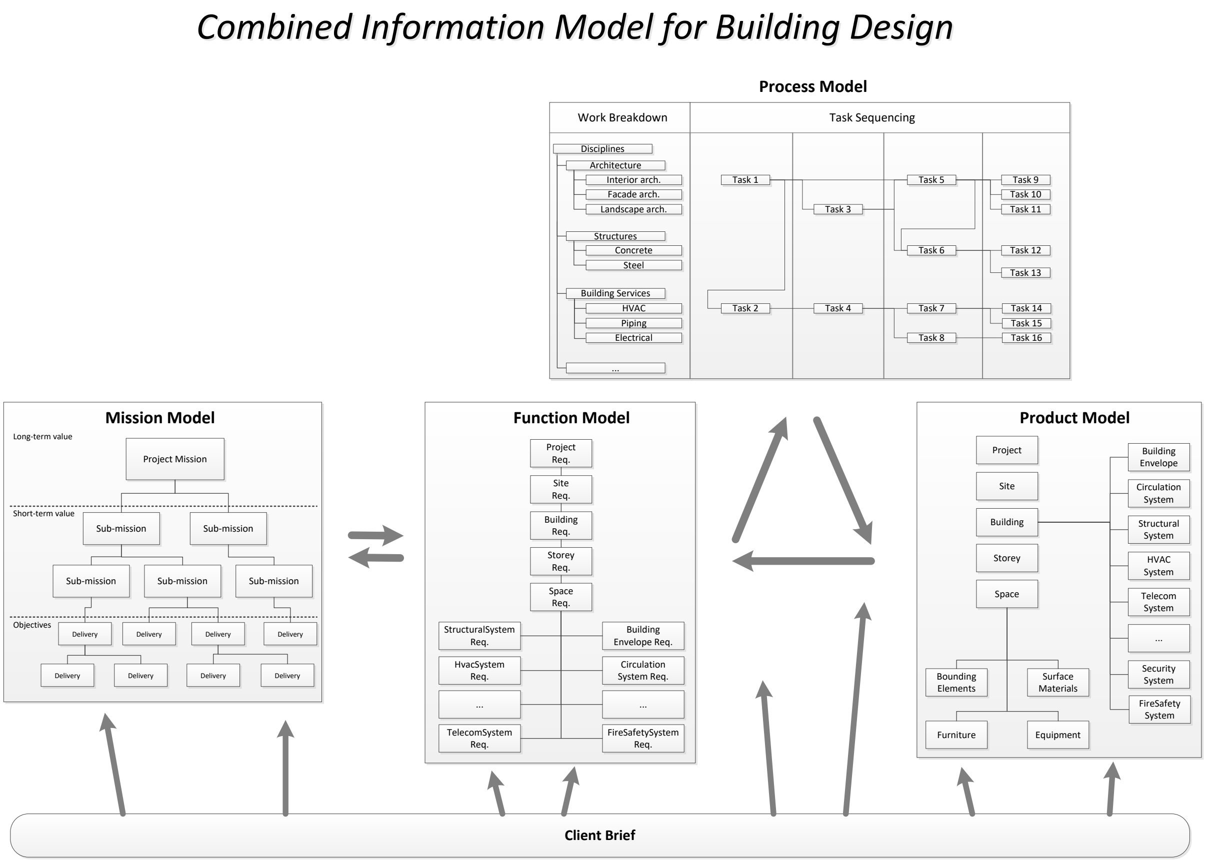


Figure 14. Combined information model for integration of information, organization, process and product

The client brief is also included in the combined information model above, because it serves as a basis for the design development process. A client brief can, however, include input to all four models (cf. Section 1.1.2) and the iterative nature of design would entitle that the client brief should be seen as a basis for further development. To support such development, the model above promotes client requirements to be integrated into the four models as opposed to be developed and maintained in parallel.

The mission model can capture information regarding the problems (or desires) which a client needs to be solved in the design process. How the final product (building) should function can be defined on this basis in the function model and linked to elements in the mission model to understand relations. Based on functional requirements, the work required can be decomposed into tasks and organized in the process model to optimize the flow of information. Results of the synthesis of functional requirements to design solutions can be captured in the product model. The entire process is iterative and as design develops, functional requirements might need adjustment if the design result is not desirable. Changing functional requirements should include consideration of whether the mission can still be accomplished and all information models are for this reason part of the design iterations.

The combined information model has been developed retrospectively to the research completed in this thesis to illustrate the connection between the findings in each scientific paper. The goal of the research has been to validate different elements of this model to understand how these can contribute to improved digitalization and design management. The above model can act as a basis for the discussion of the research conducted and based on research findings the combined model is elaborated further in Section 11.

Part III – Research Design and Findings

8 Research Question

The research in this thesis places itself in the intersection between digitalization and design management. The research draws on findings from research in information management, socio-technical science, and design management and focuses in particular on an improved basis for efficient planning and decision making processes. As described in the point of departure, a framework such as IPD addresses several identified areas which require improvements in the AEC industry, including efficient planning and decision making processes. When successful, IPD can foster collaboration and considerably increase possibilities for achieving project success (cf. Section 1.5). The utilization of such a framework is still relatively new to the industry, and it seems that solutions to integrate the different elements into a coherent methodology are still less explored. Digitalization is a foundation in such a methodology to support an efficient way of working, but multiple barriers exist for its expansion. Furthermore, such a methodology requires integration of information, organization, process, and product and compared to the manufacturing industry this seems more complicated in unique and fragmented AEC projects.

The goal of this thesis is for this reason to increase the understanding of the relation between information needs, standardisation, and efficient design management. This is expected to contribute to knowledge of how integration within design processes and digitalization can improve planning and decision making processes and how implementation barriers can be decreased.

Based on this motivation, the following research question was formulated:

> **Primary research question:** How should information in building design be managed to support an efficient building design process?

The primary research question was divided into three sub-questions:

> **Sub-question 1:** What is an efficient building design process?
>
> **Sub-question 2:** How to manage *product* information within building design to support the desired design process?
>
> **Sub-question 3:** How to manage *process* information within building design to support the desired design process?

The research question and sub-questions shaped how the research design was composed as described in the next section. Based on findings from the scientific papers, the questions will be answered in Section 12.

9 Research Design

This thesis comprises the results of an Industrial PhD which can be seen as the tension field between research and business. The results should for this reason be considered in a broader transdisciplinary social and economy context as opposed to traditional knowledge development based on a disciplinary, primarily cognitive, context (Gibbons et al. 1994). Gibbons et al. describe research related to this thesis as "… characterised by a constant flow back and forth between the fundamental and the applied, between the theoretical and the practical".

Such continuous evaluation of both the current knowledge base and the practical problems identified, is following with what Hevner et al. (2004) describes as design science research (DSR). In DSR the research artefact (the proposed product or process) is evaluated based on linking the problems in the surrounding environment to the actual research and grounding the research based on the existing knowledge base. Hevner et al. describe the research process in two cycles: the rigor cycle and the relevance cycle as illustrated in Figure 15.

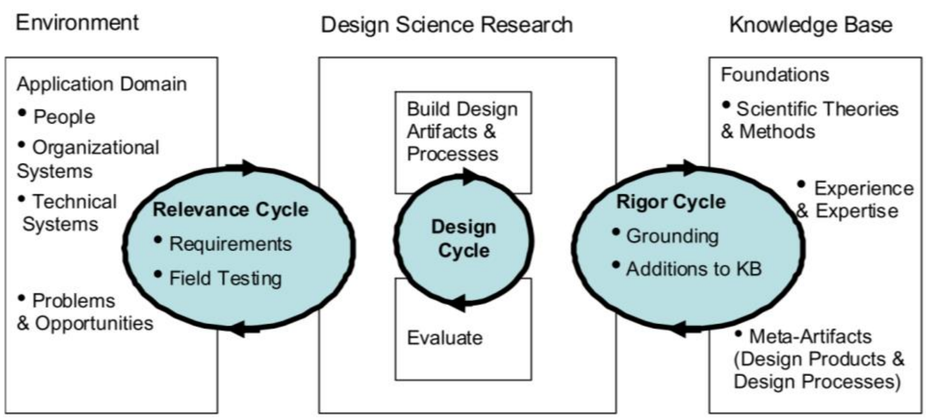


Figure 15. Design Science Research Cycles (Hevner et al. 2004)

At its core, DSR is concerned with the systematic creation of new knowledge about a problem and its solution through building and evaluating innovative artefacts (Chatterjee and Hevner 2010). In the relevance cycle, problems in the environment are identified, and the developed artefact is evaluated on this basis. In the rigor cycle, the research artefact is grounded in the current knowledge base, and findings from evaluation are added back to the knowledge base. The entire process is considered as a continuous iterative process where the quality of the artefact can be strengthened and the value add to the knowledge base made stronger.

DSR is research through learning and useful within research of information systems (Vaishnavi and Kuechler 2015). Findings from the evaluation can contribute to improve the knowledge base in three levels where the highest level is considered most complete and mature:

Level 3 – Well-developed design theory about embedded phenomena
Level 2 – Nascent design theory – knowledge as operational principles/architecture
Level 1 – Situated implementation of artefact

(Gregor and Hevner 2013)

This thesis is based on established theories on information management, socio-technical science, and design management and uses this existing knowledge base to establish elements in a novel design management methodology. The goal is to contribute with knowledge on new operational principles referred to in level 2 above.

Evaluation is the most essential part in establishing a contribution to the knowledge base, and Hevner et al. (2004) defines utility, quality, and efficacy as key elements in such evaluation. Utility is evaluated based on whether the artefact is unique, fits the environment, and solves a problem. Quality can be evaluated based on a range of criteria including functionality, completeness, consistency, accuracy, performance, reliability, usability, and organizational fit. For the research in this thesis, functionality, completeness, and usability are selected as main criteria. Efficacy relates to whether the artefact provides a result which is relevant and meaningful.

Several research methods were used in the scientific papers to evaluate the different elements in the design management methodology proposed. In all papers, substantial literature reviews were used to define the current knowledge base and in Paper A and F, literature reviews were also used to identify problems in the environment which were to be solved. In Paper B to E, quantitative and qualitative methods were used to identify problems in the environment using surveys, semi-structured interviews and workshops.

The goal of Paper D was primarily to identify and refine the understanding of challenges in design management and no development activities were involved. The goal of paper A and F was to use experimental development to propose new concepts for management of product and process information respectively. The findings in Paper A was evaluated and further developed in Paper B. The findings in Paper F were evaluated based only on needs identified in literature, but the general concept of task management was evaluated thoroughly in Paper E. The LOD framework developed in paper C was based on a constant comparative method (Denscombe 2014) were multiple workshops with experienced practitioners were used to develop and refine the LOD framework in a constant interaction between the problems and the solutions. A constant comparative method including semi-structured interviews and workshops were also used in Paper B to further develop a modular IDM concept. Based on recently completed design projects, the concept was tested and evaluated further with the design team. In Paper E, the goal was to evaluate applicability of agile project management, and several case studies were completed for evaluation. During the case studies the agile methodology was refined to match AEC industry needs, also based on a constant comparative method in close interaction with the design teams.

The findings in individual papers are believed to constitute novel knowledge on how design and information management methods can be improved. On this basis, a framework for a design management methodology is proposed by the end of this thesis to answer the research questions and evaluate findings as described by Hevner et al. (2004).

10 Research Methods and Findings

The research presented in this thesis is intended to target different elements in the combined information model described in Section 7.1. The focus area of each scientific paper is shown in Figure 16 to illustrate what elements in the combined information model are in focus in each paper.

Combined Information Model for Building Design

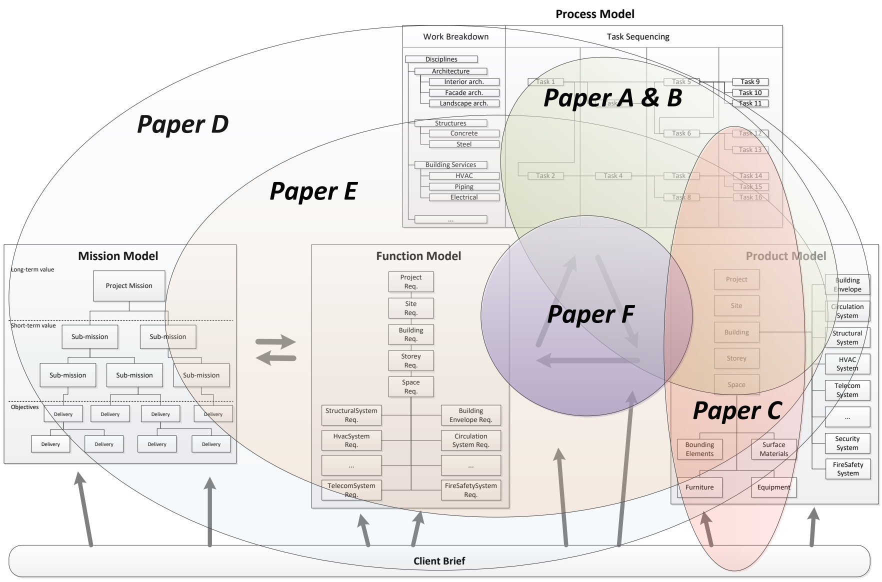


Figure 16. Focus area of each scientific paper

The following sections discuss the methods and completed research included in the six scientific papers along with key findings and how these contribute to the knowledge base. Furthermore the research quality is assessed in each case.

10.1 Paper A and B - Modularization and Standardization of Work Packages

The research in Paper A and B is motivated by a need to improve abilities to standardize product information exchange requirements, acknowledging that building design projects are unique, dynamic, iterative and interdependent in nature. This implies that the static nature of the current IDM standard for information exchange requirements is changed to a more modular approach to better match industry needs. The concept is described as an IDM packages methodology. In paper A, the elements of the proposed methodology are presented. In Paper B the methodology is grounded further in the theoretical foundation and practical implementation is evaluated by use of a developed tool, the IDM Manager.

10.1.1 Methods

The basis for the proposed methodology was a literature review of current approaches to AEC information flow management and a theoretical framework built on existing theories on information and design management. 21 bachelor and master students at the Technical University of Denmark took part in developing a total of 24 IDM packages along with work by this author in the Danish organisation *cuneco*. This work was used to iteratively refine the methodology. In total 53 discipline experts from 25 different AEC companies were interviewed for data collection using semi-structured interviews (Kvale and Brinkmann 2015). Based on the findings a software tool named the IDM Manager was developed with support from an external programmer to evaluate practical implementation. Two case studies of a 15.000 m2 laboratory building and a 2.000 m2 kinder garden were used for testing. Retrospectively, the tool was used to describe the required information flow for the design and specification of the ventilation system in the case studies and interviews with project managers and design team in the first case study were used to assess applicability.

10.1.2 Findings

The methodology is defined to consist of small IDM packages, each describing the process along with input and output requirements for individual work packages as illustrated in Figure 17. A work package is the lowest level in a work breakdown structure and can contain one or more tasks for one discipline only.

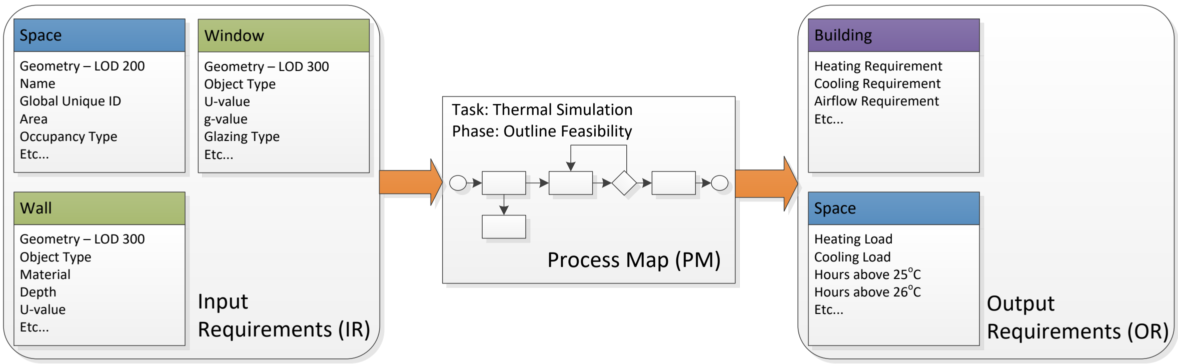


Figure 17. IDM package content based on object-oriented attribute requirements.

Each IDM package is intended to be captured in a library, the IDM Framework. From the library, the IDM Manager tool can support project managers in selecting the appropriate packages required for a specific design project and, based on this, optimise the order of IDM packages in an IDM Project Plan to ensure an efficient flow of information in the project. The outcome of the plan is automatically calculated exchange requirements for each phase or sub-phase in the project.

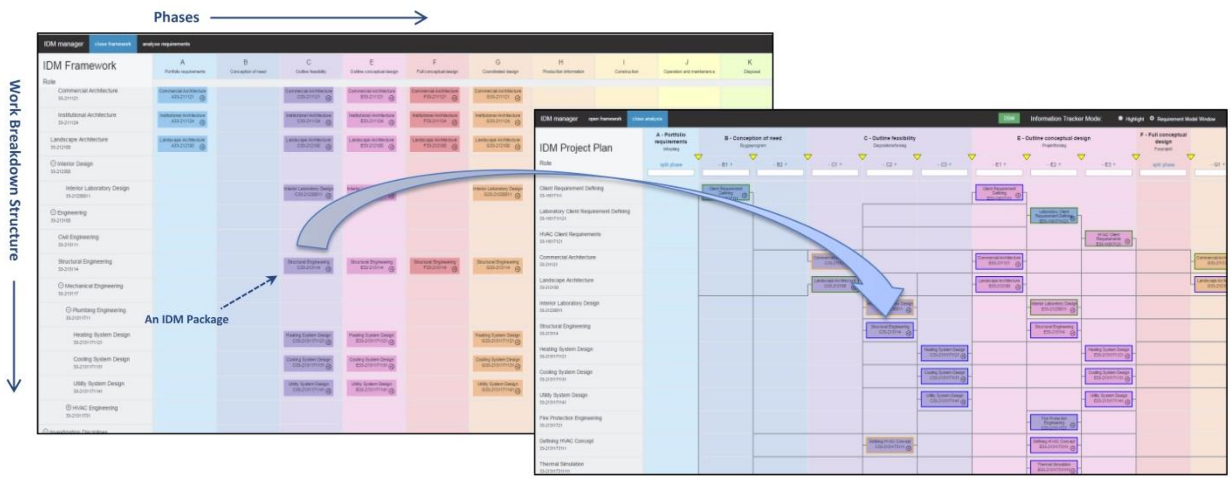


Figure 18. The IDM Manager with the IDM Framework (left) acting as a library of standardized work packages and the IDM Project Plan (right) to capture a specific project execution plan.

Based on the developing of the first 24 IDM packages and case study testing, it was concluded to be a useful process for defining information exchange requirements. The methodology was useful as it limited dependencies from organizational and/or contractual agreements by focusing purely on the exchange requirements for each specific work package. This allowed for work packages to be included in many different project constellations, increasing standardization abilities across communities.

The proposed use of relational constraints for specific attributes improved the ability to create packages which are applicable in a multitude of scenarios and allowed for a 69 % reuse of packages from the first to the second case study. The methodology furthermore clearly separated the need for discipline expert involvement in the development of project specific work plans. Instead planning can rely on predefined packages more easily accessible in the IDM Framework. From a standardisation view point this is of great interest as each work package can still be optimized based on standardized input and output. This is essentially where standardisation is most needed as design tools can then be adjusted to effectively support specific work packages. Based on the testing in the first case study, the design team found the tool useful to gain common understanding of constraints between activities. Furthermore, the project manager believed to have been given an improved overview of potential implications when packages continue to change location in the project plan – as was the case in that project.

The relation to MVD development to allow for stating data format specific requirements was not described in the papers. For the methodology to fully add value it would be desirable for a more modular approach to MVD development as well. Currently MVDs are mostly developed ad-hoc similar to IDMs, however, creating a library of MVD elements for each attribute in the IDMs could allow for auto generation of MVDs based on the IDM Project Plan. For non-graphical attributes this is most often a simple task of mapping to corresponding attributes in IFC or other data formats. For graphical attributes the solution should follow the principles from the IDM packages which mean that there should be a MVD concept present for each LOD level of each object class. This will limit the possible variations of how geometry can be defined in e.g. the IFC format, but based on the interviews with discipline experts the need for multiple variations seemed very limited. Such concept is illustrated in Figure 19.

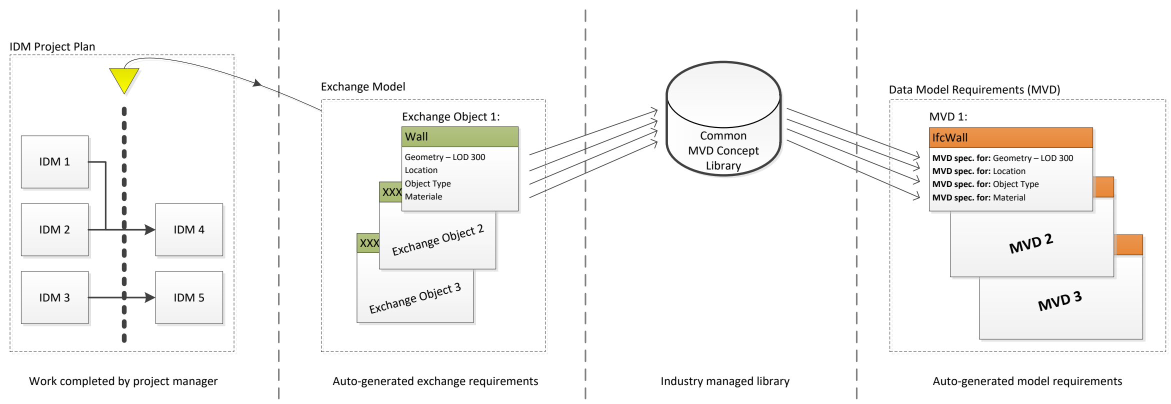


Figure 19. Proposed concept to translate exchange requirements to model requirements (MVD) based on a MVD Library (not part of papers).

Creating a library of MVD elements is a considerable task, but current initiatives like the Danish CCS Navigate (bips 2016) or Norwegian bSN Guiden (buildingSMART Norway 2015) could align to the concept and further ease implementation requirements to IFC and other data interfaces in AEC software.

10.1.3 Research Quality

Several hundred packages are expected to be required for the solution to be applicable in actual projects and this limits abilities for current testing on ongoing projects. Instead, the research relied on several development iterations in what was described by Hevner et al. (2004) as relevance cycles where business needs – identified during workshops and interviews – were used to evaluate the value of the methodology and adjust it accordingly. The range of cycles improves the validity of research quality (Denscombe 2014), and the final IDM package methodology is for this reason well-grounded in industry needs. The use of semi-structured interviews can allow for bringing up new ideas during interviews, however, limited prior knowledge by the interviewer and personal interpretation can result in misleading data collection (Brinkmann and Tanggaards 2010). For this reason students were asked to revisit their interviewee to present their final work for validation. This was completed in most groups and in all the cuneco work and the range of interviews and packages developed is believed to further reduce misleading results in the findings. The included case studies confirm applicability and relevance, but how well the methodology adopts to and improves information flow management in ongoing projects, where many other factors are also of high priority, will have to be identified in future research.

10.2 Paper C - Standardization of Model Concretization

As identified in Paper B, a methodology to accurately describe the concretization of objects is needed when defining exchange requirements because geometry definitions are otherwise difficult to describe unambiguously by discipline experts. The motivation for Paper C is for this reason to develop a framework based on the Level of Development (LOD) concept to address this need. Numerous previous approaches has been developed to address the limitation of the LOD concept being either too simple to fully describe the requirements for BIM deliverables or too complex to be operational in practice and the industry still seems challenged in selecting a valid approach.

10.2.1 Methods

The goal of the research was to identify the needs of the industry by evaluating eight current LOD concepts and comparing these solutions to findings from more than 15 workshops conducted as part of the development for a set of new Danish Information Levels (LOD levels) in the organisation *DiKon*.

The author took part in the development work in DiKon which resulted in detailed type-specific definitions for 22 commonly used BIM object types along with a LOD table to link requirements to phases. Based on this work, the findings were translated into a generic framework in Paper C intended to be applicable to LOD development initiatives in other organisations to harmonize the conceptual understanding of LOD definitions.

10.2.2 Findings

There is still a considerable misunderstanding in the industry that LOD should refer to the *detailing* of deliveries, but none of the current LOD concepts evaluated address detailing explicitly in their definitions. Nevertheless, the concepts that include illustrations of the development stages, do implicitly address detailing, which can lead to misunderstandings about their intent. For this reason a generic LOD framework is proposed, which clearly describe what is needed for stating unambiguous requirements for concretization of BIM objects.

Based on conclusions in the paper, three definitions were developed to describe the requirements for BIM objects in seven levels ranging from 0 to 6:

- *Level of Reliability (LOR)* – the reliability of content related to contractual agreements.
- *Level of Completeness (LOC)* - the concretization of the object and the scope of included components. The combination of a description and an illustration defines each LOC.
- *Level of Information (LOI)* - the requirements for non-graphical information defined as explicit requirements for object attributes.

There is a clear overlap in solutions between LOI and the IDM package methodology as they are both addressing exchange requirements for specific attributes. However, it was concluded to be beneficial to select four high level use cases (IDM packages) and include their scope in the LOD Framework to make the solution work autonomous of IDM packages for basic exchange requirement needs.
For the solution to have broader applicability, a methodology was proposed for combining the LOD Framework with IDM packages as illustrated in Figure 20.

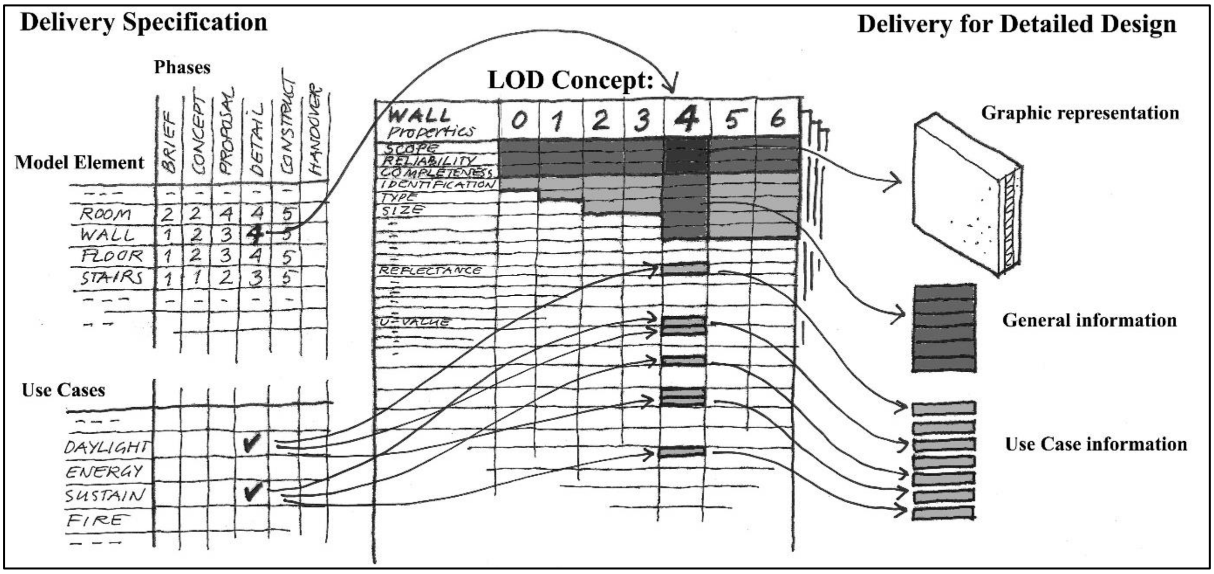


Figure 20. Modular approach of defining delivery requirements based on LOD selection for model elements and supplementing requirements with desired use cases.

Using a *Delivery Specification* to define LOD levels for each object type in each project phase and supplement this with additional use cases represented by IDM packages could allow for a configuration system to point unambiguously to the information required for e.g. a wall object as illustrated. The sum of information required based on the LOD 4 level and the additional information required by the two selected use cases constitute the total requirements of what object attributes are to be delivered at (in this case) the Detailed Design phase for that specific object type. By combining the LOD requirements with IDM-based use case requirements, the solution is also highly modular.

The solution is pragmatic, but using the IDM package methodology proposed in Paper A and B would insure a more customized information flow which is likely to be more efficient than using just the LOD framework. To move the industry forward, the LOD methodology could act as a first step towards improved standardisation of *product information* and then a graduate transition to the IDM package methodology could be a second step where *process information* (information in the IDM Project Plan) is linked to *product information* (the exchange requirements for the product model).

10.2.3 Research Quality

It was out of scope of this research to evaluate the proposed methodology in actual projects. The research was instead grounded in the past 10 years of experience by DiKon members in working with LOD requirements. The current extensive variety in proposed LOD solutions indicates that a clear theoretical framework for such work is missing. The current paper contributes to this need by its clarification of terms and proposed framework for harmonization. Several pilot projects have now started using the DiKon solution with a delivery specification to define information levels for each object types in each phase, and evaluation from these pilots will be needed to justify the value of this part of the proposed framework. As more IDM packages are built, the inclusion of requirements for use cases in the framework could also start to be evaluated.

10.3 Paper D - Resource Utilization in Building Design

From the work with standardisation of product information, it became clear that the industry was not only challenged by lack of standardisation, but also in the way information was utilized to generate value in projects. The motivation for Paper D was for this reason to investigate which problems were faced by project managers in order to achieve successful projects.

The original hypothesis of the research was expected to be related to difficulties in translating strategic objectives into tactical instruments from which the project managers could operate. Based on the findings it was instead clear that project managers were far more challenged in relation to the social aspects of team formation and this was then the key focus of the paper.

10.3.1 Methods

To identify problems in building design management, a survey was first created and send to 149 potential project managers in Ramboll. 65 project managers (around 8 % of the total staff in the building unit) provided useful response to the 64 questions asked. The survey was designed to include both descriptive and explanatory research (De Vaus 2002 p. 22) by firstly identifying what project managers believed were the greatest challenges and secondly to identify perceived knowledge and behaviour by these project managers.

Based on the findings in the survey, five project managers were selected from the building unit to participate in semi-structured interviews for further elaboration on the results. They were selected based on recognition from senior management as being able to execute successful projects and representing different types of projects. All project managers had five years or more management experience and their typical projects had a complexity score above 'medium' according to the internal assessment score.

The use of a mixed method approach (Johnson et al. 2007; Kvale and Brinkmann 2015) with both survey and interviews proved highly relevant in the study as responses from the survey could be misleading due to the social implications described by interviewed project managers which were not explicitly addressed in the survey. Based on the theory presented on both production systems and socio-technical systems, the discussion and conclusion could furthermore be elaborated to reach improved understanding of the problems faced.

10.3.2 Findings

Based on the survey, several critical problems were identified. Lack of coordination and implications from design changes were clear issues which need to be addressed, however, in general it was concluded that high variability on the projects were likely a root cause for many problems faced as it creates unpredictability. Furthermore, the utilization of BIM and other ICT technology did not induce as great effects on quality and productivity as expected.

In the survey, limited availability of required resources when needed was rated highest among challenges listed. From the interviews it was found, that this was related to a key problems for project managers to build a strong community of practice as this was believed to be the far best safeguard to manage the variability on projects. The argumentation was that variability is inevitable and that only strong team spirit and collaborative design in a community could limit variability sufficiently.

This is somewhat in contrast to the current strategy initiatives in Ramboll which focus instead on the explicit framework and boundary conditions for projects, and it was concluded that better alignment between strategy initiatives and support for strong community building is required. Furthermore, it was concluded that a company must balance technological requirements in projects. If a project does not consist of actors who have the necessary negotiated community, implementation of new technology is not likely to be successfully. This clearly supports the understanding that BIM and other ICT initiatives cannot generate collaboration, but they can act as useful tools in assisting teams – who are already within strong negotiated community – to reduce project variability.

10.3.3 Research Quality

The selected mixed method approach used for data collection reduces the source of errors from the survey and interviews respectively, however, the research was conducted only within one company and the applicability of the findings for the industry is therefore questionable. In the survey this was addressed by asking participants who had worked in a different company within the last 10 years if they believed that they would have given similar responses if they were to rate the same questions in their previous company. 75 % believed so, and at least 30% of those who would have provided different answers had worked at different company type previously. This provides a strong indication that the responses are representative to at least the Danish engineering industry.

The research only targeted project managers but project success can also be evaluated from the view of the design team, senior management, external stakeholders, society etc. As the scope of this thesis is focused on design management, the focus has been on problems experienced by project managers. It is likely that the senior management and other external stakeholders have more focus on the explicit framework or boundary conditions to identify and understand project uncertainty and ensure an acceptable level of risk in their project portfolio. However, if would seem that this is only touching the 'surface' as the performance of the design team is highly influenced also by social implications. A well performing team should be seen as highly attractive to the involved team members and for this reason the design team are believed to align to the conclusions in this paper more clearly. Based on this, the observations in the paper seem highly relevant for future improvement of strategic initiatives in such engineering companies.

10.4 Paper E - Agile Approach to Building Design Management

From the conclusion that community building is important along with better coordination and management of a changing environment, the motivation for Paper E was to evaluate the effect of using a different approach to building design management. *Agile Project Management* (APM) was selected as the basis because it specifically targets community building, coordination, and a changing environment. The agile method, *Scrum,* was furthermore selected as the structured approach for applying APM in the case studies.

From the literature study it was clear that APM seems less founded in a theoretical framework as opposed to other management approaches and for this reason, a theoretical framework was developed for the methodology as it was applied in the research. Due to the nature of building design where the end product is a physical artefact, there was a need to adjust the methodology to somewhat adhere to high level fixed deadlines and therefore the methodology was also inspired by principles from the Last Planner System™ (LPS).

The three case studies in the research made use of an agile online software tool called *JIRA* to support the APM methodology and to capture data for progress monitoring. JIRA is widely used for supporting agile projects but is originally targeting software development. For this reason the tool was adjusted to fit the needs of building design which primarily resulted in all purely software related functionalities to be deactivated if possible.

10.4.1 Methods

The DSR method described by Hevner et al. (2004) was selected to assess the proposed APM methodology and 12 selected questions from the survey in Paper D were used as criteria for evaluation of the methodology. Three case study projects of building design to the pharmaceutical industry were completed and the monitoring period lasted for five to six months in each case. Three other case studies were intended for the research as well, but due to external factors these three projects were stopped before reaching the preliminary design phase.

The author participated in each case study project by providing introduction, configuring the software platform and supporting the project management team in acting in the agile roles throughout the case studies. Continuous evaluation and adjustments to the APM methodology was conducted on bi-weekly or monthly basis during design meetings with the teams. Together with a master student from DTU, both an evaluation survey and semi-structured interviews were completed at the end of each project with a total of 16 participants. The participants included the project manager and selected design team members in each project. The clients in all three case studies were also interviewed at the end of the monitoring period. The master student assisted with data collection and analysis of results from interviews.

The purpose of the survey was to ask participants to evaluate their experience on past projects and similarly evaluate their experience in the case studies in relation to the 12 questions selected from Paper D. These results were then compared to identify differences between current practice and the APM methodology.

10.4.2 Findings

Based on the theoretical framework described, an APM methodology believed to match the needs in building design was developed as illustrated in Figure 21.

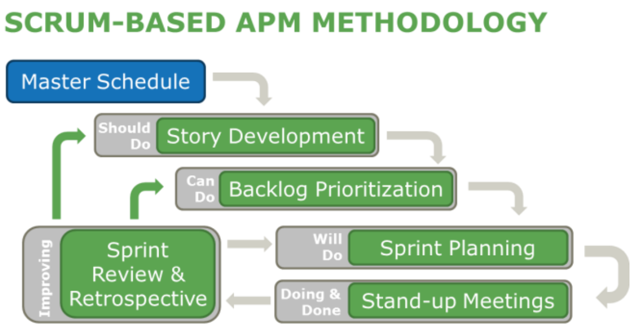


Figure 21. APM methodology applied in the three case studies

From data analysis and evaluation of different task constellations, it was concluded that the teams requested the following tasks types to be used on their projects:

- Design Issues – representing stories of what each design discipline needed to complete to meet design targets and/or support other disciplines in meeting their design targets.
- Tasks – representing assignments which need to be resolved
- Clarification Issues – representing questions to the client or external suppliers
- Change Requests – representing identified scope changes which needed a client decision

The design teams found it difficult to manage functional requirements as intended in the Scrum method, however, based on the final evaluation, it was concluded that functional requirements need to be addressed better to allow for structured evaluation of design solutions from each sprint.

The design teams argued that agile principles were already in use in building design and the contribution of the APM methodology was for this reason seen primarily to provide more structure to the process. Such structure was clearly missing as the current design approach do not address the need for a collaborative and changing planning process but instead use only traditional Gantt charts and task lists originating from traditional waterfall planning.

The case studies did experience many changes due to both internal and external factors. For this reason, the need for an approach to address such changing environment seems required. The results from the evaluation survey in the three case studies are illustrated Figure 22.

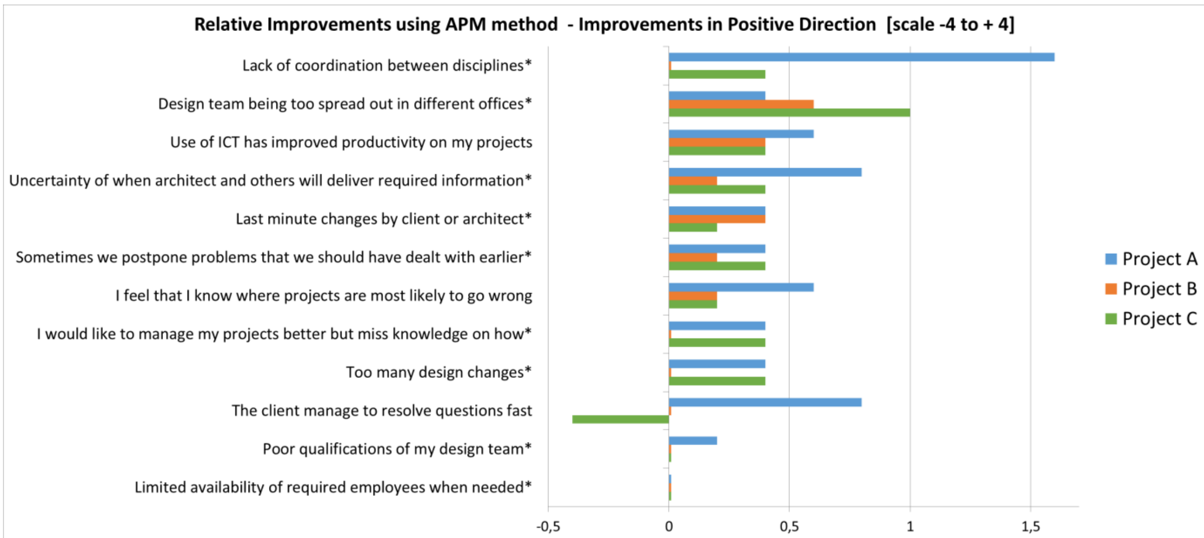


Figure 22. Average differences in the rating of key questions by design team interviewees in terms of their experience in previous projects and their experience in the case study they took part in. An * indicates questions where a decrease between previous experience and now on the 5-point rating of the question is an improvement.

The survey identified improvements in most areas addressed. Findings were confirmed in interviews and were related to improved shared understanding and common ground which for most cases resulted in better coordination and better management of changes. Increased team member involvement resulted in better team performance and continuous backlog prioritization insured that nothing was lost or ignored which was believed to result in less mistakes and improved quality. Empowering the team members did not seem to be a challenge to flow or value generation – instead the project managers found better abilities to monitor project progression in such cases.

The improvements were in several cases lower than expected, especially in relation to the impact of changes, and considerable differences in the three case studies were also identified. Moreover, the Percent Plan Complete (PPC) score was relatively low in all case studies compared to other research studies evaluating building design management methods. Based on findings in the interviews, it was clear that three elements were critical to success and these were not addressed well in all case studies. These elements include the establishment of an agile organization, a clear structure for evaluation and focus on facilitation in the design process.

In relation to organisation it was concluded that all stakeholders with assignments which are mostly interdependent must be part of the APM approach and engaged in the intermediate community created. In relation to structure, the lack of abilities to manage functional requirements in a changing environment does make the improvement process less structured, which is a clear risk of generating less value. Furthermore, in relation to facilitation there is a need to involve the team and complete more planning sessions than what was initially expected by the project managers. Essentially, the described Scrum Master role should be addressed more directly in such projects to ensure success. Failing to address these issues can result in non-value adding design iterations. If these elements can be handled, the APM methodology seems highly applicable to building design and its complex and change nature.

The APM methodology clearly address needs identified in the current research in relation to community building, structured evaluation and learning and continuous prioritisation of the entire design process which previously proposed lean based methods do not address as explicit. At the same time, the low PPC score experienced in the current study compared to e.g. the results by (Fundli and Drevland 2014) indicate that elements in their method framed as Collaborative Design Management (CDM) (cf. Section 1.4) could be of interest to include in the APM methodology. (Bølviken et al. 2010) describe that CDM adds (among other) a *Decision Plan* and a *Dialog matrix* to LPS along with focus on six preconditions for sound design tasks. The inclusion of such focus on the decision making process would add clear value to the APM methodology and should be considered in future implementation.

10.4.3 Research Quality

The evaluation relays on the subjective assessment by design team members of past and current experience. There is a clear risk in such assessment of opinions being either too positive or too negative depending on personal preferences, however, using the mixed method approach of both survey and interviews along with data analysis of the actual progress of the three case studies was found to add to validate the findings. The key conclusions for this reason seem well-grounded.

The variation in experienced improvements indicated clearly that the success of new management approaches relies heavily on the skills and willingness of all stakeholders to engage in the process. The APM methodology can provide structure and guidance in how to improve the design process but if some stakeholders are not accepting the premise that changes in processes are needed and are reluctant to change their mind-set, effects will be limited. The value of such methods is for this reason closely related to the willingness of stakeholders to change as well.

Furthermore, it can be argued that the current practice seems to be somewhat unstructured in its approach to manage changes as it relies on waterfall planning techniques which are not designed to handle change. This is likely why both the APM methodology proposed here and other previous studies using the original Last Planning System or other Lean based methods are all experiencing positive effects as they all at least add some structure to the current somewhat unstructured practice. Evaluating which approach is better than the other is more difficult as case study projects are not comparable. The APM methodology presented here addresses identified needs more explicitly than other methods justifying its value. As previously described, combining elements from several methods is most likely a solution to achieve even better results in future research.

10.5 Paper F - Standardization of Task Management in Building Design

From the case study findings in Paper E, it was clear that efficient management of tasks only becomes more important as new design management methods are introduced in building design. The BIM Collaboration Format (BCF) adopted by buildingSMART is a solution to capture the process information within tasks and ensure interoperability. The current scope of BCF is narrow and the motivation for Paper F was for this reason to evaluate the BCF format as a potential solution for support a broader scope of task management.

10.5.1 Methods

The goal of the paper was three-folded: First industry needs for task management was identified, secondly current software implementation for BCF support was assessed and thirdly a potential expansion of the BCF format was proposed based on a comparison with the specification for IDM Part 2, which also address process related information.

The identification of industry needs was completed based on a literature study on previous findings from using AEC collaboration tools where requirements specifically targeting task management were extracted. The literature selected was based on various approaches such as interviews, implementation attempts, and research of existing tools.

The assessment of current software implementation was conducted by a structured comparative review of the BCF packages exported from seven widely used tools supporting BCF. Each BCF package was created based on the same IFC model and a set of similar information was defined in each software solution to evaluate export capabilities. The content of each BCF package was reviewed in a text editor and compared to the bcfXML v2 specification.

To compare the BCF specification with the specification for IDM Part 2, each specification was analysed and distinct functionalities were identified. Based on the sum of identified functionalities, each specification was evaluated to provide a clear picture of the similarities and differences of the two standards.

Finally, the findings of the paper were used along with findings from similar research to develop a theoretical proposal on how process and product information could be managed and exchanged within the framework of building design and how the BCF specification could be expanded to support this concept.

10.5.2 Findings

28 industry needs in relation to task management were identified and confirm the importance for an unambiguous data structure for task management in general. The identified needs related to capturing and saving the history of decisions, agreements, comments, and questions along with linkage to schedules, BIM models, and other tools including social networking. Structured and yet adjustable workflows and user rights and roles must be supported, management activities should be automated, and it should be possible to categorise and prioritise tasks. The management tool itself should, furthermore, be able to visualise the information to improve understanding, leverage knowledge, and support transparency.

From the assessment of current BCF software implementation, many export errors were detected. No tool was able to export a BCF file fully in accordance with the current bcfXML v2 specification, and elements and attributes available in the tools were not always exported. This indicates a clear need for a certification process similar to the certification for IFC software implementation – currently operated by buildingSMART – in particularly if the scope of BCF is to be expanded further.

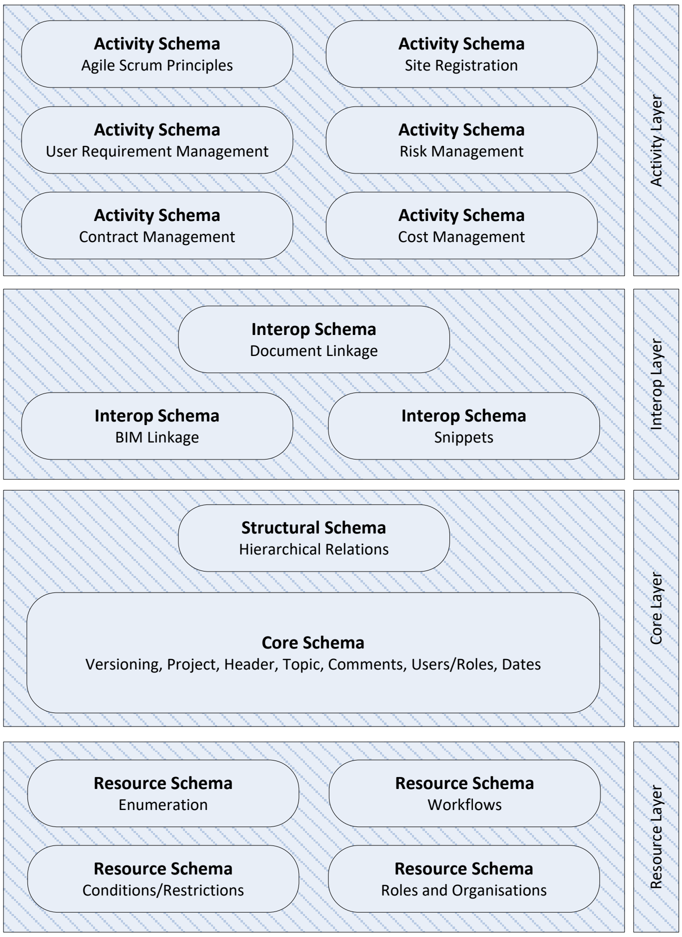


Figure 23. Proposal for an expanded BCF data schema architecture

Comparing the BCF specification with the specification of IDM Part 2 showed that the two standards have many similarities. Workflow support in IDM Part 2 and BIM support in BCF was identified as the main differences. Neither standard seemed superior to the other when their abilities were compared with the industry needs identified because needs for both predefined workflows, BIM linkage and a number of the elements and attributes from either of the two standards are requested. This suggested that harmonisation of the two standards would allow for improved support of industry needs. The proposed architecture for a potential expansion of the BCF format to support such harmonization and match industry needs is illustrated in Figure 23.

Should the BCF format be expanded as described, it could support capturing, structuring and exchange of process information in more elaborative ways. Based on the findings, a proposal for an information system with such abilities was described and is illustrated in Figure 24.

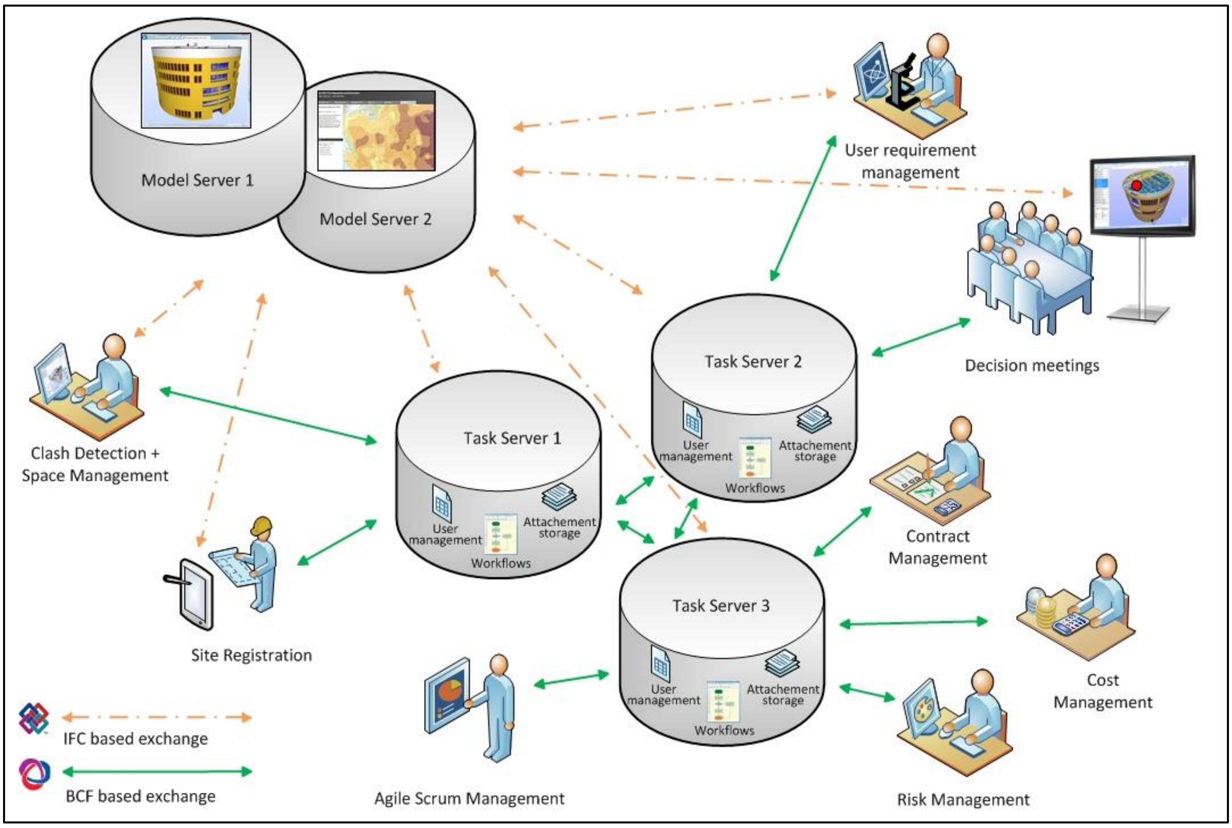


Figure 24. Proposal for information management and exchange in building design

The information system consists of decentralised model and task servers using both BCF and IFC. Each of the process activities is handled by one or more tools communicating with one or more task servers. Each task server can contain its own user management setup, workflow definitions and document storage to function independently. The need for decentralised solutions was identified similar to current practice in managing product information in decentralised model servers and is related to confidential and full-scale interoperability issues.

The JIRA platform used in Paper E was essentially working as a task management server and linking this server to other platforms would provide clear benefits. An open source plug-in has already been proposed (WeWork 2017) to link JIRA with product models using BCF, indicating industry needs in this regard. The testing of such linkage was out of scope of this thesis, but from findings in Paper E it was clear that misunderstanding of task content was a considerable issue and a better linkage to task authoring tools, the product model, functional requirements etc. would add to the understanding of task content. It was also clear in Paper E that standardized information exchange alone will not insure efficient collaboration and for this reason physical meetings with strong visual presentation abilities were important. This corresponds to the industry needs identified in this current paper of visualising the information and leveraging knowledge. This points to a required ability to balance standardized information flows with design management procedures which encourage collaboration and shared understanding.

10.5.3 Research Quality

The identified industry needs were grounded in selected literature only, but the different approaches in the literature including interviews, implementation attempts, and evaluation of existing tools is believed to validate findings as being representative to general needs in the industry.

Since the assessment of current BCF software tools, the BFC implementation has improved in most tools, however, with the high level of inconsistency identified it seems likely that new errors and misaligned implementation will continue. For this reason, the conclusion regarding need for certification seems valid to ensure reliable interoperability – in particular if the scope of BFC is to expand.

The need for harmonization of IDM Part 2 and BCF can have other implications than addressed in the paper because current implementation and usage of, in particular, IDM Part 2 will need to be changes. Since this is related to current contract management processes, some reluctance from current users must be expected.

Further development and testing of the information system proposal is required to validate its potential, however, research in Paper D and E clearly indicates a need to improve management of process information and based on the findings in the current paper, the proposed BCF data schema architecture has the potential to support this and the other identified industry needs.

This page is intentionally left blank.

Part IV – Discussion and Conclusion

11 Summarizing Research Findings

The findings in paper D confirm that high variability exist in current building design processes. From a design thinking perspective, this could be acceptable if the goal is to increase the understanding of the design problems to solve. As identified in paper E, there is a risk, however, that non-value adding design iterations will occur too frequently if the variability is not carefully managed. Building a strong community within the design team is vital to manage and reduce variability as it allows project managers to entrust the team to find solutions and coordinate activities more efficiently. Appling the APM methodology fits into this design practice and adds structure to the design development process. Only when such applicable management practices are in place, digitalization can add proper value (cf. Section 1.5). For digitalization to add value, efficient information management also needs to be in place, which requires that information can be captured, structured and exchanged in a standardized way (cf. Paper B and F).

The combined information model described in Section 7.1 includes four information models. In Paper B, the process and product model is identified as relevant and in Paper E, the mission and function model is identified as relevant. PLM systems are already in use in the manufacturing industry and support the integration of the four identified information models. The goal for the AEC industry should clearly be to implement solutions similar to PLM systems to achieve support for information integration. But, the nature of AEC projects requires a more pragmatic approach for PLM systems to be implementable. Modularisation concepts in standards and frameworks for information management – such as the IDM and LOD solutions in Paper A, B and C – address this challenge. Instead of needing to define the PLM structure and relations in each unique AEC project, product information requirements and relations to the process model can be automatically generated based on predefined standard work packages using e.g. the proposed IDM Manager.

Such solution requires initial work by national organisations, suppliers, clients, consultants, etc. to predefine the content of work package libraries. Considerable work is already ongoing in many countries to defining product information requirements, but so far the work is difficult to harmonize and reuse. An agreement to use a standard framework for IDM and LOD development – as proposed in this thesis – could not only improve standardization efforts but it could also provide a basis for improved abilities to introduce PLM systems to the AEC industry. The modular yet structured approach allows for automation of information requirements, flow optimization and identification of relations between information models, lowering the barriers for PLM system implementation.

The main focus in this research has been related to the process and the product model, but it seems that a similar modular approach could be applicable for linking the other information models as well. Creating a library of mission deliverables for the mission model could for example include derived functional requirements. The Danish energy frame requirements (The Danish Transport and Construction Agency 2015) with 'Building Class 2015' and 'Building Class 2020' is one example which allow clients to describe their ambition for energy performance of a building by simply referring to a certain energy class. This class translates into a set of functional requirements for energy consumption, window performance and ratio etc. – generating automatic content for the function model.

A specification defining the link between the functional model and the product models is already established and described by (Kiviniemi 2005). Based on this specification, the relation between requirements in the function model and objects in the product model can be established automatically for alignment between the two models.

Based on the type of building systems defined in the function model, it would also be possible to generate a work breakdown structure for the work to complete in the process model. For example, if cooling requirements are specified, engineering work to dimension a cooling system is required, and if vacuum outlets are required, a utility engineer dimensioning a vacuum system is required. Relations between the functional model and tasks in the process model can in this way also be built automatically if prior concepts for the relations between systems and activities are defined.

The modular approach adds value when used in relation to activities and processes in building design which are repeated across projects. Paper B illustrates that there is considerable overlap in work packages in the two different case study projects with almost 70 % of the work packages being reusable. A modular approach should, however, not aim to represent *all* possible project and organization types. Yet, using predefined packages can provide a consistent starting point for building content in a PLM system, and this seems highly attractive in order for such systems to be implemented in the AEC industry.

Combining the above findings – in particular the Scrum based APM methodology proposed in Paper E – with the combined information model described in Section 7.1, a methodology for building design management is proposed as shown in Figure 25. The methodology is referred to as the mission, function, process and product (MFPP) methodology for building design management and describes how to integrate information, organization, process and product into a platform which supports an agile development process in a pragmatic approach.

The client brief was included in the illustration of the combined information model in Section 7.1, but is removed in the MFPP methodology. Instead this author argues that the client brief should be an integrated part of the methodology – a starting point for the first content in the information models. This will ensure far better integration between client needs and design solutions and motivate further for keeping the mission model continuously updated throughout the design process.

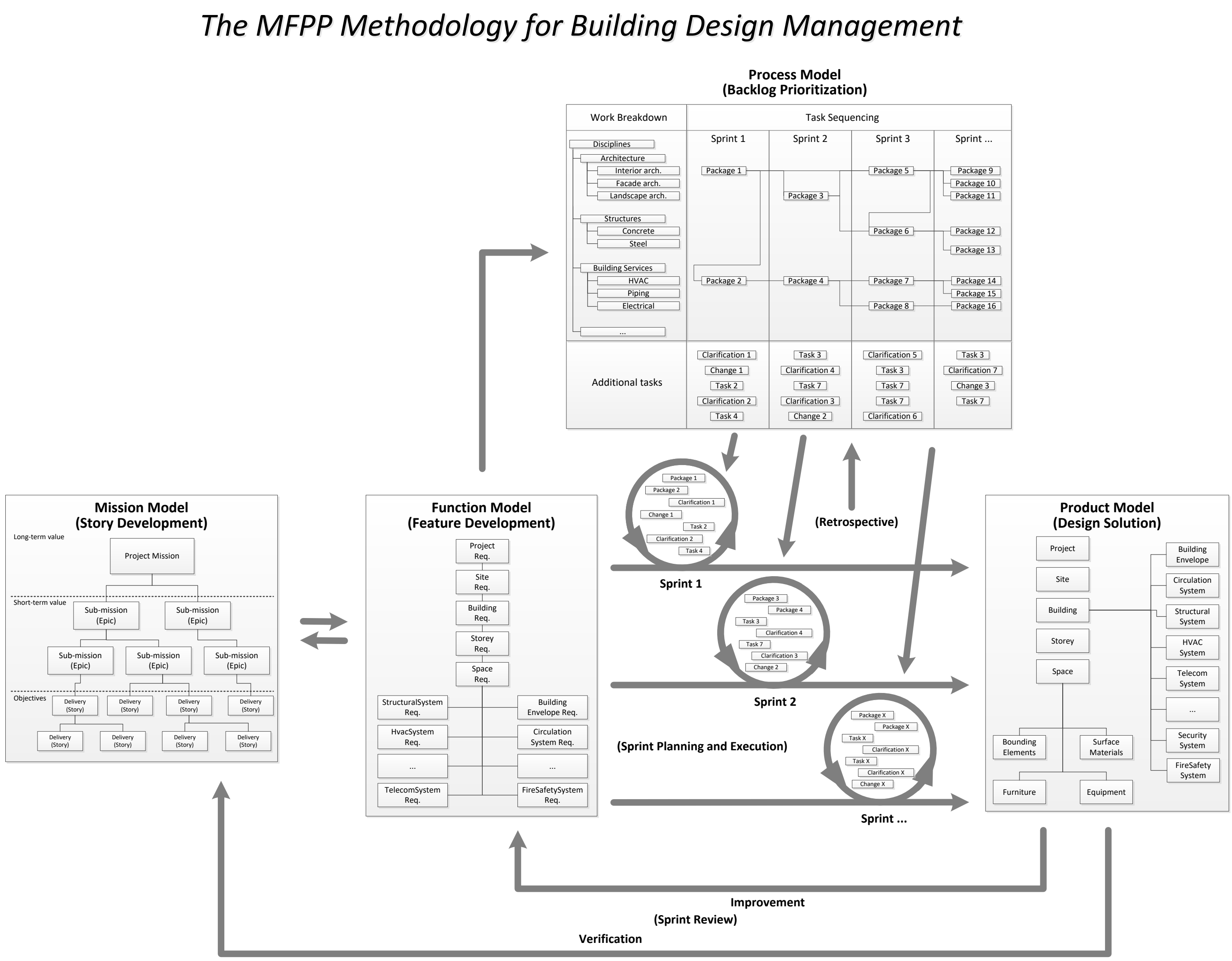


Figure 25. The MFPP methodology proposed as a result of the research in this thesis

In brackets in the illustration above is the APM terminology used in Paper E to illustrate how the information models relate to the APM development steps. The illustration in Figure 26 is introduced in Section 6.4 and also represents the APM development steps but in general terms. The map in Figure 26 can be used as a guide to understand the intention with the MFPP methodology as following:

1. The Mission model should capture information from the requirement analysis step which is referred to as story development in APM.
2. The Function model should capture information from the functional analysis step which is referred to as feature development in APM.
3. The Product model should capture information from the synthesis step which is referred to as the design solution developed incrementally during sprints in APM.
4. The Process model should capture information on tasks required in primarily the requirements and design loop referred to as backlog prioritization and sprint planning in APM.

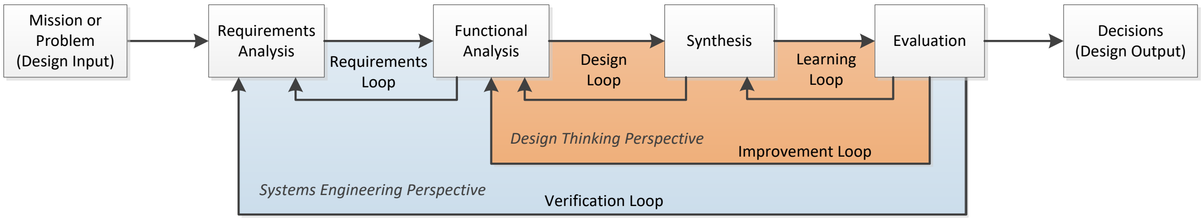


Figure 26. Map of the design process from both a systems and a design thinking perspective – identical to Figure 12

The process model should be considered as a combination of the task management platform proposed in Paper F and the IDM Manager presented in Paper B. Some distinction is required in this regard as the term 'task' is used differently in the scientific papers. A *task* should be considered as a general term for any elements in a process. In Paper E, four types of tasks are identified as *design issues*, *tasks* (here as low-level tasks), *clarification issues* and *change requests*. *Design issues* should, however, be split into *deliverables*, which are defined in the Mission model, and *work packages* which are defined in the Process model. This differentiation was a lack in the APM methodology tested because it mixed what should have been stories of client needs with high level design activities – probably adding to the difficulties of describing clear functional requirements in the case studies. Work packages for the design activities should be used to plan the information flow efficiently in the IDM Manager and all additional tasks related to decision-making, feedback etc. should be planned alongside the work packages to prioritize which tasks are to be solved in what sprints. Tasks related to decision-making and feedback should not be included in the IDM Manager, as these should not influence the information flow planning as discussed in Paper B, page 10.

The MFPP methodology is not tested within this thesis as it is proposed retrospectively to the work completed. However, several elements have been evaluated in the scientific papers resulting in findings which support the content of the MFPP methodology. For this reason, the methodology is believed by this author to be a valid solution for a pragmatic approach to a PLM platform to the AEC industry which supports the needed agile development steps. As discussed previously in this section, it is further supportive of modular approaches which allow for automated creation of internal structures and content along with creation of relations between the information models.

This research, furthermore, makes use of a range of different theories and methods which have previously been evaluated individually in the AEC industry and found useful. Based on the findings in this thesis it is clear that a multitude of theories and methods are required to support the diverse needs in building design management. The existing theories and methods should for this reason not be considered as alternatives to each other but as elements in an integrated approach. A key challenge ahead for the AEC industry is to find ways to integrate these theories and methods rather than executing these in parallel and thereby not achieving the required level of improvement. The MFPP methodology can serve as a contribution to how several perspectives can be integrated in a common approach for efficient building design management.

12 Answering the Research Questions

This section revisits the research questions described in Section 8 and elaborates on how the findings can provide solutions to the questions raised. The research questions consist of three sub-questions which were:

Sub-question 1: What is an efficient building design process?

Sub-question 2: How to manage *product* information within building design to support the desired design process?

Sub-question 3: How to manage *process* information within building design to support the desired design process?

Together these were intended to support the primary research question:

Primary research question: How should information in building design be managed to support an efficient building design process?

The research questions were investigated through the research conducted in the scientific papers and the relevance of each scientific paper to the research questions are describe in Table 7.

Table 7. Degree of relevance for each scientific paper to the research questions raised

	Paper A & B	Paper C	Paper D	Paper E	Paper F
Primary research question	High	Low	Low	High	High
Sub-question 1	Low		High	High	
Sub-question 2	High	Low			
Sub-question 3	Low			High	High

Several papers contribute in answering each research question and are supplemented with the summarizing of findings in Section 11. On this basis, each research question will be answered in the following sections. In the following chapter, the findings will be evaluated.

12.1 Sub-question 1

What is an efficient building design process?

An efficient building design process is a process which is well managed to reduce variability while producing design. The design process must also allow for learning by including design iterations which may or may not add direct value to the design. However, unnecessary or negative iterations should be avoided by ensuring a strong community within the design team, efficient flow of information and clear understanding of project values and requirements.

Agile project management is a useful method to support the needs identified because it combines a systems engineering perspective with a design thinking perspective and adds structure to the design development process. The APM methodology defined in Paper E promotes the need for aligning functional requirements with design in an incremental approach where continuous evaluation of solutions is important to ensure value generation. In relation to organisation, it is important that all stakeholders with assignments which are mostly interdependent are part of the APM approach and engaged in the intermediate community required. Tools from other design methods should be included in relation to understanding of constraints and decision making workflows, as it seems that this is a weakness in the tested APM methodology. Furthermore, the APM methodology is simple in its approach to validate design proposals but could benefit from including improved decision making tools as the ones described in Section 6.1.

It is a clear misunderstanding in the AEC industry that digitalization is able to create collaboration and strong communities. Instead it is important that an efficient design process must be in place before implementing digitalization initiatives. If the right management practices are in place, digitalization can improve knowledge sharing, planning and decision making processes and thereby further improve the efficiency of the design process.

12.2 Sub-question 2

How to manage product information within building design to support the desired design process?

Product information must be seen in relation to the specific design process in each individual project. This will often make information requirements project specific and the information system setup must be supportive of such required flexibility – including design and simulation tools and their information exchange interfaces.

Essentially, there is a need to narrow the flow of information between product models and designers (cf. Section 4.1). This can be done by focusing on what information is design specific and needed by others. To formulate such requirements, needs must be related to specific use cases by using for example the IDM package methodology. In relation to geometry, there is a need to simplify the way requirements are specified using a LOD framework, but such a framework must address concretization specifically to avoid misunderstanding.

To match the needs in unique and fragmented AEC projects, standards related to information management must be modular as there is otherwise a clear risk that standards will counteract the intentions in an efficient design process. It must be avoided that standardization takes ownership from the design team members. Instead standards should be used to eliminate doubt and allow for a pragmatic understanding of the design problems at hand. The IDM package methodology and generic LOD framework developed in Paper A, B and C supports these needs. Ensuring simple access to information in the product model is for this reason also a key concern and shared data repositories with product information must be set up to accommodate this need.

12.3 Sub-question 3

How to manage process information within building design to support the desired design process?

Process information is related to tasks of various kinds and their relation to other elements such as organisation (work breakdown), time (scheduling), functions (clarification/changes), product (feedback/coordination) and status (workflow). Tasks can be identified in several tools and processes and solved in several other tools and processes.

Work packages consisting of one or more design tasks must be well-defined in relation to their information needs and the planning of work packages must be completed so that an efficient information flow is achieved. The IDM Manager developed in Paper B allow for such abilities to manage work packages efficiently. Other types of tasks, such as clarification or decisions, should also be defined unambiguously, captured in a structured manner and be part of the continuous planning and prioritization process, but they should not be part of the planning in the IDM Manager as they do not influence the information flow. The management of tasks in the AEC industry could for this these reasons be supported by using a combination of the IDM Manager, to manage IDM packages, and one or more task repositories based on the BFC format as described in Paper F to capture and store tasks. For the task repositories to capture the range of task types identified in this research, the BFC format needs to be expanded and the proposed schema architecture in Paper F could be used as basis for such expansion.

The APM methodology provides a solution to how tasks can be utilized efficiently in building design. For the method to be successful, it is essential that the task repositories allow for efficient integration with other systems used. Moreover, it seems essential that the way tasks are managed must promote for dialog and discussion because the case studies in Paper E clearly indicate that collaboration is not efficient if tasks are only assigned in a system as opposed to a face-to-face dialog.

12.4 Primary Research Question

How should information in building design be managed to support an efficient building design process?

The primary goal for managing an efficient design process should be to integrate information, organization, process and product. The IPD framework (cf. Section 7) can contribute to create the required contractual arrangements and ensure motivation for such integration. Essentially, the goal for the AEC industry should be to implement solutions similar to PLM systems used in manufacturing to support the required integration. To achieve this in the AEC industry, the entry barriers for using PLM systems must be lowered. The MFPP methodology proposed in Section 11 summarizes the findings from the scientific papers and allows for lowering the entry barriers for integration and digitalization within the building design process. The MFPP methodology is for this reason a proposal to manage both information and the building design process as such.

The MFPP methodology relies on easy access to structured data. In the solutions developed in the scientific papers, the IFC, IDM, and BCF standards from buildingSMART are used to ensure open and easy access to data. The IDM and BCF standards need adjustments or expansions to be supportive of the MFPP methodology, but the industry needs in both cases are well documented and would benefit considerably from such adjustments or expansions. The MFPP methodology is a contribution to a next and challenging step for the AEC industry where both information and several different design methods, tools and workflows needs to be integrate. Such integration is a prerequisite for improvements to tackle the low productivity still troubling the AEC industry.

13 Evaluation of Solutions

The goal of this thesis is to contribute to practice and the knowledge base with new operational principles to already established theories on information management, socio-technical science, and design management. Evaluation is an essential part to establish a contribution and as described in Section 9, Hevner et al. (2004) defines utility, quality, and efficacy as key elements in such an evaluation. The evaluation must be carried out by comparing how well the developed solutions respond to the problems identified in the environment. In this research, problems are related to difficulties in the AEC industry to improve productivity, lack of an efficient design processes and limited digitalization of the industry. Each element in the evaluation will be addressed in the following section.

13.1 Utility

Utility is evaluated based on whether the solutions are unique, fits the environment, and solves a problem.

The AEC industry has for many years been aware that better collaboration and increased digitalization is needed for the industry to improve. The nature of AEC projects is, however, a barrier to achieve collaboration and digitalization. Multi-party contractual arrangement and in particular the IPD framework seem to be an important first step to increase possibilities for collaboration. The next step is to achieve integration and digitalization in the design process.

The MFPP methodology includes integration of several information models and similar concepts are already used in the manufacturing industry (Bruun et al. 2014), This is a needed foundation for further digitalization of the AEC industry as it has been for the manufacturing industry. What is unique in the proposed solution is the pragmatic and modular approach of its usage. This is found to fit the AEC industry needs for a more simple approach to the PLM system concept. The APM methodology is also new to the AEC industry and fits the needs in the building design process – compared to previous lean based methods – as it supports the iterative and interdependent development process in building design but adds structure to a process which has previously been managed with purely plan-driven management tools.

It was out of scope of this research to validate the entire MFPP methodology, but findings include confirmation that the modular approach has ability to lower implementation barriers and the APM methodology is a solution to support an efficient design process. Fischer et al. (2017) concludes that the integration abilities which is addressed in the MFPP methodology is an industry need and as such, the MFPP methodology solves a well-defined problem in the industry.

13.2 Quality

Quality is evaluated based on the functionality, completeness, and usability of the proposed solutions.

The MFPP methodology is a conceptual model and process for building design and needs tools to become operational. The IDM Manager developed within Paper B and the commercial tool JIRA, which were customized to support the APM methodology in Paper E are examples of tools which can make parts of the MFPP methodology operational. Both tools were evaluated by design teams and found to solve the required functionality within their area. Both tools provided improved overview and added increased understanding of the design process.

Further tools need to be included to support the required functionality of the complete MFPP methodology, but as noted by Kim et al. (2015) commercial tools already exist to capture requirements related to spaces, and both model and task servers exist to capture at least some process and product information (Berlo et al. 2012; Linhard and Steinmann 2014). Supporting the complete MFPP methodology will require for these tools to be expanded and allow for increased integration. The MFPP methodology defines guidelines for such integration and a needed scope, and the guidelines do not seem to involve radical changes to current tools. In relation to managing functional requirements, further research and development is needed as the scope of the function model was expanded considerably compared to the original requirement model developed by Kiviniemi (2005) focusing mostly on space requirements. The way to handle performance metrics and building system requirements and relations is less researched and to some extend requires other solutions than for space requirement. The design teams found it difficult to capture and use functional requirements as discussed in Paper E and Kim et al. (2015) also points to difficulties in keeping requirements updated in a changing design process. This area is in clear need for further research and development for the methodology to be complete and useful.

The IDM and LOD framework along with the APM methodology are all pragmatic approaches to an often complex building design process. They all rely on more work to be completed prior to commencing the design process, but the design process is then found to be more straight forward, better structured and easier to understand. Some project managers and design team members in Paper D and E were clearly struggling in keeping up with technology, and with the MFPP methodology promoting a highly technology driven design process these people will only feel more challenged. However, most of these people acknowledged that if they understood the purpose and experienced clear benefits, the motivation for engaging in new technology increased considerably. This implementation barrier should, however, not be underestimated as a potential key limitation for success of the solutions.

13.3 Efficacy

Efficacy is evaluated based on whether the solutions provide a result which is relevant and meaningful.

The global potential of $1.6 trillion annual in the AEC industry if it could increase its productivity to match the general economy (cf. Section 1.1) should be a key motivation for change in the industry. The solutions in this thesis contribute with elements which are essential for several of the improvement areas identified to increase productivity and are as such meaningful to the industry.

The specific request by project managers in Paper D to improve abilities for creating strong project communities and use ICT solutions which add clear value, further emphasise the importance of management methods, digitalization and standardization initiatives which support rather than limit collaboration and knowledge sharing.

The MFPP methodology can motivate for collaboration as identified in Paper E and can improve knowledge sharing by ensuring well-structured information and logic relations between information models as described in Paper B and F. Several elements in the methodology still need to be made operational, but the contribution can be meaningful by adding a framework for the industry to continue development upon.

14 Implications

In the following the main contributions, the practical impact and suggestions to future research will be described to summarize the research completed within this thesis.

14.1 Contribution to the Knowledge Base

The contribution of this research is made in the intersection between digitalization and design management and focuses on an improved basis for efficient planning and decision making processes. The thesis adds three primary contributions to the knowledge base:

1. **Operational principles to the TFV-theory in building design**
   The MFPP methodology adds knowledge on a pragmatic approach to implementation of the TFV-theory (cf. Section 6.3) in building design. It contributes with knowledge on how tools and methods proposed by Koskela and Huovila (1997) and described in Table 6 can be made operational and also suggest for corrections to the proposed range of tools and methods.

2. **Operational principles for combining system and production theory with socio-technical and reflective theory**
   The evaluation of the APM methodology adds knowledge of how to utilize solutions in building design which address the balance between efficient design production and abilities to allow for a learning process. The MFPP methodology further links the agile management method with information models to improve support for efficient decision making.

3. **Frameworks for modular and expandable solutions to industry information exchange standards**
   The IDM package framework, the generic LOD framework and the BFC schema architecture proposed within this research can add as contributions to the continuous development of standards in the AEC industry. The contributions to the development are solutions to ensure that standards can add value in the iterative and interdependent AEC design process.

In addition to the above, the research adds improved understanding of the challenges for project managers in relation to the building design process and identifies a range of limitations in current tools and design methods which needs to improve.

14.2 Barriers and Practical Impact

The solutions in this thesis includes methods which can support improved collaboration in building design, but the ability to achieve collaboration can be limited by organisational issues within most stakeholders involved. The IPD framework or a similar multi-party contractual arrangement will for this reason be a prerequisite in many cases as the motivation for collaboration could otherwise be missing.

In particular the incremental development of both design solutions and functional requirements in the APM methodology can be a challenge to traditional 'fixed' contracts. On the other hand, if the project is well-defined and includes limited needs for further requirement development it could be too much work to engage with the range of solutions within this research. As argued in Section 6.1 such well-defined projects seem, however, to be limited in number in the current practice and transitioning to methods which better support ill-defined and wicked problems should for this reason be attractive to the industry.

For some individuals in design teams, clients or other stakeholder organisations, the digital transformation seems to be a challenge as discussed in Section 13.2. The digital transformation already ongoing in the AEC industry is only to increase in momentum as better solutions are developed and this will add pressure on many individuals. For this reason, it seems important for the industry to ensure that competences within this area are increasing rapidly as the pace of innovation required will otherwise be limited from slow adoption in practice.

Modularisation and integration of solutions require commitment from the AEC industry organisations as content is required for the solutions to be of value. Currently strong opinions by different national organisations and large clients point in different directions and it could be a barrier if consensus on the direction for AEC development cannot be aligned to the principles of more modular yet integrated solutions.

The current work in the European Committee for Standardization (CEN 2015) on standardization of structured semantic life-cycle information for the built environment is an interesting example of cross-country collaboration on developing standards highly relevant to this research. The work completed in Paper B and C is directly applicable in two of the working groups in the CEN initiative and has been part of the Danish contribution to the debate.

The MFPP methodology can serve as a contribution to justify the need for solutions proposed within this research and in this way increase understanding for the direction of future research. At least in Ramboll, focus on methods to define more clear functional requirements and better incremental planning methods have intensified during the course of this thesis.

14.3 Future Research

The MFPP methodology sets a frame for an integrated approach to building design. The methodology needs to mature by further testing of each element and also by trying to apply several elements more consistently in case studies. In particular the capturing, structuring and linking of functional requirements needs further research as this has received limited focus within this thesis as well as in previous research, but also concluded to be a clear lack in the current design process. Research on functional requirements could be completed in a step-wise approach as the scope of research is large. Even smaller contributions on how functional requirements for building services can be develop alongside the design solutions would add clear value to the design process.

The APM methodology tested indicated that further tools should be included in this method as the decision making process in the case studies was clearly more complicated than expected. Research in how the APM methodology could be more efficient by improved understanding of agile decision making is for this reason also of great interest. From the findings in this study, it was also clear that the way information is presented visually to the design teams and other stakeholders is highly important to ensure shared understanding and collaboration. Further research on how information in the different information models is presented to the involved parties is for this reason of interest as it could increase motivation for using the methodology also for individuals who are reluctant to take on new technology in their design work.

The technology platforms required to support information capturing and management are still undergoing considerable development, but as discussed in Section 4.1 the development has been on a wrong path for quite some years aiming for *one* common shared data repository for at least all product information. The focus of platforms are now changing to a more modular and flexible setup, but there is still much research and development work to complete to understand how information is stored and linked efficiently in a more distributed manner. The MFPP methodology can add as a contribution to illustrate which interactions is required between the different information models and how information can be structured in unambiguous ways.

14.4 Concluding Remarks

The MFPP methodology can be subject to many further discussions in academia as well as in practice. The different elements need further improvements to support a fully efficient design process, but as a frame for new development initiatives the methodology provides a clear direction for matching the broad range of needs in building design processes. The methodology is of interest as it combines several theories and methods often analysed individually. This allows for improved understanding of the implications facing the AEC industry.

References

Andersen, E. S., Grude, K. V, and Haug, T. (2009). *Goal directed project management: Effective techniques and strategies*. Kogan Page Ltd., London, U.K.

Andersen, U. (2017). “Niels Bohr Bygningen bliver mindst 160 mio. kr. dyrere end planlagt [The Niels Borh Building will at a minimum be 160M DKK more expensive than planned].” *Ingeniøren*, <https://ing.dk/artikel/niels-bohr-bygningen-bliver-mindst-160-mio-kr-dyrere-end-planlagt-196176> (Mar. 30, 2017).

Anumba, C. J., Kamara, J. M., and Cutting-Decelle, A.-F. (2007). *Concurrent engineering in construction projects*. Taylor & Francis, London, U.K.

Appel, A., Dhadwal, A., Dorgan, S., and Dowdy, J. (2005). “When IT Creates Value.” *McKinsey Quarterly*, 6(4).

Aram, S., Eastman, C., Sacks, R., Panushev, I., and Venugopal, M. (2010). “Introducing a new methodology to develop the information delivery manual for AEC projects.” *Proc., CIB W78 2010: 27th International Conference*.

Arroyo, P. (2014). “Exploring Decision-Making Methods for Sustainable Design in Commercial Buildings.” University of California, Berkeley.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., and Brown, S. (2017). *Reinventing Construction: A Route To Higher Productivity*. McKinsey&Company.

Beck, K., Beedle, M., van Bennekum, A., Cockburn, A., and Fowler, M. (2001). “Manifesto for Agile Software Development.” <http://agilemanifesto.org> (Feb. 24, 2017).

Bell, B. S., and Kozolowski, S. W. J. (2002). “A Typology of Virtual Teams, Implications for Effective Leadership.” *Group and Organization Managment*, 27(1), 14–49.

Berard, O. (2012). “Building Information Modeling for Managing Design and Construction Assessing Design Information Quality.” Technical University of Denmark.

Berard, O., and Karlshoej, J. (2012). “Information delivery manuals to integrate building product information into design.” *ITcon Journal of Information Technology in Construction (ITcon)*, 17(17), 63–74.

Berlo, L. Van. (2015). “BIM Data Flow through Standards: Reducing Interfaces.” *BIM Show Live UK*, <https://www.slideshare.net/Stumico/bim-show-live-uk-lon-van-berlo> (Feb. 25, 2017).

Berlo, L. Van, and Krijnen, T. (2014). “Using the BIM Collaboration Format in a server based workflow.” *Procedia Environmental Sciences*, 22, 325–332.

Berlo, L. A. H. M. van, Beetz, J., Bos, P., Hendriks, H., and Tongeren, R. C. J. van. (2012). “Collaborative engineering with IFC: new insights and technology.” *Proc., 9th European Conference On Product And Process Modeling In The Building Industry (ECPPM)*, Reykjavik, Iceland, 811–818.

Bertelsen, S. (2003a). “Construction as a complex system.” *Proc., 11th Annual Conference in the International Group for Lean Construction*, Virginia, U.S., 143–168.

Bertelsen, S. (2003b). “Complexity – Construction in a New Perspective.” *Proc., 11th Annual Conference in the International Group for Lean Construction*, Virginia, U.S.

bips. (2016). “CCS Navigate.” *CCS Services*, <http://ccs.bips.dk> (Dec. 1, 2016).

Brinkmann, S., and Tanggaards, L. (2010). *Kvalitative metoder - En grundbog (in Danish)*. Hans Reitzels Forlag.

Brown, J. S., and Duguid, P. (1991). “Organizational Learning and Communities-of-Practice: Toward a Unified View of Working, Learning, and Innovation.” *Organization Science*, 2(1), 40–57.

Bruun, H. P. L., Hauksdóttir, D., Harlou, U., and Mortensen, N. H. (2014). “Mapping requirements to a product architecture supported by a PLM system." *Proc., International Design Conference, DESIGN*, Dubrovnik, Croatia, 1741–1752.

Bucciarelli, L. L. (2003). "Designing and Learning: A Disjunction in Contexts." *Design Studies*, 24(3), 295–311.

Buchanan, R. (1992). "Wicked Problems Thinking in Design." *Design Issues*, 8(2), 5–21.

BuildingSMART. (2016). "BCF intro." <http://www.buildingsmart-tech.org/specifications/bcf-releases/bcf-intro> (Jul. 19, 2016).

buildingSMART Norway. (2015). "bSN Guiden - Prosessveiledninger." <http://buildingsmart.no/bs-guiden/prosessveiledninger> (Oct. 19, 2015).

Bølviken, T., Gullbrekken, B., and Nyseth, K. (2010). "Collaborative Design Management." *Proc., 18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel, 103–111.

Carlile, P. R. (2004). "Transfering, Translating, and Transforming: An Integrative Framework for Managing Knowledge Across Boundaries." *Organization Science*, 15(5), 555–568.

CEN. (2015). *CEN/TC 442 Business Plan*. European Committee for Standardization, Brussels, Belgium.

Chatterjee, S., and Hevner, A. (2010). "Design Research in Information Systems: Theory and Practice." Springer US, New York, NY.

Cheng, R., Allison, M., Sturts-Dossick, C., Monson, C., Staub-French, S., and Poirier, E. (2016). *Motivation and Means: How and Why IPD and Lean Lead to Success*. University of Minnesota, Minneapolis, Minnesota.

Coates, P., Arayici, Y., Koskela, L., and Kagioglou, M. (2010). "The limitations of BIM in the architectural process." *Proc., 1st International Conference on Sustainable Urbanization (ICSU 2010)*.

Cobb, C. G. (2011). *Making Sense of Agile Project Management: Balancing Control and Agility*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Cross, N. (2011). *Design thinking: Understanding how designers think and work*. Berg, Oxford, U.K.

Dave, B., Koskela, L., Kagioglou, M., and Bertelsen, S. (2008). "A critical look at integrating people, process and information systems within the construction sector." *Proc., 16th Annual Conference of the International Group for Lean Construction*, Manchester, U.K.

Davenport, T. H. (1997). *Information Ecology*. Oxford University Press, New York, US.

Deming, W. E. (1982). *Out of crisis*. Massachusetts Institute of Technology, Cambridge, Mass.

Denscombe, M. (2014). *The Good Research Guide - For small-scale social research projects*. Open University Press, Berkshire, U.K.

Dorgan, S. J., and Dowdy, J. J. (2004). "When IT lifts productivity." *McKinsey Quarterly*, (4), 13–15.

Eastman, C., Sacks, R., and Lee, G. (2002). "Strategies for realizing the benefits of 3D integrated modeling of buildings for the AEC industry." *Proceedings of the 17th International Symposium on Automation and Robotics in Construction*, 9–14.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Emmitt, S., and Ruikar, K. (2013). *Collaborative design management*. Routledge, London, U.K.

Fischer, M., Khanzode, A., Reed, D., and Ashcraft, H. (2012). "Benefits of Model-Based Process Integration." *Proc., Lake Constance 5D-Conference*, Konstanz, Germany.

Fischer, M., Ashcraft, H. W., Reed, D. P., and Khanzode, A. (2017). *Integrating Project Delivery*. Wiley & Sons Inc., Hoboken, New Jersey.

Fundli, I. S., and Drevland, F. (2014). "Collaborative Design Management – A Case Study." *Proc., 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway.

Gallaher, M. P., O'connor, A. C., Dettbarn, J. L., and Gilday, L. T. (2004). *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. NIST, Gaithersburg, Maryland.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., and Trow, M. (1994). "Evoluiton of knowledge." *The new production of knowledge. The dynamics of science and research in contemporary*, SAGE Publications Inc., London, U.K., 17–45.

Gregor, S., and Hevner, A. R. (2013). "Positioning And Presenting Design Science Research For Maximum Impact." *MIS Quarterly*, 37(2), 337–355.

Gu, N., Singh, V., and London, K. (2014). "BIM Ecosystem: The Coevolution of Products, Processes, and People." *Building Information Modeling: BIM in Current and Future Practice*, (K. Kensek and D. Noble, eds.), John Wiley & Sons, (MAY), 197–210.

Hamzeh, F. R., Ballard, G., and Tommelein, I. D. (2009). "Is the Last Planner System Applicable To Design? a Case Study." *Proc., 17th Annual Conference of the International Group for Lean Construction*, Taipei, Taiwan, 407–416.

Hartmann, T., Fischer, M., and Haymaker, J. (2009). "Implementing information systems with project teams using ethnographic-action research." *Advanced Engineering Informatics*, Elsevier Ltd, 23(1), 57–67.

Hevner, A. R., March, S. T., Park, J., and Ram, S. (2004). "Design Science in Information Systems Research." *MIS Quaterly*, 28(1), 75–105.

Highsmith, J. (2009). *Agile project management: Creating innovative products*. Addison-Wesley Professional, Boston, US.

Hjelseth, E. (2015). *Foundations for BIM-based model checking systems*.

Hoeber, J. G., Alsem, D. M., and Willems, P. H. (2015). "The management of information over the life-cycle of a construction project using open-standard BIM." *Proc., 32nd CIB W78 Conference*, Eindhoven, The Netherlands.

Hooper, M. (2015). "BIM Anatomy II - Standardisation needs and support systems." Lund University.

INCOSE. (2015). *Systems engineering handbook a guide for system life cycle processes and activities*. (D. D. Walden, G. J. Roedler, K. Forsberg, R. D. Hamelin, and T. M. Shortell, eds.), John Wiley & Sons, Inc., Hoboken, New Jersey.

ISO. (2012a). "Building information models - Information delivery manual - Part 2: Interaction framework." *ISO 29481-2*, Geneva, Switzerland.

ISO. (2012b). "Industrial automation systems and integration - Product data representation and exchange - Part 239: Application protocol: Product life cycle support." *ISO 10303-239*, Geneva, Switzerland.

ISO. (2013). "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries." *ISO 16739*, Geneva, Switzerland, 23.

ISO. (2016). "Building information models - Information delivery manual - Part 1: Methodology and format." *ISO 29481-1*, Geneva, Switzerland.

Johansson-Sköldberg, U., Woodilla, J., and Çetinkaya, M. (2013). "Design Thinking : Past, Present and Possible Futures." *Creativity and Innovation Management*, 22(2), 121–146.

Johnson, R. B., Onwuegbuzie, A. J., and Turner, L. A. (2007). "Toward a Definition of Mixed Methods Research." *Journal of Mixed Methods Research*, 1(2), 112–133.

Kamara, J. M., Anumba, C. J., and Cutting-Decelle, A.-F. (2007). "Introduction to Concurrent Engineering in construction." *Concurrent Engineering in Construction Projects*, J. M. Kamara, C. J. Anumba, and A.-F. Cutting-Decelle, eds., Taylor & Francis, London, UK, 1–11.

Kerosuo, H., Miettinen, R., Paavola, S., Mäki, T., and Korpela, J. (2015). "Challenges of the expansive use of Building Information Modeling (BIM) in construction projects." *Production*, 25(2), 289–297.

Kim, T. W., Kim, Y., Cha, S. H., and Fischer, M. (2015). "Automated updating of space design requirements connecting user activities and space types." *Automation in Construction*, Elsevier B.V., 50(C), 102–110.

Kiviniemi, A. (2005). "Requirements management interface to building product models - CIFE Technical Report #161." Stanford University, USA.

Kleinsmann, M., and Valkenburg, R. (2008). "Barriers and enablers for creating shared understanding in co-design projects." *Design Studies*, 29(4), 369–386.

Knorr Cetina, K. (2001). “Objectual practice.” *The Practice Turn in Contemporary Theory*, T. R. Schatzki, K. Knorr Cetina, and E. von Savigny, eds., 184–197.

Knotten, V., Svalestuen, F., Hansen, G. K., and Lædre, O. (2015). “Design Management in the Building Process - A Review of Current Literature.” *Procedia Economics and Finance*, Elsevier B.V., 21(2212), 120–127.

Knotten, V., Svalestuen, F., Aslesen, S., and Dammerud, H. (2014). “Integrated methodology for design management - A research project to improve design management for the AEC industry in Norway.” *Proc., 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 1391–1399.

Koskela, L. (2000). “An Exploration towards a Production Theory and its Application to Construction.” *VTT Publications 408*, Technical Research Centre of Finland.

Koskela, L. (2007). “Foundations of Concurrent Engineering.” *In Concurrent Engineering in Construction Projects*, J. M. Kamara, C. J. Anumba, and A.-F. Cutting-Decelle, eds., Taylor & Francis, London, UK, 12–29.

Koskela, L., and Huovila, P. (1997). “Foundations of concurrent engineering.” *In Concurrent Engineering in Construction – Papers presented at the 1st International Conference*, C. J. Anumba and N. F. O. Evbuomwan, eds., London, U.K., 22–32.

Koskela, L., Pikas, E., Gomes, D., Rahim, N., Biotto, C., Talebi, S., and Tzortzopoulos, P. (2016). “Towards Shared Understanding on Common Ground , Boundary Objects and Other Related Concepts.” *Proc., 24rth Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, 63–72.

Krippendorff, K. (2006). *The semantic turn: A new foundation for design*. CRC/Taylor & Francis, Boca Raton, Fl.

Kroll, E., and Koskela, L. (2015). “Applying the proto-theory of design to explain and modify the parameter analysis method of conceptual design.” *International Journal of Design Creativity and Innovation*, 4(1), 1–25.

Kunz, J. (2013). “Integrated Concurrent Engineering.” *Center for Integrated Facility Engineering*, <https://web.stanford.edu/~kunz/Chalmers/W2ICEOverview.pdf> (Mar. 2, 2017).

Kvale, S., and Brinkmann, S. (2015). *InterViews: learning the craft of qualitative research interviewing*. SAGE Publications Inc., Thousand Oaks, California.

Lahdenperä, P. (2012). “Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery.” *Construction Management and Economics*, 30(1), 57–79.

Lave, J., and Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press, Cambridge.

Lawson, B. (2005). *How Designers Think: The Design Process Demystified*. Architectural Press, London, UK.

Lee, G., Eastman, C. M., and Sacks, R. (2007). “Eliciting information for product modeling using process modeling.” *Data & Knowledge Engineering*, 62(2), 292–307.

Lee, G., Park, Y. H., and Ham, S. (2013). “Extended Process to Product Modeling (xPPM) for integrated and seamless IDM and MVD development.” *Advanced Engineering Informatics*, Elsevier Ltd, 27(4), 636–651.

Lightsey, B. (2001). *Systems Engineering Fundamentals*. Defense Acquisition University Press, Fort Belvoir, Virginia.

Liker, J. K. (2004). *The Toyota way : 14 management principles from the world’s greatest manufacturer*. McGraw-Hill, New York, NY.

Linhard, K., and Steinmann, R. (2014). “BIM -collaboration processes – from fuzziness to practical implementation.” *Proc., 11th European Conference on Product and Process Modeling (ECPPM)*, Vienna, Austria, 27–31.

Malleson, A. (2016). *International BIM Report 2016 - The International picture*. *NBS*, Newcastle upon Tyne, U.K.

Martínez-Rojas, M., Marín, N., and Vila, M. A. (2015). “The role of information technologies to address data handling in construction project management.” *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

McDermott, R. (1999). “Why Information Technology Inspired But Cannot Deliver Knowledge Management.” *California Management Review*, 41(4), 103–117.

McGraw-Hill Construction. (2014). *The Business Value of BIM for Construction in Major Global Markets: How contractors around the world are driving innovation with Building Information Modeling*. *SmartMarket Report*, Bedford, USA.

Miettinen, R., and Paavola, S. (2014). “Beyond the BIM utopia: Approaches to the development and implementation of building information modeling.” *Automation in Construction*, Elsevier B.V., 43, 84–91.

Moon, H., Kim, H., Kamat, V. R., and Kang, L. (2015). “BIM-Based Construction Scheduling Method Using Optimization Theory for Reducing Activity Overlaps.” *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

Nicolini, D. (2012). *Practice Theory, Work and Organization. An Introduction*. Oxford University Press, Oxford, U.K.

Nicolini, D., Mengis, J., and Swan, J. (2012). “Understanding the Role of Objects in Cross-Disciplinary Collaboration.” *Organization Science*, 23(3), 612–629.

Oh, M., Lee, J., Hong, S. W., and Jeong, Y. (2015). “Integrated system for BIM-based collaborative design.” *Automation in Construction*, Elsevier B.V., 58, 196–206.

Otter, F. den, and Prins, M. (2011). “Architectural design management within the digital design team.” *Engineering, Construction and Architectural Management*, 9(3), 162–173.

Owen, R., Koskela, L., Henrich, G., and Codinhoto, R. (2006). “Is agile project management applicable to construction?” *Proc., 14th Annual Conference in the International Group for Lean Construction*, Santiago, Chile, 51–66.

Owen, R. L., and Koskela, L. (2006). “An Agile step forward in project management.” *Proc., 2nd Specialty Conference on Leadership and Management in Construction*, Grand Bahama Island, Bahamas, 216–224.

Parrish, K. D. (2009). “Applying A Set-Based Design Approach To Reinforcing Steel Design.” University of California, Berkeley.

Pemberton-Billing, J., Cooper, R., Wootton, A. B., and North, A. N. W. (2003). “Distributed Design Teams as Communities of Practice.” *Proc., 5th European Acafemy of Design Conference*, Barcelona, Spain.

Pikas, E., Koskela, L., Sapountzis, S., Dave, B., and Owen, R. (2011). “Overview of building information modelling in healthcare projects.” *Proc., HaCIRIC 11 Conference*.

Pikas, E., Koskela, L., Thalfeldt, M., Dave, B., and Kurnitski, J. (2015). “Complexity in Designing Energy Efficient Buildings : Towards Understanding Decision Networks.” *Proc., 23rd Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, 213–222.

Pikas, E., Koskela, L., Treldal, N., and Ballard, G. (2016). “Collaborative Design – Justification , Characteristics and.” *Proc., 24rth Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts.

Pinto, J. K. (2016). *Project Management : Achieving Competitive Advantage*. Pearson Education, Boston, US.

PMI. (2013). *A Guide to the project management body of knowledge (PMBOK guide).* Project Management Institute, Inc., Newtown Square, Pennsylvania.

Reed, B. (2009). *The integrative design guide to green building : redefining the practice of sustainability*. Wiley, Hoboken, N.J.

El Reifi, M. H., and Emmitt, S. (2013). “Perceptions of lean design management.” *Architectural Engineering and Design Management*, 9(3), 195–208.

El Reifi, M. H., Emmitt, S., and Ruikar, K. (2013). “Developing a conceptual lean briefing process model for lean design management.” *Proc., 21th Annual Conference in the International Group for Lean Construction*, Fortaleza, Brazil, 329–338.

Riedel, R., Jentsch, D., Horbach, S., Ackermann, J., and Müller, E. (2013). “Agile Planning Processes.” *Advances in Production Management Systems. Sustainable Production and Service Supply Chains*, 414, 143–150.

Riis, E. (2013). “Methods for setting objectives and mission breakdown structure.” *Projektledelse*, 17(2).

Rowe, P. G. (1987). *Design thinking*. The MIT Press, Cambridge, Massachusetts.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. Basic Books, New York, USA.

Serrador, P., and Turner, R. (2005). “The Relationship Between Project Success and Project Efficiency.” *Project Management Journal*, 46(1), 30–39.

Shafiq, M. T., Matthews, J., and Lockley, S. R. (2013). “A study of BIM collaboration requirements and available features in existing model collaboration systems.” *Journal of Information Technology in Construction*, 18, 148–161.

Shenhar, A., and Dvir, D. (2007). *Reinventing Project Management: The Diamond Approach to Successful Growth and Innovation*. Harvard Business Press, Boston, Mass.

Shenhar, A. J., Levy, O., and Dvir, D. (1997). “Mapping dimensions of projects success.” *Project Management Journal*, 28(2), 5–13.

Simon, H. A. (1996). *The sciences of the artificial*. *Computers & Mathematics with Applications*, MIT Press, Cambridge, Massachusetts.

Soibelman, L., and Kim, H. (2002). “Data Preparation Process for Construction Knowledge Generation through Knowledge Discovery in Databases.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 16(1), 39–48.

Star, S. L. (2010). “This is Not a Boundary Object: Reflections on the Origin of a Concept.” *Science, Technology & Human Values*, 35(5), 601–617.

Star, S. L., and Griesemer, J. R. (1989). “Institutional Ecology, `Translations’ and Boundary Objects: Amateurs and Professionals in Berkeley’s Museum of Vertebrate Zoology, 1907-39.” *Social Studies of Science*, 19(3), 387–420.

Star, S. L., and Ruhleder, K. (1996). “Steps Toward an Ecology of Infrastructure: Design and Access for Large Information Spaces.” *Information Systems Research*, 7(1), 111–134.

Tang, L. C. M., Zhao, Y., Austin, S., Darlington, M., and Culley, S. (2008). “Overload of Information or Lack of High Value Information: Lessons Learnt from Construction.” *Proc., 9th European Conference on Knowledge Management*, 851–860.

Tarandi, V. (2011). “The BIM Collaboration Hub: A model server based on IFC and PLCS for Virtual Enterprise Collaboration.” *Proc., CIB W78 2011: 28th International Conference*, Sophia Antipolis, France, 951–960.

Teicholz, P. (2013). “Labor-Productivity Declines in the Construction Industry: Causes and Remedies (Another Look).” *AECbytes Viewpoint*.

The Danish Transport and Construction Agency. (2015). “Danish Building Regulations 2015.” <http://bygningsreglementet.dk/file/591081/br15_english.pdf> (Mar. 30, 2017).

Tilley, P. a. (2005). “Lean Design Management — a New Paradigm for Managing the Design and Documentation Process To Improve Quality ?” *Proc., 13th Annual Conference in the International Group for Lean Construction*, Sydney, Australia, 23–35.

Tribelsky, E., and Sacks, R. (2011). “An Empirical Study of Information Flows in Multidisciplinary Civil Engineering Design Teams using Lean Measures.” *Architectural Engineering and Design Management*, 7(2), 85–101.

Universitets- og Bygningsstyrelsen. (2010). *Niels Bohr Science Park - Københavns Universitet - Competition Brief*. Copenhagen, Denmark.

Vaishnavi, V., and Kuechler, B. (2015). “Design Science Research in Information Systems.”

<http://www.desrist.org/design-research-in-information-systems/> (Nov. 4, 2016).
De Vaus, D. A. (2002). *Surveys in social research*. Allen & Unwin, St. Leonards, N.S.W., Australia.
Wallaert, J., and Knudsen, S. (2017). "Configuring Generative AECO Dynamics: A Case Study." *AUGIWorld*, 32–35.
Wang, L., and Leite, F. (2016). "Process Knowledge Capture in BIM-Based Mechanical, Electrical, and Plumbing Design Coordination Meetings." *Journal of Computing in Civil Engineering*, 30(2).
Ward, A. C., Liker, J. K., J., C. J., and Sobek II, D. K. (1995). "The Second Toyota Paradox: How delaying decisions can make better cars faster." *Sloan Management Review*, 36(3), 43–61.
Wegner, D. M. (1987). "Transactive memory: A contemporary analysis of the group mind." *Theories of Group Behavior*, Springer, 185–208.
Wegner, D. M., Erber, R., and Raymond, P. (1991). "Transactive memory in close relationships." *Journal of Personality and Social Psychology*, 61(6), 923.
Wenger, E. (1998). *Communities of practice : learning, meaning, and identity*. Cambridge University Press, Cambridge, U.K.
WeWork. (2017). "BCF to JIRA client for the Building Industry." *WeWork Digital*, <https://github.com/WeConnect/issue-tracker> (Mar. 27, 2017).
Yalcinkaya, M., and Singh, V. (2016). "A Visual Transactive Memory System Approach Towards Project Information Management." *CIB W78 Conference 2016*.
Yassine, A., and Braha, D. (2003). "Complex Concurrent Engineering and the Design Structure Matrix Method." *Concurrent Engineering*, 11(3), 165–176.
Zhang, J., and El-Gohary, N. M. (2015). "Automated Information Transformation for Automated Regulatory Compliance Checking in Construction." *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

This page is intentionally left blank.

Part V – Scientific Papers

This page is intentionally left blank.

Paper A -
Introducing A New Framework for Using Generic Information Delivery Manuals

Introducing a new framework for using generic Information Delivery Manuals

T.F. Mondrup
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

N. Treldal
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
Ramboll Denmark A/S, Copenhagen, Denmark

J. Karlshøj
F. Vestergaard
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

ABSTRACT: Information flow management plays a significant role in ensuring the reliable exchange of Building Information Modeling (BIM) data between project team members in the Architecture, Engineering, Construction, and Facility Management (AEC/FM) industry. The buildingSMART standard approach to resolving this issue is based upon the Information Delivery Manual (IDM), which provides a collaborative methodology for specifying AEC/FM process flows and their information contents. The IDMs in current use indicate that focus has mainly been on formalizing more general parts of the building design process, where multiple project team members perform a wide range of design tasks. Because IDMs typically describe such complex processes, they are difficult to manage and complicated to implement in real-world AEC/FM projects. In this study, we address these challenges by proposing a Work Breakdown Structure (WBS) methodology, breaking down the IDMs into smaller IDM Packages. We introduce a modular IDM Framework aimed at defining and organizing generic IDM Packages for all main use cases of the AEC/FM project life cycle. In this methodology, an IDM Project Plan can be created by selecting the specific IDM Packages required for a specific AEC/FM project. Ultimately, we believe that the IDM Framework will help improve information flow management and the reusability of IDM Packages amongst unique AEC/FM projects. In addition, we believe that the IDM Framework will support the potential harmonization of the development of new IDMs, as the specific context of each IDM Package, and the relationship to other IDM Packages, becomes clearer. Such harmonization is also necessary, if improved interoperability between AEC/FM software tools is the goal.

1 INTRODUCTION

1.1 *Study background*

During recent years, a great deal of effort has been devoted to improving interoperability between software tools in the Architecture, Engineering, Construction, and Facility Management (AEC/FM) industry. Despite some progress, streamlined information exchange remains a challenge (Eastman et al. 2010).

To achieve this interoperability, a common understanding of the AEC/FM processes, and the information needed by and resulting from these processes, is required (Wix et al. 2009). Software vendors need this understanding as a basis to develop software tools that support the multiple AEC/FM processes and associated information exchange structures. End users, however, also need this understanding, as the use of relevant software tools has limited impact if the AEC/FM process is confused at the outset (Koskela et al. 2002).

Generally, an increasing integration of software tools and information systems accelerates the amount of information available in AEC/FM projects. However, to ensure optimum information quality, the amount of information in information systems should be kept to a minimum (Hjelseth (2011). Therefore, the need to define and organize AEC/FM information exchanges is of fundamental importance in trying to improve interoperability and implementation of software tools in real-world AEC/FM projects.

To address these issues, the buildingSMART alliance has introduced the Information Delivery Manual (IDM), which provides a methodology to specify AEC/FM process flows and their information content (Wix et al. 2009). Despite the great potential of IDMs, and the fact that more than 100 IDMs are currently registered on the buildingSMART website (Karlshoej 2013), the industry-wide use of IDMs is limited (Karlshoej 2012).

1.1 *Study goals*

This study has two goals. The first is to explore the benefits and possible challenges associated with successful AEC/FM information flow management. The second is to introduce a common IDM Framework to define and organize AEC/FM processes and associated information exchanges.

The study goals are addressed by: (1) a review of current approaches to AEC/FM information flow management to understand the background, and (2) the development of an IDM Framework to facilitate improved AEC/FM information flow management and interoperability between AEC/FM software tools.

2 METHODOLOGY

2.1 *Review of current approaches*

A review of AEC/FM information flow management trends has been conducted. The review included articles conducted by academic institutes; industry work practice; technical reports from software vendors; guidelines generated by government institutions; and currently available IDMs.

The review was carried out to explore the benefits and challenges of AEC/FM information flow management, and specifically focused on the critical role of integrating buildingSMART standard approaches (See et al. 2012) and Work Breakdown Structure (WBS) technologies (Brotherton et al. 2008).

In a series of supplementary discussions, selected experts validated the components identified in the review.

2.2 *Development of IDM Framework*

Based upon the findings of the review, a structure for the development of an IDM Framework has been planned. The IDM Framework has been developed to address challenges highlighted in the review, more specifically the challenge of ensuring successful information flow management. To address this particular challenge, generic and modular management approaches are proposed.

3 REVIEW

3.1 *Industry Foundation Classes (IFC)*

The Industry Foundation Classes (IFC), developed by buildingSMART, is a data model standard that has been proposed to describe, exchange, and share information in an open and neutral format (See et al. 2012). Although IFC is the means of achieving software interoperability within AEC/FM projects, the industry-wide use and implementation in specific software tools remains a challenge (Aram et al. 2010). To date, IFC-based information exchanges mainly focus on geometry exchange.

To improve the reliability of IFC, specifications and well-documented guidelines for specific information exchange scenarios are required. For this reason, buildingSMART has proposed the Information Delivery Manual (IDM) and Model View Definition (MVD) (Karlshoej 2012; Wix et al. 2009).

3.2 *Information Delivery Manual (IDM)*

The Information Delivery Manual (IDM), developed by buildingSMART, is a process standard that has been proposed to define information exchanges between any two project team members in an AEC/FM project, with a specific purpose, within a specified stage of the project's life cycle (See et al. 2012). The IDM consists of four deliverables:

- IDM Use Case: Defines the activities, project participants, and information exchanges, as required for a specific AEC/FM process.
- IDM Process Map (PM): Formalizes the relationship between these activities, project participants, and information exchanges.
- IDM Exchange Requirements (ERs): Define the information units, as required for each use-case-specific information exchange.
- IDM Exchange Requirements Models (ERMs): Organize the ERs into Exchange Objects (EOs), that is machine-interpretable information exchange packages.

The core of an IDM is the process that is to be standardized. However, limited guidance is provided by buildingSMART on how much of the AEC/FM project life cycle, and which specific processes, should be included in the individual use cases that form the basis of new IDM developments. Generally, buildingSMART recommends that industry experts and team members of specific IDM development groups be allowed to determine the areas of need (See et al. 2012). Of particular interest is that these experts and development groups often represent specific disciplines or organizations.

Accordingly, currently available IDMs describe a diverse scope of the AEC/FM project life cycle, making them difficult to reuse and implement in unique AEC/FM projects.

Furthermore, the researchers found that using the currently available IDMs to describe greater areas of the AEC/FM project life cycle may result in both significant process overlaps and critical gaps between sub-processes that are not yet included.

3.3 *Model View Definition (MVD)*

The Model View Definition (MVD), developed by buildingSMART, is a technical standard that has been proposed to document the required information exchanges defined in one or more IDMs (See et al. 2012). The MVD consists of four deliverables:

– MVD Description: Defines the information exchanges, as required for specific IDMs.
– MVD Concepts. Address these information exchanges, by linking with the corresponding EOs.
– MVD Diagrams: Identify and structure the IFC entities, as required for exchanging these Concepts.
– MVDXML: Generates a machine-interpretable representation of the information exchanges, as subject of the Diagrams.

Generally, the MVD is designed to document the required IFC information exchanges, against which IFC software certification testing can be applied. Officially, there exists only a single buildingSMART MVD for such certification, that is the IFC2x3 Coordination View V. 2.0 MVD (Wix et al. 2009).

3.4 *Work Breakdown Structure (WBS)*

The Work Breakdown Structure (WBS), developed by the United States Department of Defense, is a project management methodology that defines and organizes the processes of a project (Brotherton et al. 2008) (O'Donnell 2012).

The WBS methodology uses a hierarchical tree structure, and enables the processes of a specific project to be broken down into smaller, more manageable sub-processes, which makes it possible to uniquely identify sub-processes. Figure 1 shows an example of a WBS for building design.

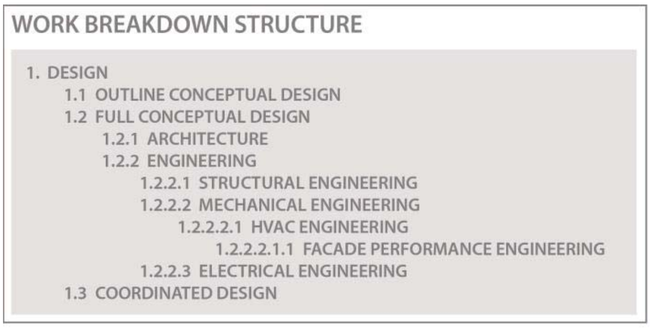


Figure 1: WBS for building design.

If processes described in IDMs are intended to be reusable across disciplines or organizations, it will require that these processes can be mapped against a unified WBS. Arguably, it could be beneficial to define a commonly accepted WBS, representing all processes within the AEC/FM project life cycle, and to require all IDM processes to be mapped against this WBS.

3.5 *Increasing project complexity*

As previously stated, the main purpose of developing IDMs is to define the specifications for selected processes and information exchanges. However, as Berard & Karlshoej (2012) indicate, current AEC/FM projects are perceived as unique and ever changing. Therefore, AEC/FM processes and information exchanges are unique. This presents a considerable challenge to the concept of developing a standardized framework to define and organize information exchanges. Furthermore, it limits the potential industry-wide use and reusability of IDMs amongst unique AEC/FM projects.

Hjelseth (2011) recommended that BIM Guidelines be decomposed, similar to IDMs, into individual Information Modules (IMs), with each IM representing a specific use case and a set of associated information exchanges. The IMs would provide the basis for BIM Guidelines to be implemented in a wide range of AEC/FM projects, as compared to traditional BIM Guidelines, which tend to focus on the authoring organization or project, and therefore make them less useful in other organizations or project types.

Generally, BIM Guidelines are not sufficient to support AEC/FM information exchange. However, IDMs are. By defining IDMs in the above manner, improved approaches to standardizing information exchanges in unique AEC/FM projects can be realized.

3.6 *Review findings*

Information flow management and standardization methodologies were the most prominent points in the review. The review findings are summarized as follows:

– AEC/FM information flow management should be based upon integrated approaches, common standards, and well-documented procedures.
– Unique AEC/FM projects require modular approaches and flexible methodologies if standardized information exchanges are to be reusable throughout the entire AEC/FM project life cycle.
– IDM processes should be decomposed and identified in accordance with a commonly accepted AEC/FM WBS, such that the IDM can be reused and applied within any given AEC/FM project.

4 IDM FRAMEWORK

4.1 *IDM Framework structure*

The proposed IDM Framework introduces a two-dimensional WBS-based methodology aimed at de-

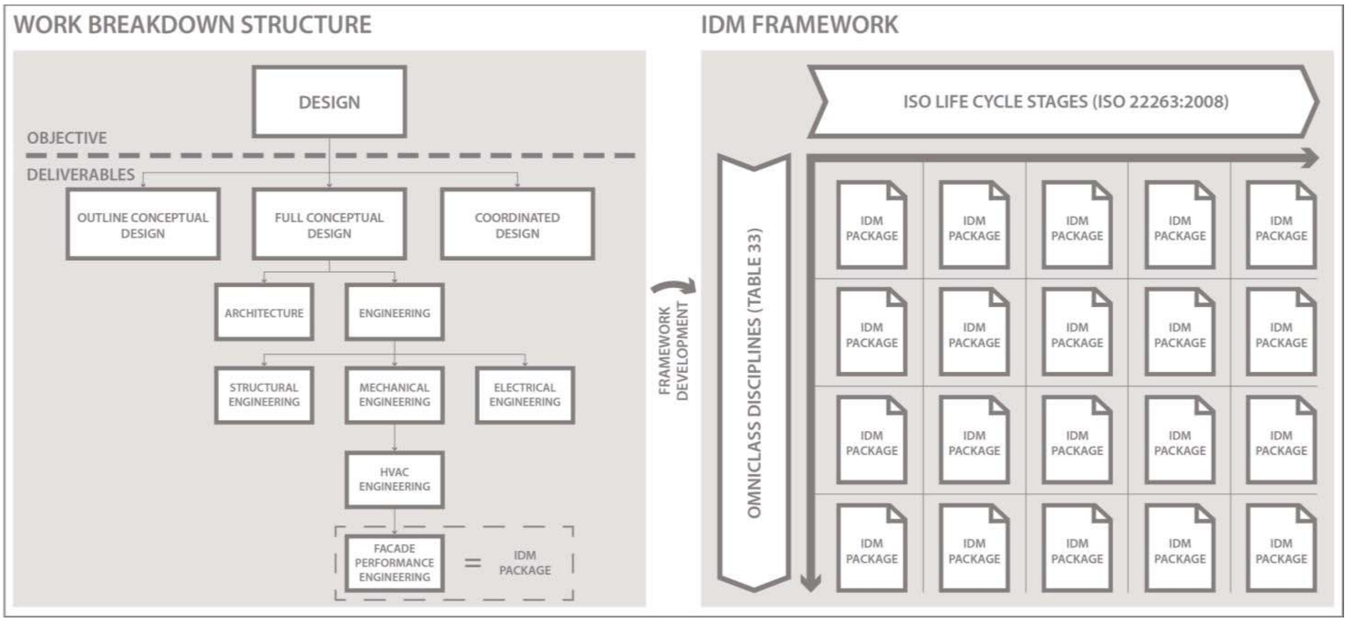


Figure 2: WBS for building design and IDM Framework structure.

fining and organizing the information exchanges within an AEC/FM project.

The IDM Framework builds upon a simple matrix structure of AEC/FM disciplines and project life cycle stages (Hall 2012). This structure serves as an "umbrella", covering all main use cases of the AEC/FM project life cycle. Given that use cases generally are defined to establish a basis for IDM developments, each use case defined in the IDM Framework represents a specified IDM Package. Figure 2 shows the WBS approach and the IDM Framework structure.

As illustrated, the framework disciplines (vertical axis) build upon the OmniClass Construction Classification System Table 33 – Disciplines (OmniClass 2012). OmniClass Table 33 was selected because of its deliverable-oriented hierarchical decomposition of the different AEC/FM disciplines, ranging from high-level (e.g. design disciplines) to more detailed (e.g. HVAC engineering). Accordingly, the OmniClass Table 33 structure allows for each discipline, or sub-discipline, to be mapped with a specific IDM Package within the IDM Framework.

Notably, because of the inadequate level of decomposition in some disciplines, the OmniClass Table 33 discipline definition is not ideally suited for the task. However, the OmniClass decomposition of AEC/FM disciplines appears beneficial as a basis for the layout of disciplines within the IDM Framework.

As illustrated, the AEC/FM project life cycle stages of the IDM Framework (horizontal axis) build upon the international standard ISO 22263:2008 Organization of Information about Construction Works – Framework for Management of Project Information (ISO 2008). ISO 22263:2008 was selected because of its well-documented definition of the AEC/FM project life cycle stages, consisting of eleven stages in total, from inception to production or demolition.

In addition, the ISO AEC/FM project life cycle stages are also not ideal, as they mainly focus on pre-construction stages, such as inception and design. Accordingly, these stages appear more documented than, for example, construction stages. In other words, the ISO AEC/FM project life cycle stages do not necessarily reflect the number of use cases within specific AEC/FM project life cycle stages, as several domain-specific stages are missing. However, the ISO decomposition of AEC/FM project life cycle stages can be used as a basis for the layout of life cycle stages within the IDM Framework.

4.2 *Decomposing into IDM Packages*

Ideally, the IDM Packages within the IDM Framework should be decomposed into appropriate detail to efficiently define and organize the specific use case and information exchange in question (Brotherton et al. 2008). Arguably, the IDM Packages should be decomposed into detail, where the ERs of each defined IDM Package are stable and independent of any specific project or organization. For this reason, the need to define optional ERs should be eliminated. If that is not possible, the specific IDM Package is either not decomposed sufficiently, or the information exchange is not absolutely necessary, and hence should not be required.

The IDM Packages cannot represent all use cases within every sub-discipline of the AEC/FM industry, as local diversities and the need for customization of AEC/FM processes would require adjustments for specific purposes (Aram et al. 2010). For this reason, it could be argued that the purpose of the IDM

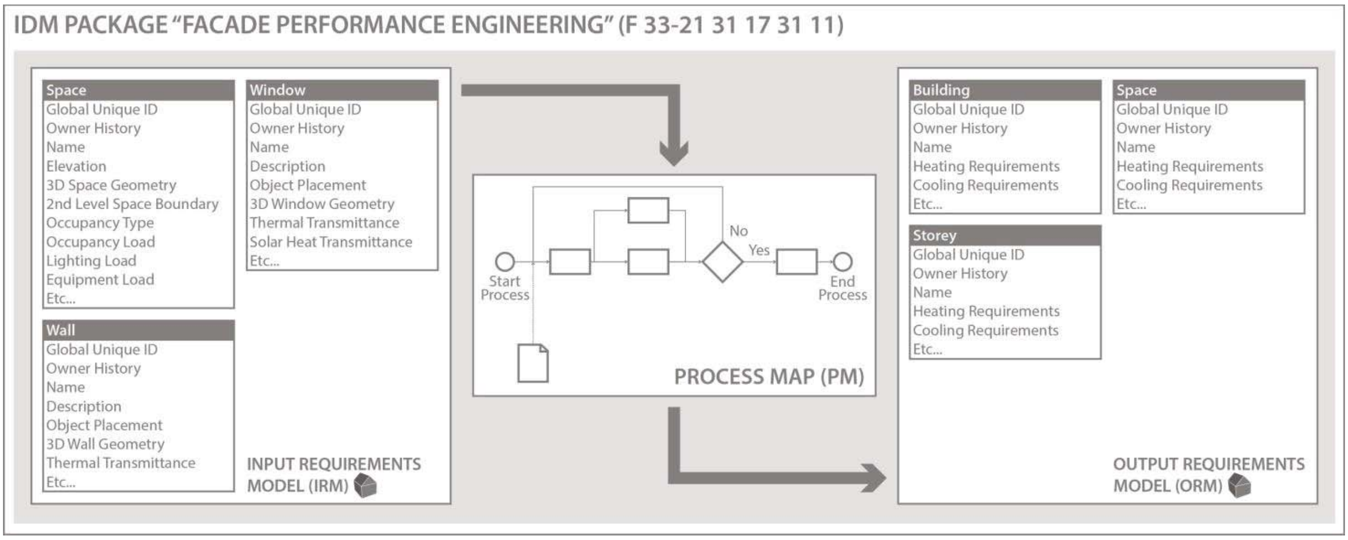


Figure 3: IDM Package for façade performance engineering.

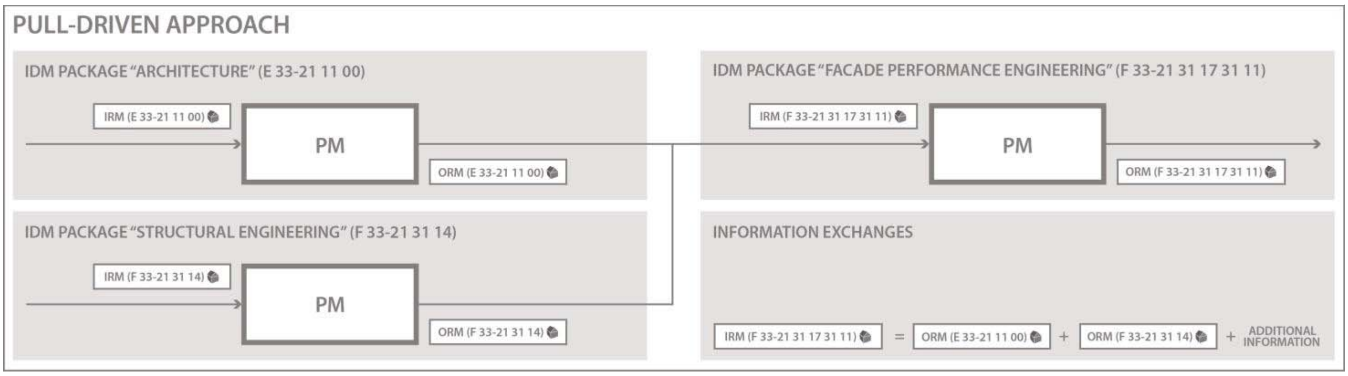


Figure 4: Pull-driven approach.

Framework should be to identify the AEC/FM industry's best practices. Accordingly, the IDM Packages defined in the IDM Framework should describe generic use cases and best practices, thereby allowing for later adjustment to local needs.

It is essential that, when defining the ERs of specific IDM Packages, focus should be on both input and output requirements. Therefore, ERs should be subdivided into Input Requirements (IRs) and Output Requirements (ORs), and ERMs should be subdivided into Input Requirements Models (IRMs) and Output Requirements Models (ORMs). This concept is similar to that proposed in (Anumba et al. 2010).

As this study focuses on describing the overall concepts of the IDM Framework, we will not define the specific content of the IRMs and ORMs for each IDM Package. However, Aram et al. (2010) recommended that industry experts should always be involved in the process of defining the IRMs and ORMs. Figure 3 shows an example of an IDM Package for façade performance engineering, and Figure 4 shows an example of the "pull-driven" exchange approach and the relationship between IDM Packages and associated IRMs and ORMs. Note that the downstream IDM Package is affected by what is produced by the upstream IDM Packages.

4.3 *Defining IDM Project Plan*

An important function of the IDM Framework is its ability to serve as a basis for defining an IDM Project Plan. Using this modular approach, the IDM Project Plan can be created by selecting the specific IDM Packages required for a specific AEC/FM project. In addition, the IDM Project Plan provides an explicit description of the overall project scope, sequence flow, organizational interaction, and information exchanges. Furthermore, the graphical nature of the IDM Project Plan helps project managers to predict AEC/FM process flows and to communicate requests for deliverables throughout the project. Figure 5 shows an example of how selected IDM Packages can be placed in the IDM Project Plan.

4.4 *IDM Packages and MVDs*

Traditionally, MVD developments are based upon IDM-specific Exchange Requirements Models

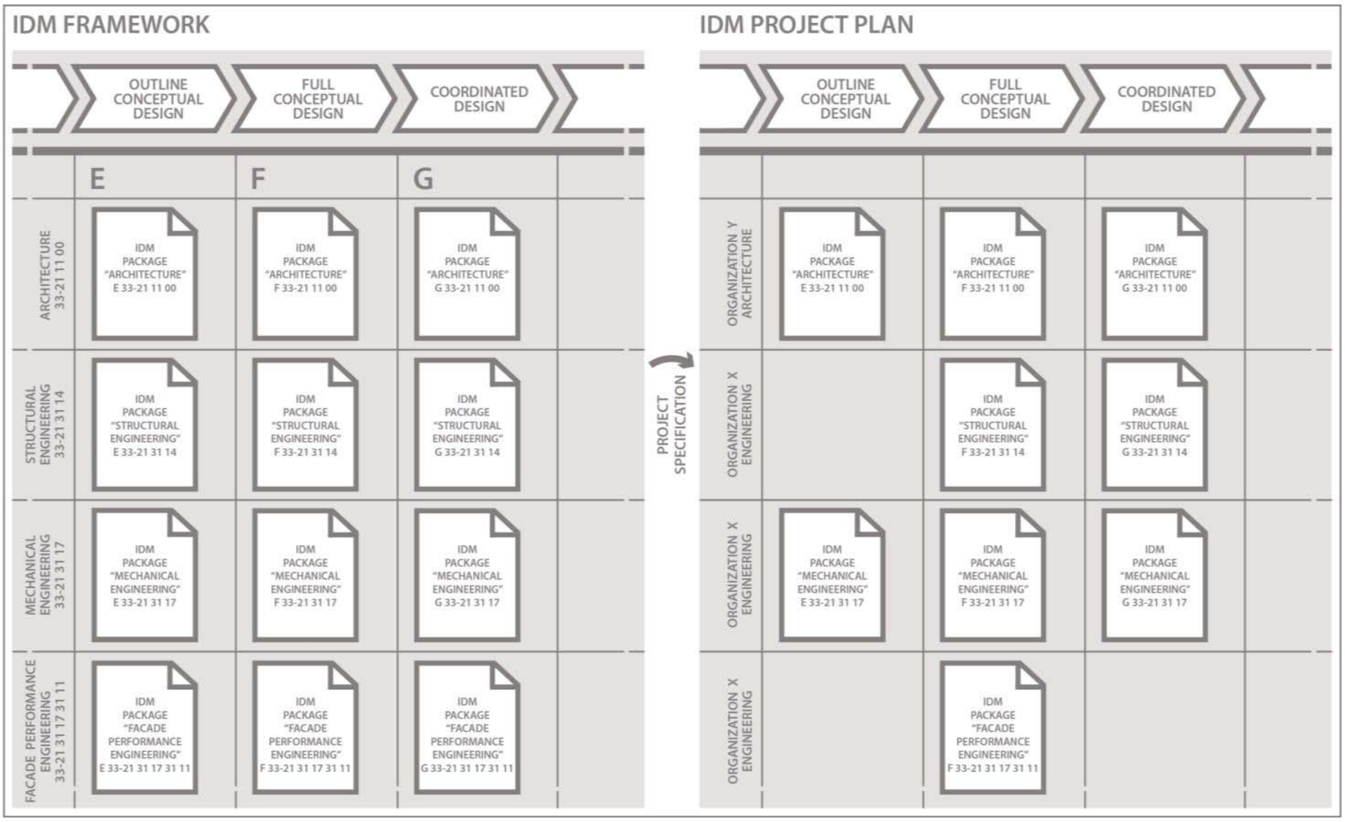


Figure 5: IDM Framework and IDM Project Plan.

(ERMs) and associated Exchange Objects (EOs). However, bearing in mind the concept of IRMs and ORMs, it is recommended to define MVDs based upon the IRMs and ORMs of individual IDM Packages. Given that MVDs are generally defined to establish a basis for AEC/FM software integration, they can be used to describe the precise information that specific software tools should be able to import and export, as subject of specific IRMs and ORMs. This is particularly beneficial as it enables the end user to carefully select the most appropriate tool for the specific AEC/FM process in question.

Potentially, the IDM Framework, which will consist of hundreds of IDM Packages with an equal number of corresponding MVDs, will challenge unified AEC/FM software implementation. Therefore, for software certification purposes, it is recommended to combine multiple IDM Packages into each MVD.

However, if quality assurance of software-based deliverables across individual IDM Packages is the goal, each IDM Package should be linked with an associated MVD.

4.5 *Potential of IDM Framework*

Generally, the IDM Framework provides a modular methodology to define and organize processes and information exchanges in unique AEC/FM projects.

Furthermore, it also has the potential to conduct many additional analyses and optimization tasks. For example, the selected IDM Packages in an IDM Project Plan could analyze gaps in information exchanges, and, by observing senders and receivers of specific IRMs and ORMs, could also identify non-value propositions of specific AEC/FM processes.

Another example could be to identify specific processes and IDM Packages, which are affected by building design changes, by observing changes in specific IRMs and ORMs. By extension, sensitivity analysis could be conducted to identify the full range of downstream and upstream impacts of stage-specific IDM Packages.

Finally, the IDM Framework could also be used to describe the content of MVD-based software certification testing systems.

5 CONCLUSIONS

In this study, we introduced an IDM Framework aimed at defining and organizing generic IDM Packages for all main use cases of the AEC/FM project life cycle. The IDM Framework was developed from the findings obtained from a review and supplementary expert discussions.

Ultimately, we believe that integration of this IDM Framework will provide a wide range of opportunities for AEC/FM project team members, and also project managers, to measure and improve information exchanges in unique AEC/FM projects.

Furthermore, we believe that the IDM Framework makes it possible to harmonize the development of new IDMs. Such harmonization is also necessary, if improved interoperability between AEC/FM software tools is the goal.

The IDM Framework represents a tool for information management improvement. However, the potential benefits do not lie in simply specifying common IDM standards. Rather, the benefits lie in the implementation and continuous development by industry experts and AEC/FM project team members.

Future areas of focus could be to investigate the detailed information exchange structures for selected IDM Packages, more specifically the structures of use-case-specific Input Requirements Models (IRMs) and Output Requirements Models (ORMs).

6 ACKNOWLEDGEMENTS

The authors would like to thank all of the people and organizations involved in this study, particularly the expert participants, Arto Kiviniemi, Professor of Digital Architectural Design, University of Liverpool, UK, and Ghang Lee, Associate Professor of Architectural Engineerinig, Yonsei University, Korea.

REFERENCES

Aram S.V., Eastman C., Sacks R., Panushev I. & Venugopal M. (2010) Introducing a new methodology to develop the information delivery manual for AEC projects, In: CIB W78 IT for Construction Conference in Cairo, Egypt, 16-19 October 2010.

Berard O. & Karlshoej J. (2012) Information delivery manuals to integrate building product information into design, Journal of Information Technology in Construction, 17:64–74.

Brotherton S.A., Fried R.T. & Norman, E.S. (2008) Applying the Work Breakdown Structure to the Project Management Lifecycle, PMI Global Congress Proceedings, 1–15.

Anumba C., Dubler C., Goodman S., Kasprzak C., Kreider R., Messner J. & Zikic N. (2010) BIM Project Execution Planning Guide – Version 2.0, Pennsylvania: The Pennsylvania State University, University Park, PA, USA, p. 127.

Eastman C.M., Jeong Y., Sacks R. & Kaner, I. (2010) Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards, Journal of Computing in Civil Engineering, 25–34.

Hall K. (2012) Making the Matrix Work - How Matrix Managers Engage People and Cut Through Complexity, Nicholas Brealey Publishing, p. 240.

Hjelseth E. (2011) Modular BIM Guidelines, In: CIB W78 IT for Construction Conference Conference in Sophia Antipolis, France, 26-28 October.

ISO. (2008) ISO 22263:2008 Organization of information about construction works - Framework for management of project information, p. 14.

Karlshoej J. (2012) Process and building information modelling in the construction industry by using information delivery manuals and model view definitions, In: European Conferences On Product And Process Modeling In The Building Industry (ECPPM) in Reykjavik, Iceland, 25-28 July.

Karlshoej J. (2013) Overview - buildingSMART International User Group, Available from http://iug.buildingsmart.org/idms/overview

Koskela L., Huovila P. & Leinonen J. (2002) Design Management In Building Construction: From Theory To Practice, Journal of Construction Research, 3(1):1–16.

O’Donnell M. (2012) Work Breakdown Structure: A Project Management Fundamental, Available from http://cmd.rutgers.edu/blog/work-breakdown-structure-project-management-fundamental.

OmniClass. (2012) OmniClass: A Strategy for Classifying the Built Environment, Available from http://www.omniclass.org/

See R., Karlshoej J. & Davis, D. (2012) An Integrated Process for Delivering IFC Based Data Exchange, Available from http://iug.buildingsmart.org/idms/

Wix J., Nisbet N. & Liebich, T. (2009) Using constraints to validate and check building information models, eWork and eBusiness in Architecture, Engineering and Construction, 467–476.

Paper B
Information Flow Management in Building Design based on IDM packages

Information Flow Management in Building Design based on IDM Packages

Niels Treldal[1], Jan Karlshøj[2]
[1]Ph.D. Candidate, Department of Civil Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby and Chief Specialist, Pharma Department, Rambøll Denmark A/S, DK-2300 Copenhagen S. E-mail: nitr@byg.dtu.dk
[2]Head of Section and Ph.D., Department of Civil Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby. E-mail: jak@byg.dtu.dk

Abstract
The architecture, engineering, and construction industry is highly information-dependent, and with the introduction of building information modeling, there is an increasing need to improve the management of object-oriented information exchange requirements. Information delivery manuals (IDMs) have been introduced to assist in this, but there is a misalignment between the need for unique and dynamic building design processes and the narrow focus on fixed processes and deliverables in current IDM practice. Essentially, there seems to be a theoretical and practical gap between current IDM methodology and the need to support dynamic information management. This paper presents a theoretical framework for developing a more modular IDM package methodology based on both information and design management theory. Furthermore, it describes fundamentals and evaluates a practical approach to this methodology using a recently built tool called the IDM Manager. The paper concludes that the iterative and interdependent nature of design is pivotal, not only when defining the information flow logics required, but also in defining the content of IDM packages required to avoid complexity.

Keywords
BIM, exchange requirements, IDM, modulation, building design, TFV-theory

Introduction
The architecture, engineering, and construction (AEC) industry is highly information-dependent because the success of projects largely depends on easy access to and good management of data (Martínez-Rojas et al. 2015; Tribelsky and Sacks 2011). The introduction of building information modeling (BIM) has changed the way information is defined and exchanged in the industry. Information deliverables have traditionally been based on documents (Rezgui et al. 1998). In a BIM-oriented process, information is captured in object-oriented BIM models and exchanged directly between object-oriented software (Eastman et al. 2011). BIM can act not only as a facilitator for integration and collaboration (Aram et al. 2010) but also enable the automation of processes (Moon et al. 2015; Zhang and El-Gohary 2015). As such, BIM constitutes an information system that supports both design and construction processes (Berard and Karlshoej 2012). Over the last decade, the use of BIM has increased rapidly in the industry, and the value achieved in areas such as visualization, reducing errors, and improving collaboration is well documented (Malleson 2016; McGraw-Hill Construction 2014; Pikas et al. 2011). There is, however, a significant remaining need for additional standardization in the use of BIM (Malleson 2016). Information needs to be managed efficiently for an information system to provide value. AEC information management is currently very unstructured, so the value generation from the use of information systems is limited (Martínez-Rojas et al. 2015). To support the capturing of building-related information, buildingSMART has developed the Industry Foundation Classes (IFC) specification, which enables the generation of semantically rich data models specifically targeting the exchange of open BIM-related

information (ISO 2013). The use of IFC has increased significantly in the industry along with the implementation of BIM (Malleson and Watson 2016), but the current software implementation of IFC is often limited to simple building geometry and other basic attributes. When complicated geometry or additional attributes are introduced, the reliability of the IFC data exchange suffers significantly (Kiviniemi 2009; Oh et al. 2015). Unreliable information exchange is a key barrier to expanding the use of IFC but is often linked to the AEC industry's difficulties in defining clear exchange requirements which can be homogeneously implemented in software. Eastman et al. (2010) argue that unless equal focus is put on all aspects (functional types, geometry, attributes and relationships) in each task-specific exchange, the implementation will continue to be unreliable and faulty. It is also critical to give careful consideration to what information needs to be exchanged because exchanging too much information leads to a lack of high value information, difficult decision-making, and limited opportunities to reuse design (Tang et al. 2008). To increase value generation when using information systems the industry, therefore, needs to improve its ability to define information exchange requirements.

Linking Process and Product Models

The development of a *process* model before *product* model requirements are defined makes it easier to identify the proper amount of information to exchange (Lee et al. 2007). A product model is defined as a standard medium for sharing and exchanging information electronically among heterogeneous systems. In the case of the AEC industry, the product model could be the BIM model defined using the IFC format – or other data formats. A process model describes how activities within a process are connected, ordered, and structured. Lee et al. define an activity as an act of processing objects within the product model. The Information Delivery Manual (IDM) methodology from buildingSMART is a solution that captures the process model and generates information exchange requirements on this basis (ISO 2016). The methodology is use-case-centered, which allows the exchange requirements to be linked to a specific purpose. This makes it easier for users to understand why the information content is required, which improves the chances of proper implementation. The development of more than 100 IDMs has been initiated internationally, but the industry-wide use of IDMs is still limited (Karlshoej 2012). One key reason is that the development of IDMs is a very complex and laborious process, and industry domain experts need to identify the required input and output in each use case (Aram et al. 2010; Lee et al. 2013).

Defining Requirements

An IDM consists of a process map (PM) and a set of exchange requirements (ERs). It is recommended that the PM should be specified using the Business Process Model and Notation (BPMN) standard as defined by the Object Management Group (OMG 2011). ERs typically consist of a set of one or more objects with one or more attached attributes, but in principle ERs can point to any subset of aspects in the product model (ISO 2016). To further refine the definition of ERs in a specific data model like IFC, buildingSMART has also introduced Model View Definitions (MVDs) (ISO 2016). An MVD enables the definition of the semantics and data structure required to exchange information using a specific data format. Multiple proposals of how to define and implement IDMs and MVDs have been developed over the last decade. The latest revision of the ISO standard for IDMs (ISO 2016) introduces a clear distinction between IDMs and MVDs by defining information units that point to objects and attributes in plain text as the final outcome of an IDM. In its previous release (ISO 2010), functional parts were defined instead, with the intention of mapping an MVD solution in much more detail. Lee et al. (Lee et al. 2013) introduced the xPPM tool to define a procedure for generating the functional parts and the corresponding MVD in one process, which makes the connection between the IDM and MVD even closer. In the US National BIM Standard version 1 (NBIMS), the distinction between IDMs and MVDs was very clear, but it also introduced exchange objects that group an object type with a specific set of attributes that can be reused in different exchange requirements (Eastman et al. 2010). The need to keep exchange requirements (IDM) separate from data model requirements (MVD) has been well recognized, because IDMs are related to business needs and MVDs are related to technical implementation (Aram et al. 2010; Berard and Karlshoej 2012). The way forward for buildingSMART and the ISO standard seems to be in this direction.

However, no international consensus has yet been reached on which approach to follow in using IDMs and MVDs, and the limited results from practice support the need for further research (van Berlo et al. 2012; Eastman et al. 2010; Hooper 2015). Table 1 gives an overview of the terms used in the various IDM approaches.

Table 1. Comparison of terms used by the IDM approaches in ISO 29481-1 versions 2010 and 2016, xPPM, NBIMS v1 and the proposal for IDM packages in this paper – extended from (Lee et al. 2013)

ISO 29481-1:2010 and xPPM	ISO 29481-1:2016	NBIMS v1 and IDM packages
Process map	Process map	Process map
Exchange requirement	Exchange requirement	Exchange model
Functional parts	Information units	Exchange objects

Exchange Models and Exchange Objects

It is the need for an unambiguous link between requirements and objects in the product model that promotes the use of exchange models and exchange objects in the NBIMS approach. This need is also highly relevant in the research presented here, and the NBIMS approach was therefore adopted with some modifications. Exchange objects (EOs) are encapsulated definitions of the information objects to be exchanged, described in language that is in common use by domain experts (Eastman et al. 2010). An exchange model (EM) is a compilation of a number of EOs for a specific use case in the design process. The concept is illustrated in Figure 1.

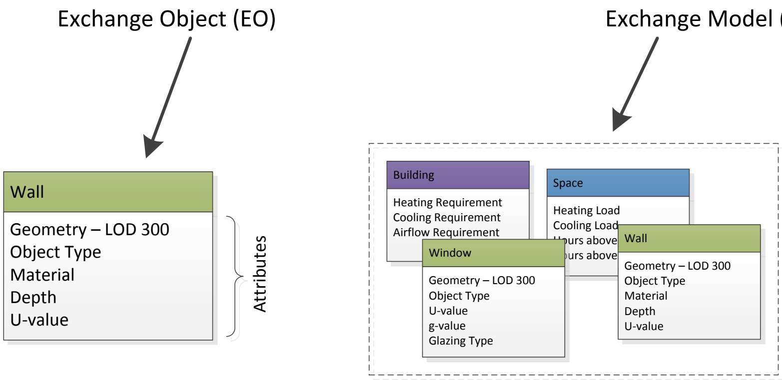


Figure 1. Illustration of an exchange object and an exchange model

EOs and EMs define generic requirements for classes of object, and each attribute of a specific object class constitutes either input or output of a work package. Traditionally, EMs are conceptually considered as entities for defining exchange requirements that support specific information exchanges in fixed processes (Panushev et al. 2010; See et al. 2012). This is why most currently available IDMs listed by buildingSMART (Karlshøj 2013) define process maps with typically 2-3 actors and the exchange requirements between them for use cases such as ‘Design for Energy Performance Analysis’ and ‘Design for Quantity Takeoff’. These are often defined with a specific organizational and contractual arrangement in mind, so the process maps and exchange requirements need to be adjusted for other projects where the project organization or the contractual arrangement is different – even if that other project needs a similar energy performance analysis or quantity takeoff, but has other actors involved or decides to change which actor delivers what information. After reviewing 47 published IDMs, Lee et al. (2013) concluded that none of them reused existing EMs or EOs from external sources. Lee et al. argue that this is due to the complexity in finding and understanding other people’s work. The process of changing existing IDMs is complex and requires expert knowledge, so this might be an additional cause for the slow implementation of the IDM concept. That is why the goal of the research presented here was to redefine IDM methodology to better support the industry’s need to reuse IDMs across individual projects while retaining an ability to define unambiguous and standardized exchange requirements.

Requirements for Information Management

The current transition to BIM-oriented work processes has shifted focus from design documentation to information management (Gu et al. 2014). The management of information, particularly the management of exchange requirements, is an important need in the industry (Treldal et al. 2016) and is closely linked to the overall project management of the design process. Concepts to define exchange requirements should, therefore, support the needs of project managers.

Needed change in current Design Management

The AEC industry suffers from low productivity. Poor design management methods are part of the problem, but BIM and lean thinking can improve this situation, if applied correctly (El. Reifi and Emmitt 2013; Pikas et al. 2015). From a lean perspective, design can be viewed in three ways: design as transformation, flow, or value generation (Koskela 2007). Transformation focuses on the individual design discipline, flow focuses on the interaction between parties involved in the design, and value generation focuses on the design's final customer (Berard 2012). A methodology that incorporates all three aspects can generate substantial productivity improvements if implemented fully in design projects (Freire and Alarcón 2002), but most design projects are currently still executed with a single-minded focus on the transformational aspect (Pikas et al. 2015; Tuholski 2008). The other two aspects are often left for informal consideration by the designers, and the focus solely on transformation leads to the sub-optimization of both processes and delivered value (Tuholski 2008). That is why an improved ability to manage flow and value generation is needed in building design.

Building design projects operate in a complex and dynamic environment, which makes the mapping and management of flow more difficult than in relatively stable and repetitive industries such as manufacturing (Emmitt and Ruikar 2013). Current IDM methodology seems unintentionally to promote solely the transformational view by defining fixed processes for the interaction between actors in key parts of the design phases and by pushing forward exchange requirements without consideration for the overall information flow in a project. Essentially, when large parts of the project plan are predefined but not aligned, it limits the ability of project managers to optimize the ordering of work packages from each actor to achieve an efficient flow of information. Furthermore, the complexity of design requires a dynamic solution to support the changing nature of such processes, and the current more static IDM methodology limits the ability of managers to continuously reprioritize work packages. To limit this misalignment between the current IDM methodology and the necessary focus on flow efficiency throughout individual projects, the focus of the research presented here was to modularize the current IDM methodology to make it more adaptable to different project types and situations, while still maintaining a standardized information flow. Value generation is equally important to the success of a project, but from an information-management perspective is of less importance because value is generated on the basis of how information is utilized rather than how it is managed.

Addressing Information Flow in Design

Focus on flow in building design requires focus on pull techniques and concurrent engineering (Ballard 2000). From this perspective, design management is about reorganizing the design process on the basis of "down-stream" needs (pull), as opposed to traditional waterfall planning (push). At the same time, it means embracing design iterations and planning for multiple concurrent activities with an uncertain outcome. As the design process gets more integrated, the information flow and information exchange no longer occur at the end of phases; instead the information exchange becomes continuous (Berard and Karlshoej 2012). Moreover, design criteria and potential design solutions are reciprocally interdependent, so it is difficult to know very far in advance about process logic and logical predecessors because that knowledge is developed as each step is taken (Ballard 1999). That is why the design process is so difficult to model, but an analysis of multiple modeling techniques has identified the Dependency Structure Matrix (DSM) and IDEF0 modeling notation as the most useful in the presence of concurrent activities (Wynn et al. 2007). A DSM is recognized as a powerful tool for optimizing flow efficiency in design processes (Ballard 2000; Koskela 2007; Yassine and Braha 2003) and IDEF0 is a function modeling methodology which sees a process as a function that interrelates data and objects to receive and deliver information (Lightsey 2001). While using such techniques, however, one must accept that there will be a continuous need to update the process model as the design develops.

On the basis of the above findings, the management of information flow in building design demands that exchange requirements are managed in a way that promotes concurrent engineering and also incorporates both the transformation view and the flow view of design. An IDM solution should therefore address the following:

- Incorporate pull-based planning
- Allow for process optimization based on dependency analysis
- Allow for continuous design iterations and support dynamic changes
- Support project-specific adjustments
- Define product model requirements based on the process model
- Standardize information flow to support interoperability
- Reduce the need for domain expert involvement.

IDM Packages

From the above recognition, it is proposed to split traditional high-level IDM Use Cases into IDM packages focusing specifically on one actor and one work package at a time. An IDM package consists of input requirements (IRs), a process map (PM) and output requirements (ORs) for a specific work package only – a narrow use case with a specific target. To define the information flow in a specific project, multiple IDM packages must be combined to represent the total work required. The concept of an IDM package is illustrated in Figure 2.

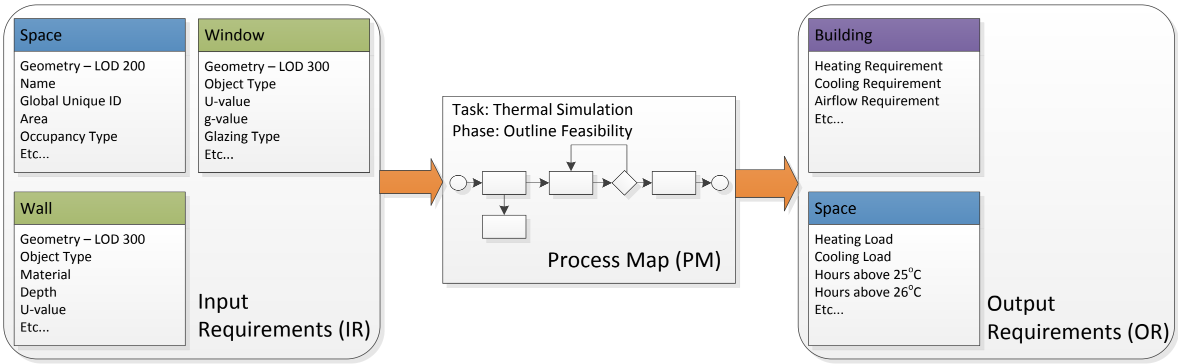


Figure 2. IDM package methodology – based on (Mondrup et al. 2014)

The hypothesis of this research is that building design projects have core processes, which are reusable from project to project. The intention is to define project-specific exchange requirements more efficiently using such standardized core work packages with agreed-upon exchange requirements.

Research goals

The goals of the research presented were: firstly, to evaluate how such core work packages can be defined efficiently using the IDM package methodology and whether this can contribute to improved standardization of exchange requirements; and secondly, to develop a software tool which can improve information flow management by supporting the required logics for a unique, dynamic, iterative and interdependent design process based on IDM packages.

Research design

The approach was based on qualitative and experimental research using semi-structured interviews for data collection. Using a constant comparative method to select new cases to back up existing findings can improve the validity of quality research (Denscombe 2014), so a five-step approach was defined. The steps are illustrated in Figure 3.

The first evaluation cycle was carried out by support from 21 bachelor and master students at the Technical University of Denmark, where 17 different design and construction work packages were documented on the basis of semi-structured interviews with 35 domain experts from 10 different AEC companies. Using an interview guide, students documented individual IDM packages, aligned them with similar packages from other students, and then optimized the IDM packages to match the information needs of others.

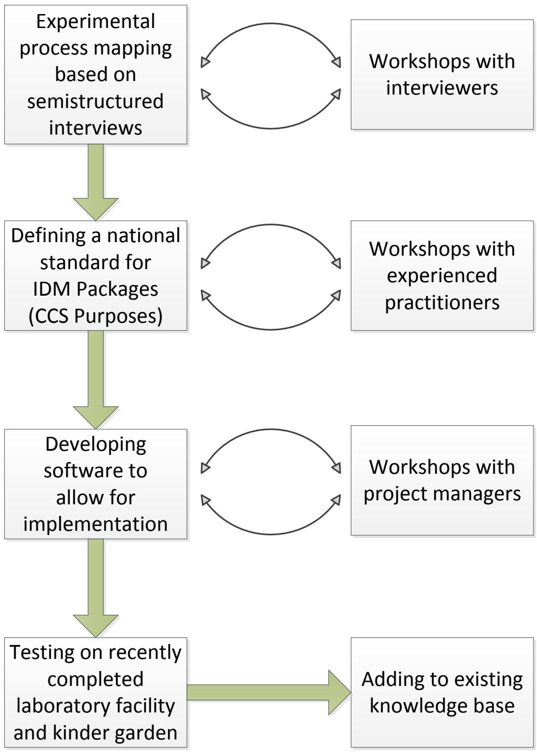


Figure 3. Research design to explore utilization of IDM packages

In the second evaluation cycle and as part of the EU-funded project *cuneco* (www.cuneco.dk), the authors documented seven additional design, construction, and facility management work packages by interviewing 18 additional domain experts from 15 different companies. The results of this work formed the basis for a new Danish standard, *CCS Purposes*, which define how IDM packages can be documented consistently in the AEC industry (bips 2016a). During the documentation process, 17 workshops with students, the cuneco steering committee, and domain experts were used to evaluate and modify the concept of IDM packages to match the requirements identified. Figure 4 shows the work packages defined in the first two steps and illustrates a wide range of core processes. The intention was to test the concept on various types of rather information-intensive use cases.

In the third evaluation cycle, the findings formed the basis for developing an online tool to support the utilization of IDM packages. Three workshops were held with six different project managers in an engineering company to identify requirements and improve the functionality of the tool. The tool was called IDM Manager, and the finished tool was tested on part of the design phase of a recently completed laboratory facility and a kindergarten project.

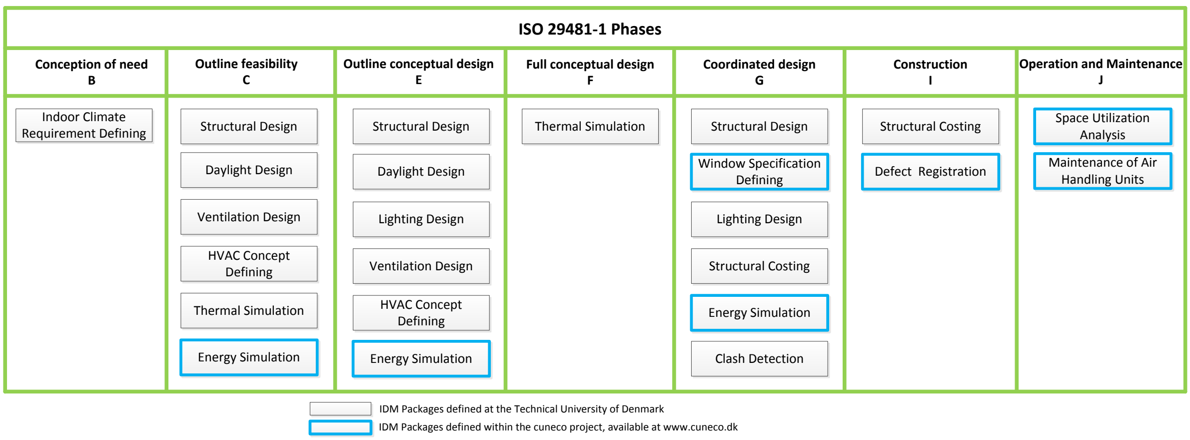


Figure 4. IDM packages defined in evaluation cycles 1–2 (see Figures 3)

Compiling IDM Packages

When the interviews with the domain experts started, there was a very noticeable resistance from these experienced practitioners to the idea that their core processes during the design phases could be standardized and compiled into IDM packages. They referred to the variety of project types and project organizations as the reason why their processes were different in every project. However, considerable inconsistency among the domain experts on what parts of the design process were unique, what was repeatable, and what was best practice clearly showed the need for a deeper understanding of the work at hand.

After the interviews, the students evaluated their findings on a five-point scale ranging from very poor to very good. They all found that the domain experts interviewed seemed to have a good or very good overview of the use case in question, but only 43% found a good or very good match between the descriptions of the process in identical use cases given by different domain experts. Similarly, the students found that the domain experts seemed to have a good or very good overview of the input (86% of cases) and output (78% of cases) required for specific use cases, but found a good or very good match between the inputs required for identical cases in only 36% of the cases, and a good or very good match between the outputs required for identical cases only in 43% of the cases.

After several iterations, it became clear that it was possible to define selected use cases as IDM packages. Due to the misalignment in the industry, however, defining IDM packages can be a highly iterative process. Similar use cases were found to be executed differently from company to company and even within a company. Some variations were more efficient than others and when documented systematically and put into context with other design processes, all the use cases were found to have optimization potential. In follow-up interviews and workshops, the domain experts confirmed that the IDM packages matched their work, although most were surprised by the number of object-specific attributes required.

Defining IDM packages is an iterative task with continuous optimization potential, and for this reason the following guidelines were developed:

1. Make IDM packages generic by defining them as high-level as possible.
2. Identify best practices in the industry and base IDM packages on these.
3. The process maps should describe a generic process and allow for internal optimization by users without the IDM package needing to be redefined.
4. Always define a project map before defining input and output. Otherwise, it is impossible to truly validate whether or not the input and output is of value to the use case.
5. Iterations are required when defining input and output because they must be harmonized with the input and output from surrounding design processes.
6. Accept that generic IDM packages in some cases will have to be individually adjusted to match use cases for particular project types, simulations etc.
7. IDM packages are intended to define project deliverables; input and output should include only such information.

In similar research, parallel conclusions have been reached on points 1–5 in the above list (Aram et al. 2010; Panushev et al. 2010), which confirms the usefulness of this approach. Using the above guidelines, students found that 71% of the use cases were easy or very easy to compile to IDM packages, while the remaining 29% could be compiled but required more iterations to fully understand their generic characteristics and deliveries.

IDM Package Structure

On the basis of the above findings, the methodology of IDM packages was defined to consist of two deliverables. The first deliverable is a use case description of the specific work package, including business value, actors and software types involved, along with a PM created using BPMN. The use case description was aligned with similar descriptions made as part of the bSN Guide (buildingSMART Norway 2015), which suggests for harmonization of such descriptions to allow for reuse internationally. The second deliverable of an IDM package is based on a template in which input and output requirements (IRs and ORs) are defined as attributes linked to object classes. Figure 5 illustrates this content with an example from the cuneco project. Full details can be found in (bips 2016a).

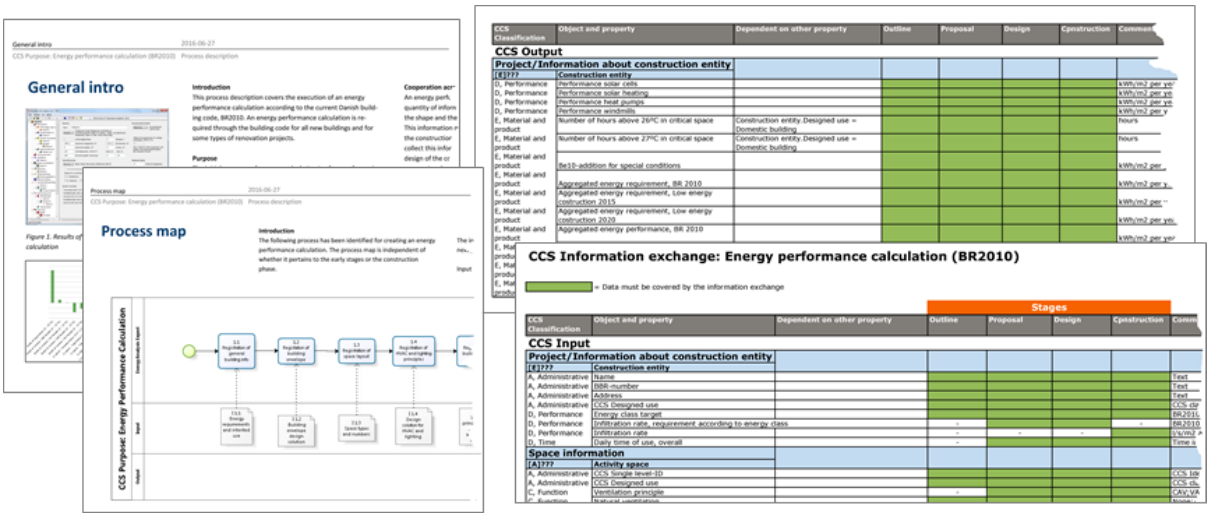


Figure 5. Content of an IDM package: 1) Process description including a process map (left) and 2) Input and output requirements (right) – illustrations from (bips 2016b).

Unlike previous solutions, the PM contains only one swim lane because it only represents work from one actor. The lanes below describe the required input and output for each step in the process. The IR and OR must be defined using a standardized product breakdown structure to identify consistent object classes. In this example, the Danish classification system CCS (available at ccs.bips.dk) was used, but any classification system with a consistent mapping to IFC or other required data exchange format can be used to provide the required interoperability. Constraints for each attribute are listed as described below and, if the use case is applicable to more than one phase, exchange requirements for each phase are listed (green indicates required, white indicates not required). In the example, four phases are relevant, so the document essentially describes four IDM packages, because packages are phase-dependent in the methodology.

For graphical requirements, the concept makes use of the principle of pointing to a Level of Development (LOD) as defined by (BIMForum 2015), although previous research suggests the need for a more granular description (Panushev et al. 2010). From the interviews with domain experts, it was notable that they had only high-level requirements for geometry concretization to match their needs for understanding, coordination and reuse of work from others. This argues for putting more focus on making clear definitions of each LOD level for each object class and aligning expectations for these throughout the industry. Further details of the structuring and organization of IDM packages can be found in (Mondrup et al. 2014).

Content of IDM Packages

For IDM packages to be operational, their content must be constrained to include only what is needed for the work to be completed by a properly skilled actor. The IDEF0 methodology addresses this need by viewing a process as a function that interrelate data and objects to receive and deliver information (Lightsey 2001). Information can be input and controls received, mechanisms to support the function, and delivered output as illustrated in Figure 6 (left).

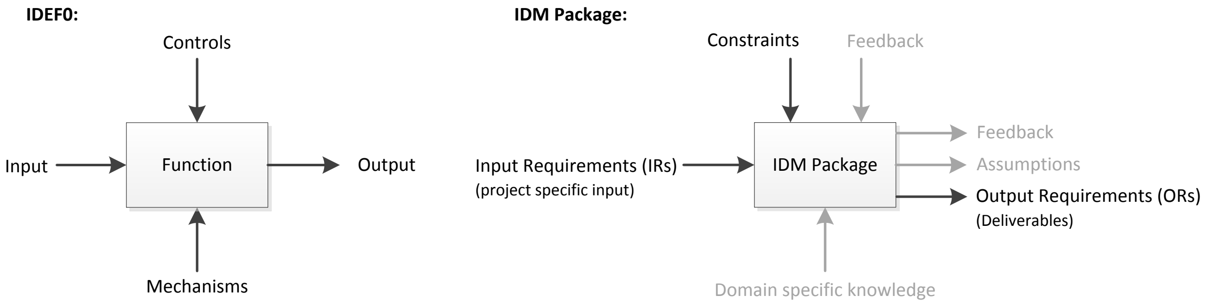


Figure 6. Notations for IDEF0 and a parallel notation for IDM packages – greyed information is not formalized in IDM packages

To constrain the content of IDM packages, the principles from IDEF0 were refined to match the specific needs of design work packages. The proposed notation for IDM packages is also illustrated in Figure 6 (right).

Project-specific input, such as height of windows, size of rooms, etc., is the only pure input to the process and, as such, input is limited to the minimum of information required for the process to function. Domain-specific knowledge should be considered as a mechanism and includes a range of information that must be available to ensure correct results. The rapid development of design – especially in the early stages – does not allow for all such information to be clarified in time, and most designers rely heavily on prior knowledge when developing design solutions. This is why such assumptions are commonly accepted, but they must be monitored carefully, and they should not constitute part of the required input because they are unlikely to be available.

Constraints and feedback should be considered as controls. Constraints can be external requirements acting as a statement of quality or a desired property of the building or its parts (Kiviniemi 2005). However, Kiviniemi suggests that it is more appropriate for client requirements at least to be directly linked to instances in the BIM models as opposed to being part of a generic delivery requirement framework. Business rules are a more generic set of constraints for deliverables. Business rules can be logical or physical constraints (Berard and Karlshoej 2012) or national, company or project-specific constraints (Aram et al. 2010). Business rules can be used to vary the result of an exchange requirement without having to change it (Wix et al. 2008), and the application of business rules helps make IDM packages as generic as possible. So far, the concept only includes logical constraints as to when specific type of attributes are relevant, as shown in Figure 7. Feedback from domain experts indicated that additional constraints based on building type or solution-specific dependencies could be valuable to make the same IDM packages applicable to other use cases. However, interdependencies in constraints can quickly make business rules too complicated to implement. Instead, increasing the number of IDM packages may prove a better solution.

CCS Classification	Object and property	Conditioned by other property	Remark, Allowed values or Unit
[L]QQA	**Window**		
	Object Type		Skylight;Fire Ventilation Opening;Mulled Double Hung
	Glazing Area Fraction		%
	Hinging	Open/Close Function ≠ No opening	Side hinged;Side Controled;Top hinged
	Motorised	Open/Close Function ≠ No opening	Yes/No
	Number of motors	Motorised = Yes	Number
	Height		mm
	Width		mm
	Aerodynamic opening area, Aa	Object Type = Fire Ventilation Opening	m2
	Geometrical area, Av	Object Type = Fire Ventilation Opening	m2
	Effective opening area	Space.Ventilation Principle = Natural Ventilation	m2

Figure 7. Example of business rules in IDM packages to constrain requirements

The first type of output is related to information incorporated into models, drawings and/or documents to represent results from the current work package. Such information is considered the deliverables. The second type is related to the fact that designers have to make assumptions to deliver results on time. These assumptions are part of the domain-specific knowledge that was included to produce the deliverables. Most often, a deliverable includes documentation of such assumptions for the client to accept or at least be aware of. In some cases, standardizing such assumptions could be valuable, but in most cases assumptions were found to vary depending on project and client type. Assumptions are therefore not formalized. The third type of output identified was feedback. Feedback is part of the iterative process of design and consists of information on how the input received could be changed to improve the results of the current work package. Although the flow description of IDEF0 may look somewhat linear, most processes or clusters of processes are repeated numerous times to reach the desired design, which results in design loops (Lightsey 2001). For each design loop, there is a flow of feedback, as illustrated in Figure 8.

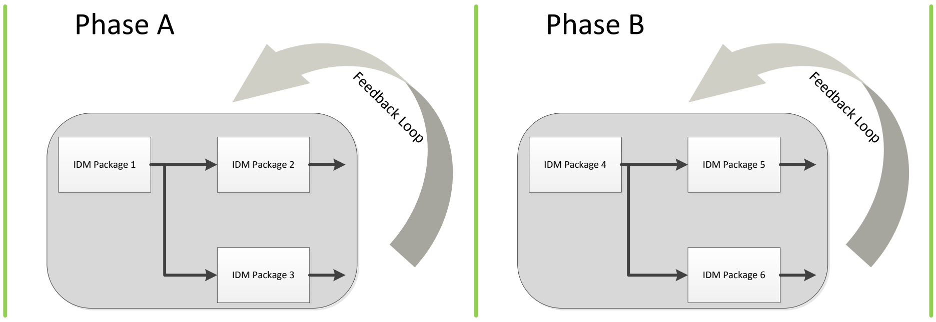


Figure 8. Feedback loops in design where processes are repeated on the basis of feedback from the previous execution of the same processes – inspired by (Lightsey 2001)

This feedback can provide information on how the output from e.g. IDM Package 1 can be changed for the output of Package 2 and 3 to be improved. In most use cases, there is a clear distinction between deliverables, assumptions and feedback. In other cases, such as clash detection, the feedback on where there are clashes may seem more relevant to deliverables, but feedback can be any type of information regarding any prior output provided, which is why it is not possible to define generic requirements for such feedback.

On the basis of these findings, input requirements, selected business rules, and output requirements are the only information formalized in IDM packages. The above findings show how the concept of IDM packages can constitute a generic framework for defining the exchange requirements for specific work packages. These IDM packages must then be used in a dynamic flow of information to match the needs of individual projects.

Managing Information Flow

Each IDM package constitutes information about the input and output required for each design work package. To manage the requirements for deliverables in a design project with focus on flow efficiency, the relevant IDM packages must be combined in a process map that describes the intended execution of an entire design process. The tool *IDM Manager* was developed using Ruby on Rails and MongoDB as the back end and the JavaScript framework Angular JS as the front end. The tool is available online for both computer and tablet use. It is intended as a tool for project managers. Firstly, they can use it to define their intended way of executing work packages in an IDM project plan. Secondly, the tool can assist in evaluating whether any packages lack the required input information, so that additional work packages need to be included in the project to ensure the generation of all the necessary design information. Thirdly, the tool can generate a DSM (Dependency Structure Matrix) to help the project manager optimize the sequence of packages to achieve the most efficient information flow. The prerequisite for the generation of a project plan is a library of predefined IDM packages called the IDM Framework. Ideally, international and national standard and industry organizations should provide and share content for such a library, which highlights the need for a common agreement on the structuring of such libraries. OmniClass Table 33 (OmniClass 2012), which describes AEC disciplines, is currently used as a framework for a work breakdown structure to organize IDM packages according to their individual use case, and the phases defined in ISO 22263 (ISO 2008) are used to define when each IDM Package is intended for use. The packages required can be collected from the IDM Framework and inserted in the IDM Project Plan to customize how a specific project is to be executed, as illustrated in Figure 9.

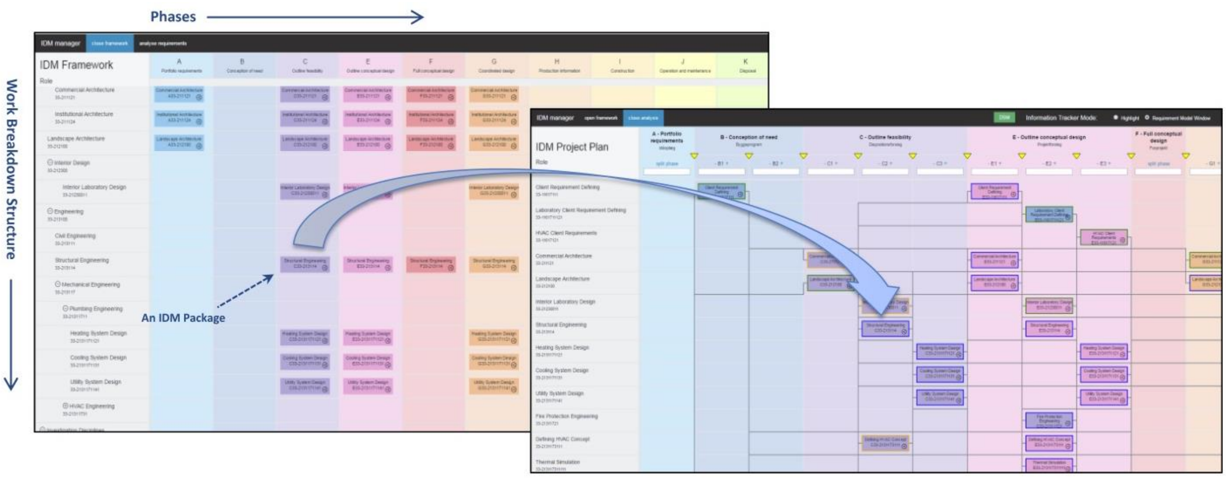


Figure 9. IDM Manager uses the IDM Framework (left), acting as a library of standardized work packages, and the IDM Project Plan (right) to capture a specific project execution plan – see Figure 14 for details on content

Once the project plan is laid out, the tool can start to analyze the information flow as indicated with grey lines and optimization of the design process can commence using a DSM visualization of the dependencies. IDM packages can be rearranged in the IDM Project Plan to allow for continuous updating as the project progresses. As IDM packages are rearranged, the information flow is continuously recalculated to reflect the current situation and allow for instant feedback on the implications of changes to the process map. To achieve this, it is necessary to take into account a number of considerations on work package sequence and workflow structure, as described below.

Organizing the Design Processes

In the literature, three main types of dependency between design work packages have been identified (Eppinger and Browning 2012; Karniel and Reich 2011): sequential (dependent), parallel (independent), and coupled (interdependent), as illustrated in Figure 10.

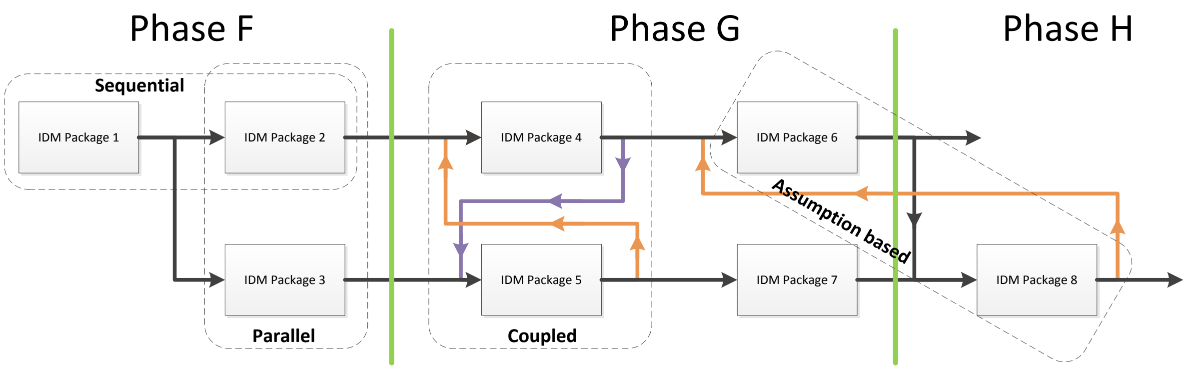


Figure 10. Type of dependencies within design processes

Such dependencies can also be shown in a DSM as illustrated in Figure 11. In the DSM, packages are listed both horizontally and vertically and a mark in the matrix indicates when and how a package on the vertical axis depends on a package on the horizontal axis.

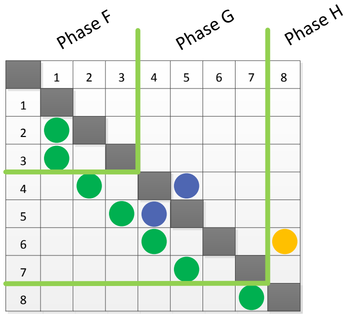


Figure 11. Dependency Structure Matrix related to activities in Figure 10

Due to the widely accepted use of assumption in building design – as also noted by Pikas (2015) – it is useful to differentiate between whether dependencies of a coupled package are part of a design loop (the dependencies do not reach into upcoming phases) or whether the dependencies will not be clarified during the current design loop (the dependencies reach into upcoming phases). In the latter case, the input required for a specific IDM package will not be available before the deliverables of that IDM package are due. Such dependencies are defined as 'assumption-based' and are indicated with an orange mark in the DSM. Dependencies of coupled packages that are part of a design loop are indicated with a blue mark, and sequential dependency is indicated with a green mark. A high concentration of blue marks therefore indicates parts of a design where careful coordination of the design development is required and a high concentration of orange marks indicates that the project is exposed to the risk of design changes due to the many assumptions.

So there are two types of iteration in design. Iterations that happen 1) within a sequential set of work packages that are repeated in design loops as illustrated in Figure 8, or 2) within a set of coupled work packages that are executed simultaneously as illustrated in Figure 10. If all the packages within a phase are located in the same column in the IDM Project Plan, this will imply that the packages are executed concurrently. However, in most design phases the architect, for example, would initially create a design proposal, which is then analyzed by engineers and followed by simulations. To capture this successive design process, functionality to divide design phases in the IDM Project Plan into a number of sub-phases was implemented to provide a better understanding of the information flow within each phase.

Information Flow Logics

To allow for the IDM Manager to calculate the information flow between packages and define exchange requirements on the basis of the dependencies described above, a set of rules were developed. The rules were based on the conceptual understanding of information flow in upstream and downstream work packages identified by (Lee et al. 2007), but their rules do not take into account interdependent dependencies between work packages, and for this reason a different set of rules are proposed to include such practice.

The intention of the rules is to identify the EM (exchange model) required in the transition between phases or sub-phases. This is achieved in Equation 4 below by comparing what information is available at this point with what information is required at this point. With regard to what information is available, only the most recent version of each attribute output from either previous phases or from packages being executed interdependently during the current phase is identified, as defined in Equation 2. If no information is available, the information required will be searched for in upcoming phases as assumptions, as defined in Equation 5, or will ultimately be identified as missing, as defined in Equation 6.

The rules are based on a process map, as illustrated in Figure 12, and are explained below.

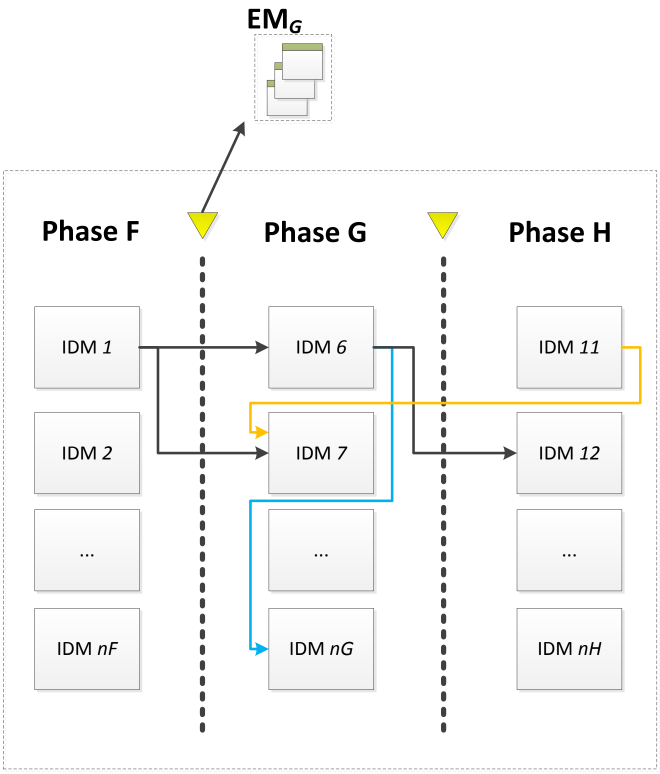


Figure 12. Conceptual illustration for the information flow logics

All input I_G available at the transition from phase F to G is the total output OR_i from every IDM Package up to the total number *nG* of all upstream and concurrent IDM packages until the end of phase G:

$$I_G = \bigcup_{i=1}^{nG} OR_i \qquad [1]$$

If several IDM Packages output identical attributes, only the most recent version of the attributes should be included in the input to select from. So, the input available to select from should be reduced to I_{Gr}:

$$I_{Gr} = \bigcup_{i=1}^{nG} \{x \in OR_i | x \notin \bigcup_{i=i+1}^{nG} OR_i\} \qquad [2]$$

IDM packages must be numbered starting with 1 at the very top left-hand corner of the IDM Project Plan for the above rule to apply.

The input IR_G required of IDM packages in phase *G* is the total input required IR_i for every IDM package in phase *G*:

$$IR_G = \bigcup_{i=nF+1}^{nG} IR_i \qquad [3]$$

The exchange model EM_G for what information to require before starting phase G is the intersection of the available input I_{Gr} at the end of phase *F* or from within phase G and the required input IR_G of IDM packages in phase G:

$$EM_G = I_{Gr} \cap IR_G \qquad [4]$$

In this way, the tool will identify the information available from either upstream or concurrent IDM packages depending on where the information has been most recently output. The input available from concurrent IDM Packages will be flagged in blue as previously mentioned because this information is output during a concurrent work package.

If not all the input required is available from upstream or concurrent IDM Packages, the tool most look to see if any downstream IDM packages up to the total number of packages *nH* will provide the output needed. Such input will be flagged in orange because it will have to be assumed until the downstream packages identify the correct values. Assumptions A_G required at the transition from phase *F* to *G* are therefore:

$$A_G = \{x \in IR_G \setminus EM_G | x \in \cup_{i=nG+1}^{nH} OR_i\} \qquad [5]$$

If no upstream, downstream or concurrent IDM package outputs information that is required as input by an IDM package in phase *G*, this information M_G will be identified as missing and flagged in red:

$$M_G = \{x \in IR_G | x \notin \cup_{i=1}^{nH} OR_i\} \qquad [6]$$

In addition to the above rules, a possibility to define what discipline in the project organization is responsible for each IDM Package was introduced. This allowed for attributes in the EM to be grouped according to the discipline responsible so that EOs (exchange objects) can then be generated on the basis of responsibility. The EOs now represent what each discipline in the design organization has to deliver at any given stage in the project. An example of the generation of an exchange model is shown in Figure 13. Two parallel work packages in phase F and two concurrent packages in phase G are planned. The exchange requirements for the information needed in Phase G are represented by exchange model G, including the people who are to deliver which EOs.

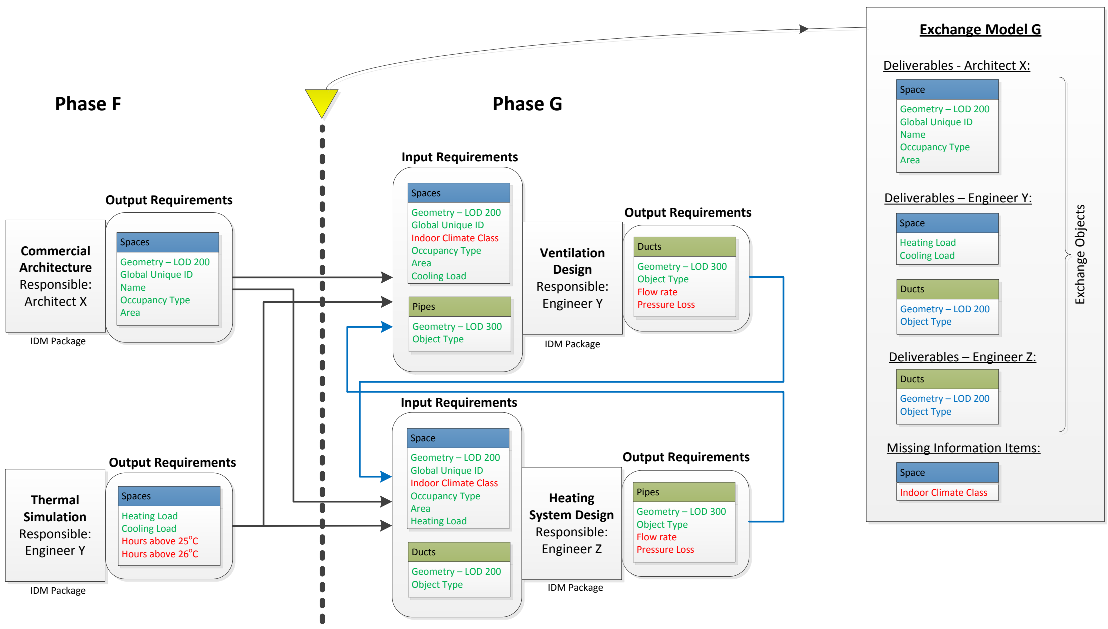


Figure 13. An exchange model for a segment of a design process
– the illustration does not list all the attributes required for the IDM Packages included

With the above rules, IDM Manager can match the information dependencies between packages and this allows the tool to autogenerate a DSM of the dependency relationships, as illustrated in Figure 15. Using a tool like IDM Manager, domain experts now have the ability to define the content of every IDM package and still allow the project manager to put the packages in the sequence most efficient for the information flow of each project. The above rules allow the process layout and information flow to be simplified and visualized in several ways to support project managers in their planning and optimization of the design process. Moreover, they reduce the need for domain expert involvement in every planning phase and still allow for standardized exchange requirements to be generated. The exchange requirements might be different in each project depending on the sequence of the work packages, but the information received by each work package is standardized, allowing efficient use of information systems to complete the specific work in each package.

Use cases

To validate IDM Manager's ability to capture a design process sufficiently and improve the standardization of exchange requirements in unique projects, the tool was tested on two case studies. In the first case study, a process map was created based on monitoring and reviewing the work completed by HVAC engineers on a project for the design of a 15,000 m^2 laboratory research facility. The process map was created in a pull-based planning session by retrospectively identifying the upstream work packages needed to complete the design and specification of the ventilation system. For each work package identified, corresponding IDM Packages with IRs and ORs were defined in IDM Manager. Figure 14 shows the process map, which defines only work packages and attributes directly related to the ventilation system design. There are 42 packages and a flow of 283 object-class-specific attributes from the requirements phase to the completed design phase. Of these packages, 27 were identified as having to be executed concurrently and 3 packages were executed based on assumptions defined in later phases due to late engagement by part of the client organization. Focusing only on the design activities for energy optimization, Pikas et al. (2015) identified 34 packages in a similar attempt to define and optimize the information flow, indicating that the number of packages seems appropriate for such effort. Focusing on flow optimization for the design of entire buildings, Austin et al. (2000) identified 410 packages for a pharmaceutical laboratory building, 346 for an office building, and 789 for a hospital building. For the process map of the first case study to represent the entire project, a considerable number of packages would clearly have to be added. Using the principles from the IDM package methodology, however, it seems that the number could be fewer than in the previous work by Austin et al., in which feedback loops and decision-making processes seem to be far more elaborate, making the process map considerably bigger. Such elaboration is not required with the IDM Package methodology where the focus is more clearly on targeting the information flow of design-specific input, as illustrated in Figure 6.

In the second case study, a similar process map for a 2,000 m^2 kindergarten project was created to make comparisons between the two process maps. In this process map, 36 packages were identified, and in Figure 14 every package used in both process maps is indicated with a red dot. A total of 29 packages were shared between the two process maps, indicating that 69% of the packages from Case Study 1 could be reused in Case Study 2.

The DSM automatically generated from the process map in Case Study 1 is shown in Figure 15. The DSM illustrates an appropriate clustering of coupled packages, but also shows how some work packages were performed by the client too late, resulting in assumption-based dependencies for a range of packages in the early stages of design.

The project manager for the design of the laboratory research facility **(**Case Study 1**)** was aware of the problem of late client decisions, but found it difficult to achieve a deeper understanding of the design risk implied. When he saw the DSM, he said it gave him a much better overview of the potential implications, especially since the DSM is constantly updated as packages change location in time. His team indicated a need for location-based process planning, which would allow work packages to be repeated for different locations of the building at different times. Such features are yet to be implemented, but since IDM Manager is object-focused, it would be feasible to split the process map into vertical layers for either general packages or location-specific packages, and continue planning as such. For upfront planning of deliverables, the team also found the tool useful to gain a common understanding of the constraints between activities, but for the tool to be used throughout the design process, a substantial number of predefined IDM Packages need to be defined, so the team concluded that the industry has a considerable standardization task ahead.

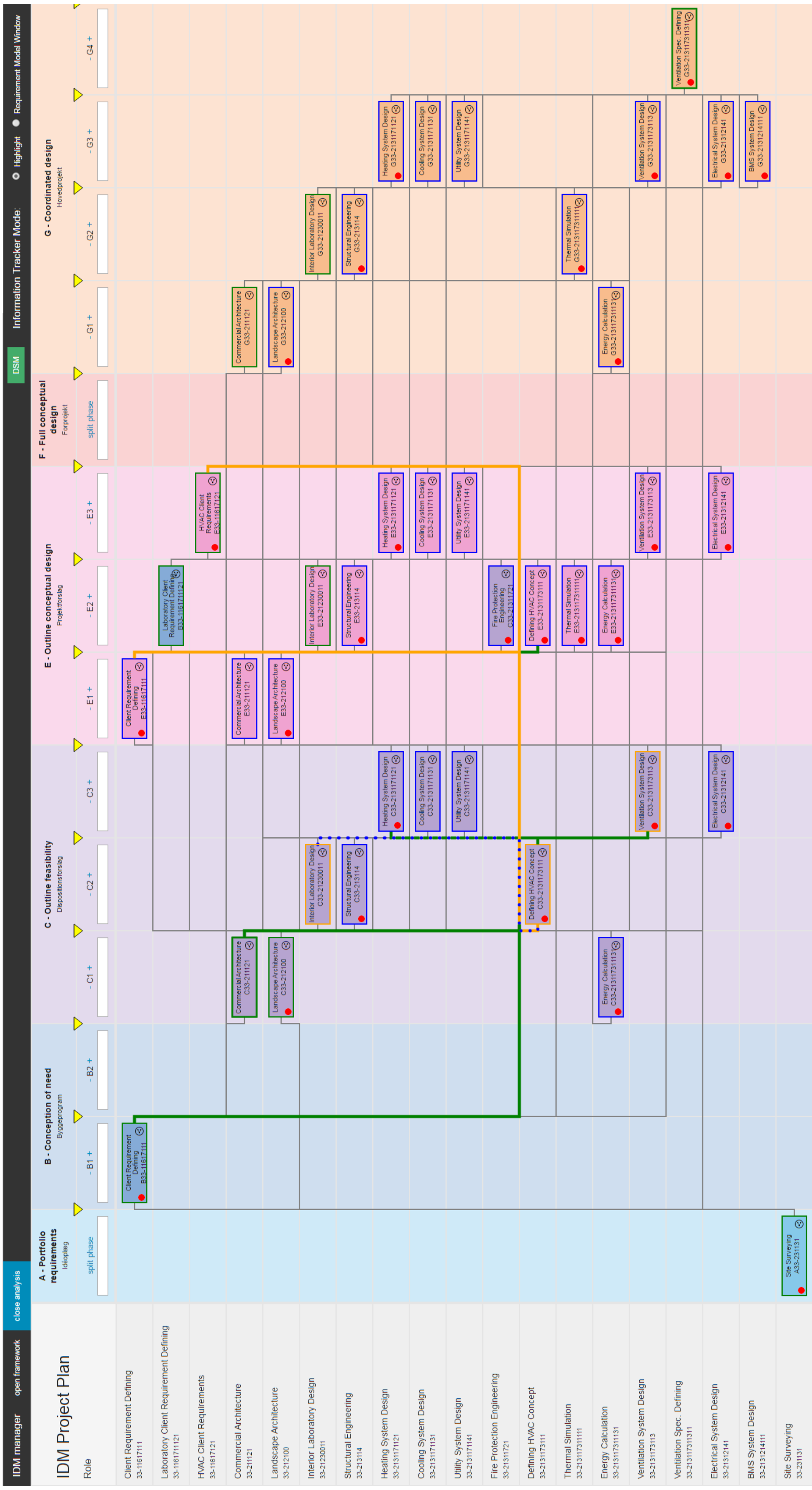


Figure 14. IDM Project Plan to complete the design and specification of the ventilation system for the laboratory research facility - the package “Define HVAC Concept” is highlighted and its dependencies are color-coded green, blue and orange depending on the dependency types

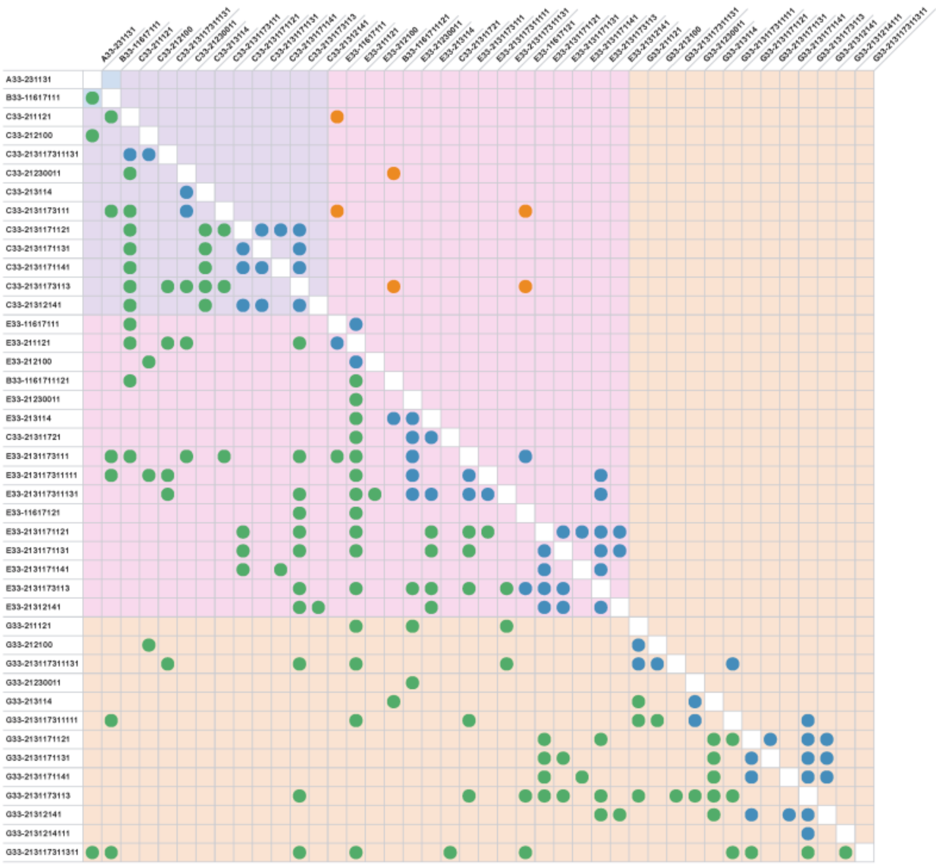


Figure 15. Automatically generated DSM for the IDM Project Plan defined (Case Study 1)

Conclusions

The AEC industry is in clear need of an improved ability to define information exchange requirements more efficiently; otherwise, the value of using information systems is limited. On the basis of the findings in this paper, it is clearly a complicated task to achieve such improvement. Considerable inconsistency among domain experts about information requirements and best practice for a given work package makes it difficult to align requirements. For the industry to improve productivity, it seems essential to change current practice. Despite considerable efforts in previous IDM development work to achieve consensus on exchange requirements, the widespread use of IDMs has been hampered by the way IDMs are compiled. The modular IDM package methodology presented here is a response to this challenge. The first goal of the research was to evaluate how core work packages can be defined and whether the methodology can help increase standardization of exchange requirements. On the basis of the findings from defining the initial 24 IDM packages, a range of principles and guidelines were developed. Using these, it was concluded to be a useful process for defining such exchange requirements. The methodology limits dependencies e.g. from organizational and/or contractual agreements by focusing purely on the exchange requirements for each specific work package. This allows work packages to be included in many different project constellations, increasing standardization across communities. The need for a standardized framework within which to define IDM Packages is pivotal in this regard. Using the framework proposed in this paper will allow different national and international communities to share IDM packages in a structured way and more easily identify and reuse other people's work. For this reason, the methodology is believed to allow for improved standardization of exchange requirements compared to the current IDM practice.

Different project types, national regulations, and differences in design and construction traditions can increase the need to define a range of IDM packages, including similar IDM packages with different contents to match individual national or organizational needs. As the second use case illustrated, the ability to reuse IDM packages in different project types is relatively high due to their generic focus. Constraints for specific attributes clearly improve the ability to create packages which are applicable in a multitude of scenarios. Still, several hundred packages need to be defined for the solution to be applicable to actual projects. Ideally, the engagement of national institutions can drive such work forward, reaching broader consensus, and in such case the work required seems manageable. National regulations and traditions seemed to be a barrier to the reuse of IDM packages internationally because several attributes were defined specifically to address national concerns. An expansion of the use of constraints to manage national differences could solve part of this problem, but other initiatives, like the buildingSMART Data Dictionary (formerly bS Dictionary), could also reduce the need for nationally specific attributes by allowing the translation of the meaning of specific attributes using such a common data dictionary. The effort required to reach an appropriate number of IDM packages is still considerable, but surely small compared to the effort currently spent by organizations worldwide on defining information exchange requirements in building design using numerous heterogeneous approaches. The IDM package methodology can make it possible to start aligning this work.

The advantages of the methodology can be seen in its ability to meet both theoretical and practical needs for efficient design management and in particular efficient information flow management. The unique, dynamic, iterative, and interdependent design process puts considerable demands on project managers to continuously ensure an efficient information flow during design. The static nature of the current IDM methodology with fixed processes makes the problem worse. With a tool like the proposed IDM Manager, the content of IDM packages can instead add value by actively supporting decision-making and achieve an efficient information flow in projects.

The methodology also reduces the need for domain expert involvement in the development of project-specific work plans. Domain experts should surely be involved in planning design work efficiently, but the in-depth knowledge of information requirements needed in the current methodologies will become less necessary as planning can rely on easily accessible predefined packages in the IDM Framework library.

The object-focused content of each package allows work package dependencies to be calculated automatically which will considerably reduce the effort required for dependency analysis. In current DSM solutions, a considerable barrier to using such optimization algorithms is the need to define work package dependencies manually and then keep them updated, but now they can be calculated continuously, which is much more attractive. Careful consideration needs to be taken to the information flow logics defined in this paper because otherwise the dependencies will not properly reflect the concurrent design process common in modern design projects.

The proposed IDM Manager already includes an automated DSM generator, and further functionalities in relation to calculating the sensitivity of object attributes and process optimization algorithms could be added. The IDM Manager could also be integrated as part of a BIM Governance Platform in the way Alreshidi et al. (2015) describe; this would facilitate both process dialog and the quality assurance of BIM deliveries. The quality assurance of BIM models would benefit from MVD (Model View Definition) requirements being generated based on the identified exchange requirements. A more modular approach to MVD generation in this case would also be of interest to match the dynamic nature of exchange requirement development and needs further investigation. Future work should also include further industry commitment in defining industry-wide accepted IDM packages as well as work to scope initiatives within buildingSMART in a more modular way.

Acknowledgments

The research reported in this paper was funded by Innovation Fund Denmark, the EU funded cuneco project, and the engineering consultancy company, Rambøll Denmark.

References

Alreshidi, E., Mourshed, M., and Rezgui, Y. (2015). "Cloud-Based BIM Governance Platform Requirements and Specifications: Software Engineering Approach Using BPMN and UML." *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487.0000539), 4015063.

Aram, S., Eastman, C., Sacks, R., Panushev, I., and Venugopal, M. (2010). "Introducing a new methodology to develop the information delivery manual for AEC projects." *Proc., CIB W78 2010: 27th International Conference*.

Austin, S., Baldwin, A., Li, B., and Waskett, P. (2000). "Analytical design planning technique (ADePT): a dependency structure matrix tool to schedule the building design process." *Construction Management and Economics*, 18(2), 173–182.

Ballard, G. (1999). "Can Pull Techniques be Used in Design Management?" *Proc., Conference on Concurrent Engineering in Construction*, Helsinki, Finland.

Ballard, G. (2000). "Positive vs. Negative Iteration in Design." *Proc., 8th Conference of the International Group for Lean Construction*, Brighton, U.K.

Berard, O. (2012). "Building Information Modeling for Managing Design and Construction Assessing Design Information Quality." Technical University of Denmark.

Berard, O., and Karlshoej, J. (2012). "Information delivery manuals to integrate building product information into design." *ITcon Journal of Information Technology in Construction (ITcon)*, 17(17), 63–74.

van Berlo, L. A. H. M., Beetz, J., Bos, P., Hendriks, H., and Tongeren, R. C. J. van. (2012). "Collaborative engineering with IFC: new insights and technology." *Proc., European Conferences On Product And Process Modeling In The Building Industry (ECPPM)*, Gudnason and Schrerer, eds., Taylor & Francis Group, London, 811–818.

BIMForum. (2015). *Level of Development Specification*. BIMForum, USA.

bips. (2016a). *CCS Purpose - Product Sheet*. Herlev, Denmark.

bips. (2016b). *CCS Purpose: Energy performance calculation*. Herlev, Denmark.

buildingSMART Norway. (2015). "bSN Guiden - Prosessveiledninger." <http://buildingsmart.no/bs-guiden/prosessveiledninger> (Oct. 19, 2015).

Denscombe, M. (2014). *The Good Research Guide - For small-scale social research projects*. Open University Press, Berkshire, U.K.

Eastman, C. M., Jeong, Y.-S., Sacks, R., and Kaner, I. (2010). "Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards." *J. Comput. Civ. Eng.*, (10.1061/(ASCE)0887-3801).

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons, Inc., Hoboken, New Jersey.

El. Reifi, M. H., and Emmitt, S. (2013). "Perceptions of lean design management." *Architectural Engineering and Design Management*, 9(3), 195–208.

Emmitt, S., and Ruikar, K. (2013). *Collaborative design management*. Routledge, London, U.K.

Eppinger, S. D., and Browning, T. R. (2012). *Design Structure Matrix Methods and Applications*. MIT Press, Cambridge, USA.

Freire, J., and Alarcón, L. F. (2002). "Achieving Lean Design Process: Improvement Methodology." *Journal of Construction Engineering and Management*, 128(3), 248–256.

Gu, N., Singh, V., and London, K. (2014). "BIM Ecosystem: The Coevolution of Products , Processes , and People." *Building Information Modeling: BIM in Current and Future Practice*, (K. Kensek and D. Noble, eds.), John Wiley & Sons, (MAY), 197–210.

Hooper, M. (2015). "BIM Anatomy II - Standardisation needs and support systems." Lund University.

ISO. (2008). “Organization of information about construction works - Framework for management of project information.” *ISO 22263*, Geneva, Switzerland.

ISO. (2010). “Building information models - Information delivery manual - Part 1: Methodology and format.” *ISO 29481-1*, Geneva, Switzerland, 34.

ISO. (2013). “Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries.” *ISO 16739*, Geneva, Switzerland, 23.

ISO. (2016). “Building information models - Information delivery manual - Part 1: Methodology and format.” *ISO 29481-1*, Geneva, Switzerland, 28.

Karlshoej, J. (2012). “Process and building information modelling in the construction industry by using information delivery manuals and model view definitions.” *Proc., 9th European Conference On Product And Process Modeling In The Building Industry (ECPPM)*, Reykjavik, Iceland, 305–309.

Karlshøj, J. (2013). “Overview of Information Delivery Manuals independent of their status.” *buildingSMART International User Group*, <http://iug.buildingsmart.org/idms/overview> (Mar. 15, 2017).

Karniel, A., and Reich, Y. (2011). *Managing the Dynamics of New Product Development Processes*. Springer-Verlag London Limited, New York, US.

Kiviniemi, A. (2005). “Requirements management interface to building product models - CIFE Technical Report #161.” Stanford University, USA.

Kiviniemi, A. (2008). “IFC Certification process and data exchange problems.” *Proc., 7th European Conference on Product and Process Modeling (ECPPM)*, Sophia Antipolis, France, 517–522.

Koskela, L. (2007). “Foundations of Concurrent Engineering.” *In Concurrent Engineering in Construction Projects*, J. M. Kamara, C. J. Anumba, and A.-F. Cutting-Decelle, eds., Taylor & Francis, London, UK, 12–29.

Lee, G., Eastman, C. M., and Sacks, R. (2007). “Eliciting information for product modeling using process modeling.” *Data & Knowledge Engineering*, 62(2), 292–307.

Lee, G., Park, Y. H., and Ham, S. (2013). “Extended Process to Product Modeling (xPPM) for integrated and seamless IDM and MVD development.” *Advanced Engineering Informatics*, Elsevier Ltd, 27(4), 636–651.

Lightsey, B. (2001). *Systems Engineering Fundamentals*. Defense Acquisition University Press, Fort Belvoir, Virginia.

Malleson, A. (2016). *International BIM Report 2016 - The International picture*. *NBS*, Newcastle upon Tyne, U.K.

Martínez-Rojas, M., Marín, N., and Vila, M. A. (2015). “The role of information technologies to address data handling in construction project management.” *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

McGraw-Hill Construction. (2014). *The Business Value of BIM for Construction in Major Global Markets: How contractors around the world are driving innovation with Building Information Modeling*. *SmartMarket Report*, Bedford, USA.

Mondrup, T. F., Treldal, N., Karlshøj, J., and Vestergaard, F. (2014). “Introducing a new framework for using generic information delivery manuals.” *Proc., 10th European Conferences On Product And Process Modeling In The Building Industry (ECPPM)*, Vienna, Austria, 295–301.

Moon, H., Kim, H., Kamat, V. R., and Kang, L. (2015). “BIM-Based Construction Scheduling Method Using Optimization Theory for Reducing Activity Overlaps.” *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

Oh, M., Lee, J., Hong, S. W., and Jeong, Y. (2015). “Integrated system for BIM-based collaborative design.” *Automation in Construction*, Elsevier B.V., 58, 196–206.

OMG. (2011). *Business Process Model and Notation (BPMN) Version 2.0*. *Business*, Needham, US.

OmniClass. (2012). “Disciplines.” *Table 33*.

Panushev, I., Eastman, C., Sacks, R., Venugopal, M., and Aram, V. (2010). “Development of the national BIM standard (NBIMS) for precast/prestressed concrete." *Proc., 27th International Conference on Information Technology in Construction CIB W78*.

Pikas, E., Koskela, L., Sapountzis, S., Dave, B., and Owen, R. (2011). "Overview of building information modelling in healthcare projects." *Proc., HaCIRIC 11 Conference*.

Pikas, E., Koskela, L., Thalfeldt, M., Dave, B., and Kurnitski, J. (2015). "Complexity in Designing Energy Efficient Buildings : Towards Understanding Decision Networks." *Proc., 23rd Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, 213–222.

Rezgui, Y., Cooper, G., and Brandon, P. (1998). "Information Management in a Collaborative Multiactor Environment: The COMMIT Approach." *J. Comput. Civ. Eng.*, (10.1061/(ASCE)0887-3801).

See, R., Karlshoej, J., and Davis, D. (2012). "An Integrated Process for Delivering IFC Based Data Exchange." buildingSMART International User Group.

Tang, L. C. M., Zhao, Y., Austin, S., Darlington, M., and Culley, S. (2008). "Overload of Information or Lack of High Value Information: Lessons Learnt from Construction." *Proc., 9th European Conference on Knowledge Management*, 851–860.

Treldal, N., Vestergaard, F., and Karlshøj, J. (2016). "Pragmatic use of LOD - a modular approach." *Proc., 11th European Conference on Product and Process Modeling (ECPPM)*, Limassol, Cyprus, 129–136.

Tribelsky, E., and Sacks, R. (2011). "An Empirical Study of Information Flows in Multidisciplinary Civil Engineering Design Teams using Lean Measures." *Architectural Engineering and Design Management*, 7(2), 85–101.

Tuholski, S. J. (2008). "Transformation, Flow, and Value Constellations in AEC Projects." University of California, Berkeley.

Wix, J., Nisbet, N., and Liebich, T. (2008). "Using constraints to validate and check building information models." *Proc., 7th European Conference on Product and Process Modelling (ECPPM)*, R. Scherer and A. Zarli, eds., CRC Press, London, U.K., 467–476.

Wynn, D. C., Eckert, C. M., and Clarkson, P. J. (2007). "Modelling iteration in engineering design." *Proc., ICED 2007 International Conference on Engineering Design*, 1–12.

Yassine, A., and Braha, D. (2003). "Complex Concurrent Engineering and the Design Structure Matrix Method." *Concurrent Engineering*, 11(3), 165–176.

Zhang, J., and El-Gohary, N. M. (2015). "Automated Information Transformation for Automated Regulatory Compliance Checking in Construction." *J. Comput. Civ. Eng.*, (10.1061/(ASCE)CP.1943-5487).

Paper C
Pragmatic Use of LOD – a Modular Approach

Pragmatic Use of LOD – a Modular Approach

N. Treldal
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
Rambøll Denmark A/S, Copenhagen, Denmark

F. Vestergaard
J. Karlshøj
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

ABSTRACT: The concept of Level of Development (LOD) is a simple approach to specifying the requirements for the content of object-oriented models in a Building Information Modelling process. The concept has been implemented in many national and organization-specific variations and, in recent years, several solutions have been proposed to address the challenge of the LOD concept being either too simple to fully describe the requirements for BIM deliverables or too complex to be operational in practice. This study reviews several existing LOD concepts and concludes that addressing the completeness and reliability of deliveries along with use-case-specific information requirements provides a pragmatic approach for a LOD concept. The proposed solution combines LOD requirement definitions with Information Delivery Manual-based use case requirements to match the specific needs identified for a LOD framework. This framework can act as a basis for future LOD solutions to harmonize the conceptual understanding of LOD definitions.

1 INTRODUCTION

1.1 *Study background*

Level of Development (LOD), Information Levels, and other similar concepts for defining requirements for Building Information Modelling (BIM) deliverables are widely used in the Architectural, Engineering and Construction (AEC) industry. LOD allows for a simple approach for specifying the requirements for the content of object-oriented models in a BIM process, but prior research (Hooper 2015; Berlo et al. 2014; Boton et al. 2015) has established that it is a considerable challenge throughout the AEC industry to define BIM deliveries accurately using existing LOD concepts.

Different design disciplines, project execution models and project organizations require different information to be available at project milestones, so there has to be a granularity within the framework of LOD. For this reason, several organizations have introduced further terms, such as Level of Detail (graphic-oriented), Level of Information (non-graphic-oriented), Level of Accuracy (tolerance-oriented), and Level of Coordination (collaboration-oriented) (BIM Acceleration Committee 2014).

Most solutions differentiate only graphical and non-graphical requirements to limit complexity. For example, the BSI defines *graphical data* as “data conveyed using shape and arrangement in space” and *non-graphical data* as “data conveyed using alphanumeric characters” (BSI 2013).

As the range of options for specifying LOD requirements increases, so does the complexity of defining requirements and the challenge is to achieve actual added project value using such approaches (Hooper 2015). Berlo et al. 2014 also describes a considerable confusion of when a BIM model actually reaches a certain LOD level and it seems that one major challenge is still the misunderstanding of *detailing* as a definition for model progression (NATSPEC 2013).

There is a close correlation between the processes undertaken in AEC projects and the BIM model deliverables (Lee et al. 2007), and this means that any requirements stated will affect how the design is executed. Using LOD can, therefore, make it a complicated matter for clients and others to state requirements that will likely be of value for the entire project. The range of proposed LOD concepts available, however, indicates a need in the AEC industry to have an approach that addresses model deliveries. The challenge seems to be how such a solution can be both unambiguous and operational?

1.1 *Study goals*

The goal of this research was first to compare existing LOD concepts in the AEC industry to clarify their scope and the terminology they use. And then secondly to propose a solution that can harmonize the LOD concept to state unambiguous BIM delivery requirements yet still practical enough to ensure common ground for all the stakeholders in a project.

2 METHODOLOGY

The research started with a review comparing known and widely-used LOD concepts from organizations in several countries. Eight LOD concepts were selected for further analysis in this research based on their individual approach. The main goal was to explore how existing solutions handle the granularity of the LOD concept and to what extent they state unambiguous requirements. Secondly, the findings from work to develop a proposal for a set of new Danish Information Levels were used to define the operational requirements for a LOD concept. The authors have been actively involved in the development of both the prior Danish bips Information Levels and more recently of a new concept by Digital Convergence (DiKon), which is a working group of BIM experts from six of the largest AEC companies in Denmark. The findings from DiKon were identified during multiple workshops within this working group. Based on these findings, a solution is proposed here that builds on top of the DiKon concept in an attempt to harmonize the usage of LOD and also includes recent research on more modular approaches to delivery requirement definitions.

3 REVIEW

3.1 *Development of LOD concepts*

Over the last decade, a number of LOD concepts have been proposed by industry and client organizations. In Denmark, the organization bips based its first proposal for a set of generic Information Levels (bips 2007) on work carried out by the Finish PRO IT organization. The Information levels were later revised (bips 2009) and recently completely reconfigured in a new set called CCS Information Levels (Cuneco 2014). The solutions define high-level and generic descriptions of the Information Levels at model level. There is an intention to define model-element-specific requirements based on the overall levels, but so far this work is still in progress within bips.

In the US, the AIA released their first contracting documents describing LOD requirements in 2008 and revised them in 2013 (AIA 2013a). The documents only cover high-level and short generic descriptions of LOD, but in 2011 the AIA allowed the US organization BIMForum to put further detail into their LOD concept at model element type level. Their latest release (BIMForum 2015) includes more than 140 element-type-specific definitions, and supplementary Element Attribute Tables define requirements per level for non-graphical information for each element type.

Building on top of the work by the AIA, first the U.S. Department of Veterans Affairs and later the Australian NATSPEC organization in 2011 released a BIM Object/Element Matrix (NATSPEC 2013) with requirements for non-graphical object properties for 28 model element types. All the object properties are categorized in groups based on 15 defined use cases and mapped to the buildingSMART IFC specifications (buildingSMART 2007).

In the Netherlands, TNO has developed a proposal for a set of Information Levels focused primarily on the purposes a model can be used for (Berlo et al. 2014). A database is currently under development to define model-element-specific requirements for non-graphical information (TNO et al. 2014). In the UK, the BSI has defined a set of model stages in its PAS standard (BSI 2013) to define requirements at model level for both graphical and non-graphical content based on descriptions of themes and purposes. A BIM Toolkit solution by NBS (NBS 2015) aims to use the PAS model stages to define individual requirements for model element types at different design stages, but this solution also seems to be still under development.

Several other solutions, such as the Finish COBIM, the New Zealand BIM Handbook, and the US Army BIM Minimum Modeling Matrix, have also been introduced, but most other concepts are either limited in their range of model requirements or based on the principles of one of the solutions above.

3.2 *Common Understanding of LOD*

Originally introduced by the AIA as an abbreviation for *Level of Detail*, the term LOD was changed in 2013 to represent *Level of Development* (AIA 2013a) based on conclusions similar to those found elsewhere (NATSPEC 2013; BSI 2013) that

LOD represents the combination of requirements for the concretization of both graphical and non-graphical information during a project.

The ambitions for LOD are somewhat multi-faceted, ranging from "the degree to which (…) information has been thought through" (BIMForum 2015) to "what the model can be used for" (Berlo et al. 2014).

The AIA defines the term *Model Element* as "a portion of the model representing a component, system or assembly within a building or building site" (AIA 2013a), and most recent LOD concepts define their requirements based on type-specific model element definitions. For the solutions that address model elements, a *LOD Table* like the Model Delivery Specification (DiKon 2015), the Model Element Table (AIA 2013b), or the BIM Object/Element Matrix (NATSPEC 2013) is needed to define delivery requirements for element types at the various project milestones. (Berlo et al. 2014) point out that the complexity of such LOD Tables quickly increases to such an extent that ordinary users lose all track of the relationship between desirable use cases and requirements. Current LOD concepts are therefore challenged by trying to address both a wide range of purposes and the need for simple and operational solutions.

3.3 *Information Delivery Manual (IDM)*

The concept of an IDM is an alternative solution to defining unambiguous exchange requirements for BIM deliveries for specific use cases and has been developed by buildingSMART (See et al. 2012). In an earlier paper, we proposed a solution using IDM Packages – each describing only a single-actor use case per IDM – to allow for a more modular approach to describing information flow in construction (Mondrup et al. 2014). IDM Packages can be rearranged more freely than traditional IDMs, which usually describe large-scale use cases involving several actors. The idea is to have the ability to define unambiguous information requirements at model element level based on specific use cases.

Both the IDM and LOD address delivery requirements, but the origin of the IDM was the need to define object-oriented and property-specific exchange requirements, whereas the origin of LOD was to define generic and high-level requirements. With a use-case-specific and information-intensive LOD concept like the NATSPEC, concepts originating from IDM and LOD get mixed together, illustrating the need for solutions to be both high-level and unambiguous at the same time.

The Norwegian bSN Guiden (buildingSMART Norway 2015) is a solution based on these principles. It provides individual users with a simple database interface for defining use-case-oriented and unambiguous delivery requirements at model element level. However, currently the solution only states limited delivery requirements, none of which relate to graphical information. It therefore needs supplementing with an existing LOD concept to make it fully useful.

3.4 *Aspects of LOD concepts*

To compare the somewhat different LOD concepts, five evaluation aspects were identified during the research:

– Content Aspect – How are completeness and/or detailing of deliveries defined?
– Format Aspect – Is graphical information separated from non-graphical information or are requirements combined?
– Context Aspect – Are levels related to phases and/or related to specific use cases?
– Structural Aspect – Does the concept target overall model requirements or model element requirements?
– Standardization Aspect – Does the concept make use of standardization solutions, like classification systems or exchange formats?

Table 1. Comparison of eight selected LOD concepts based on five defined aspects.

LOD Concepts		**Content Aspect**		**Format Aspect**		**Context Aspect**		**Structural Aspect**		**Standardization Aspect**	
Country and Organisation	**Denomination**	**Completeness**	**Detailing**	**Combined**	**Separated**	**Phase related**	**Use case related**	**Focus on model**	**Focus on model element**	**Classification**	**Exchange format**
DK bips 2007	Information Levels									DBK	IFC
DK CCS	Information Levels									CCS, intended	IFC, intended
DK DiKon	Information Levels										
US AIA 2013	Level of Development										
UK BSI	Level of Definition										
AUS NATSPEC	Level of Development									Uniformat	IFC + COBIE
US BIMForum	Level of Development									Uniformat	Partly IFC
NL TNO	Information Levels									NISfb	IFC, intended

Explicitly addressed · Implicitly addressed · Not included

The concepts address these aspects explicitly, implicitly or not at all. The comparison of LOD concepts is shown in Table 1.

3.5 *Review findings*

Notable from the comparison is that although there is still a considerable misunderstanding in the industry that LOD refers to the detailing of deliveries, none of the current LOD concepts address *detailing* explicitly in its definitions. Nevertheless, the concepts that include illustrations of the development stages, e.g. bips, DiKon and BIMForum, do implicitly address detailing to some extent, which can lead to misunderstandings about what is intended. Moreover, the UK BSI concept specifically mentions Level of Detail and includes some illustrations, but all definitions still relate to *completeness*.

No consensus has so far been reached in relation to whether graphical and non-graphical information should be defined separately or combined, whereas most recent solutions agree on defining use-case-related requirements at model element level. The relationship to classification systems and IFC/COBIE is increasing, yet still not implemented throughout the concepts, potentially leading to unclear requirement definitions in some cases.

According to Hooper, there is a lack of research on how useful LOD is in actually benefitting projects as well as a lack of research on the use of IDMs in practice (Hooper 2015). Berlo et al. report that the Dutch General Services Administration has removed all reference to LOD due to uncertainty of deliveries (Berlo et al. 2014), and although the Information Levels from bips are commonly used in public projects in Denmark (bips 2009), five out of the six AEC companies in the DiKon organization have developed supplementary definitions to improve the certainty of agreements. This illustrates the need for further definition of the success criteria for LOD concepts if they are to be unambiguous and operational.

4 FINDINGS FROM DANISH DEVELOPMENT EFFORT

4.1 *Initial work by bips*

During the development of the first set of Information Levels (bips 2007), it was concluded that the levels must be detached from phases because different project constellations require information to be utilized at different stages. However, the solution should 1) have levels representing deliveries in all main phases, and 2) allow for different parts of a delivery to be represented by different levels.

In the latest version from bips (Cuneco 2014) the levels have lost explicit connection to phases and are now defined as generic steps in the concretization of building projects ranging from 1 to 7. The challenge with this approach is that the levels are now defined so generically that it can be complicated to relate the levels to desired use cases in an unambiguous way.

4.2 *DiKon Information Levels*

So in 2015, the Danish organization DiKon decided to expand the latest set of Information Levels with a range of model element type-specific definitions and create a LOD table to link requirements to phases. The solution includes specific descriptions for 22 commonly used model element types (DiKon 2015).

More than 15 workshops were conducted by DiKon first to define the scope and then to review the content of the proposed model element definitions. The following findings summarize the conclusions from the workshops and define the scope of the proposed solution:

- The LOD levels from AIA/BIMForum do not match the delivery requirements common in the Danish AEC industry.
- The main goal is a tool for agreeing on the scope of deliverables that must be operational for clients and project managers with limited BIM experience
- The solution must make it possible to state unambiguous delivery requirements throughout a project without obstructing the processes and being too workload intensive.
- A LOD Table is required to allow for individual element types to be assigned different LODs at specific deliveries depending on 1) their type (prefab/build-on-site, etc.) and 2) their location in the building (e.g. differentiating HVAC components in plant rooms and shafts from similar components in other room types).
- Requirements for graphical and non-graphical information must be defined separately in the LOD table.
- The requirements for non-graphical information must be based only on high-level use cases and must be part of the information currently available in BIM models.

Based on the above findings, a solution was developed (DiKon 2015), as illustrated in Table 3.

Only graphical requirements are illustrated in the table. Additional requirements for non-graphical information are also part of the solution, defined per level for each selected model element type.

The graphical requirements are defined based on three criteria:

– The reliability of the elements, ranging from *Expected*, *Specified* to *Final*.
– The shape of elements related to reliability, e.g. the max. outer contours for the expected level of reliability or contours reflecting the final dimensions for the final level of reliability.
– The completeness of the elements, referring to the element representation (e.g. generic, assembly or element-divided) and the scope of components to include along with the main element.

5 DESIRED LOD TERMINOLOGY

5.1 *Comparison of DiKon and BIMForum*

The DiKon concept is very similar to the BIMForum concept because they share common goals. In Table 2 and Table 3, a comparison is made of definitions for graphical requirements of comparable building services based on the DiKon and BIMForum concepts. Three interpretations of each definition described below have been added to the tables to make it possible to compare the similarities and differences of the two concepts.

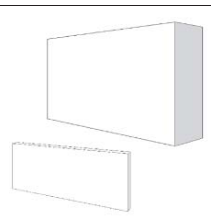
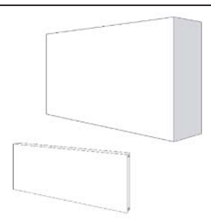
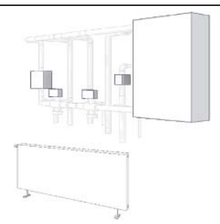
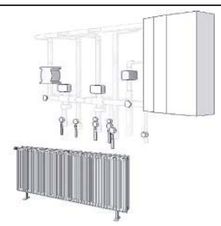
5.2 *Level of Completeness (LOC)*

The review in section 3 concluded that LOD definitions describe completeness and not detailing, so we introduce the concept of Level of Completeness (LOC) to address this need directly. LOC is defined on the basis of the concretization of the model element and the scope of included components. The combination of a description and an illustration defines each LOC. The comparison in Tables 2 and 3 illustrates why the BIMForum solution is not directly applicable in a Danish

Table 2. BIMForum 2015 LOD definition for D2010.20 – Domestic Water Equipment supplemented with an interpretation of corresponding detailing, Level of Reliability (LOR) and Level of Completeness (LOC).

LOD 100	LOD 200	LOD 300	LOD 350	LOD 400
				
Diagrammatic or **schematic** model elements; **conceptual** and/or **schematic** layout/flow diagram; design performance parameters as defined in the BIMXP to be associated with model elements as non-graphic information.	**Schematic** layout with **approximate** size, shape, and location of equipment; **approximate** access/code clearance requirements modeled; design performance parameters as defined in the BIMXP to be associated with model elements as non-graphic information.	Modeled as **design-specified** size, shape, spacing, and location of equipment; **approximate** allowances for spacing and clearances required for all specified anchors, supports, vibration and seismic control that are utilized in the layout of equipment; actual access/code clearance requirements modeled.	Modeled as **actual** construction elements size, shape, spacing, and location/connections of equipment; **actual** size, shape, spacing, and clearances required for all specified anchors, supports, vibration and seismic control that are utilized in the layout of equipment.	Supplementary components added to the model **required for fabrication** and field installation.
Interpretation: Detailing = Diagrammatic LOR = Conceptual LOC = Diagrammatic	**Interpretation:** Detailing = Medium LOR = Approximate LOC = Generic Level	**Interpretation:** Detailing = Fine LOR = Design-specified LOC =Type Level	**Interpretation:** Detailing = Fine LOR = Actual LOC = Component Level, Design	**Interpretation:** Detailing = Fine LOR = Actual LOC = Component Level, Fabrication

Table 3. DiKon 2015 Information Level definition for Heating and Sanitation Components supplemented with an interpretation of corresponding detailing, Level of Reliability (LOR) and Level of Completeness (LOC).

Information Level 2	Information Level 3	Information Level 4	Information Level 5	Information Level 6
Not defined				
	Components are modelled as **generic** volume objects in **expected** max. outer contour. **Expected** location and orientation of components.	Components are modelled in **specified** max. outer dimensions incl. **Specified** location and orientation of components.	Components are modelled in **final** outer dimensions. **Final** location and orientation of components.	Components are modelled in **final** dimensions based on actual choice of product. **Final** location and orientation of components.
	Interpretation: Detailing = Coarse LOR = Expected LOC = Generic Level	**Interpretation:** Detailing = Coarse LOR = Specified LOC = Type Level	**Interpretation:** Detailing = Medium LOR = Final LOC = Component Level, Design	**Interpretation:** Detailing = Fine LOR = Final LOC = Component Level, Fabrication

context: as similar levels, LOD 350 and Information Level 5, might both be at component level, but whereas e.g. hangers are included in LOD 350, this is not the case in Information Level 5 because this is not Danish practice. This indicates that while the concept of LOC could be used to harmonize the definitions of graphical requirements at a generic level, national or organisation-specific definitions are needed to match the content required for local practices or needs.

5.3 *Level of Reliability (LOR)*

The DiKon workshops concluded that reliability is a useful factor to include so that the concept can be used as part of a contractual agreement. It is clear that BIMForum reached similar conclusions because the terms *Conceptual*, *Approximate*, *Design-specified* and *Actual* are used throughout their definitions. A harmonization of such terms would further add to the common ground on expectations for deliverables.

5.4 *Detailing*

Believed to be of less relevance to the deliverables is the detailing or coarseness of the model elements. Detailing describes how objects are presented visually, but does not address the content. BIM authoring tools like Autodesk Revit have a functionality for easily changing the detailing of objects from *Coarse* to *Medium* or *Fine*. However, this does not necessarily imply that the LOD level has increased. The above tables indicate the interpreted detailing level on the basis of the illustrations available and this clearly shows that only limited consensus has been reached because the detailing is not aligned in the concepts. A review of illustrations for other model element types – particularly in the BIMForum concept – further adds to the conclusion that there is limited consensus about the detailing level at different LOD levels.

This partly explains the concern expressed by Berlo et al. that if people are asked to review different models, they reach very limited common agreement about what LOD level a particular model has reached (Berlo et al. 2014). Most likely this is because they focus on the detailing level of the model elements as opposed to the completeness and reliability of the elements.

5.5 *Focus on use cases*

Berlo et al. conclude that this confusion should lead to LOD levels focusing purely on use cases. The more use cases included to define a LOD level, the narrower the reuse of similar LOD levels can be in different project constellations. The review and findings in this paper indicate that there is a need to be able to define the level of concretization of model elements in a generic, simple and unambiguous way and this is why the use of LOC and LOR seems more valid as the foundation of a LOD framework. BIMForum acknowledges the need to link requirements to use cases and select 1) Quantity take-off, 2) 3D coordination, and 3) 3D control and planning as the high-level use cases which graphical and non-graphical delivery requirements should address as a minimum. Supplementing the above with drawing production as a use case still seems necessary, but leaving out requirements for additional use cases keeps the concept generic and still unambiguous.

5.6 *Level of Information (LOI)*

To define the requirements for non-graphical information accurately, we make use of the Level of Information (LOI). Such requirements are stated explicitly as object properties in some LOD concepts and in others described implicitly just as information needed to fulfil specific use cases, such as energy simulation or cost calculation. Koskela et al. conclude that the use of relevant software tools has limited impact if the AEC process is confused at the outset, so unambiguous information requirements are needed (Koskela et al. 2002). For this reason, LOI requirements should be defined explicitly and a solution like IDM Packages could be included to define requirements for additional use cases, adding a more modular approach to the LOD concept.

6 PROPOSAL FOR A PRAGMATIC LOD APPROACH

6.1 *Generic Framework*

Based on the above conclusions, we propose a solution for a generic set of LOD levels as shown in Table 4. This framework is intended to act as a basis for future LOD solutions to harmonize the conceptual understanding of LOD content. As previously indicated, there is a need to customise the LOC definitions to match local practices, while the framework is still seen as generic.

6.2 *Scope*

BIMForum uses LOD 100 to define requirements for diagrammatic or schematic layouts of model elements. As argued also by NATSPEC, 2D drawings and other informational representations

Table 4. Framework for a generic LOD solution – must be detailed on model element level based on national or organizational needs.

	LOD 0	**LOD 1**	**LOD 2**	**LOD 3**	**LOD 4**	**LOD 5**	**LOD 6**
Scope	Specification	Idea	Outline	Proposal	Design	Construction	Handover
Level of Reliability	Final (requirements)	Expected	Expected	Specified	Final	Final	As-build
Level of Completeness	Descriptive Level	Volume Level	Generic Level	Type Level	Component Level, Design	Component Level, Fabrication	Component Level, Handover
Level of Information (based on the four high-level use cases)	- Identification - Scope	- Identification - Size	- Identification - Type - Size	- Identification - Type - Size - Material - Performance requirements	- Identification - Type - Size - Material - Performance requirements	- Identification - Type - Size - Product-specific values	- Identification - Type - Size - Product-specific values

could just as well be defined by different LOD levels (NATSPEC 2013). Accordingly we argue, based on the original findings from DK bips 2007, that LOD levels should be available to represent all the main phases of the AEC industry, focusing on delivery milestones. This is why we propose a total of seven levels spanning from LOD 0 to 6. The hundred-concept used by BIMForum to allow for custom LODs like 120 or 340 has also been dropped because we argue that such in-between levels are not desirable. Instead, local variations of the LOC of the seven levels must be accepted. Some LOD concepts assign *Operation* as the last level, but we argue that operation, maintenance, renovation, etc. are all use cases which use data from the milestone *Handover*.

6.3 *LOD table and use case connection*

To make it possible for additional use cases to be addressed, we propose to use the concept of IDM Packages to define use-case-specific information requirements. Including use cases in a Delivery Specification (LOD Table) based on such IDM Packages would allow for a configuration system to point directly to the information required by the additional use cases, as illustrated in Figure 1. The sum of information required as standard based on LOD 4 and the additional information required by the two selected use cases constitute the total requirements of what is to be delivered at (in this case) the Detailed Design phase.

6.4 *Pragmatic and modular*

The proposed framework and practical solution will allow clients and project managers with limited BIM knowledge to use the Delivery Specification to agree on the scope of deliveries.

Since the Delivery Specification is backed up by unambiguous information requirements, the BIM modellers will know what content should be included in the BIM models later, how it should be modelled, and what non-graphical information should be included.

The concept is only tied to a few high-level use cases and the modular approach allows for any additional requirements to be included as long as they are derived from a use case.

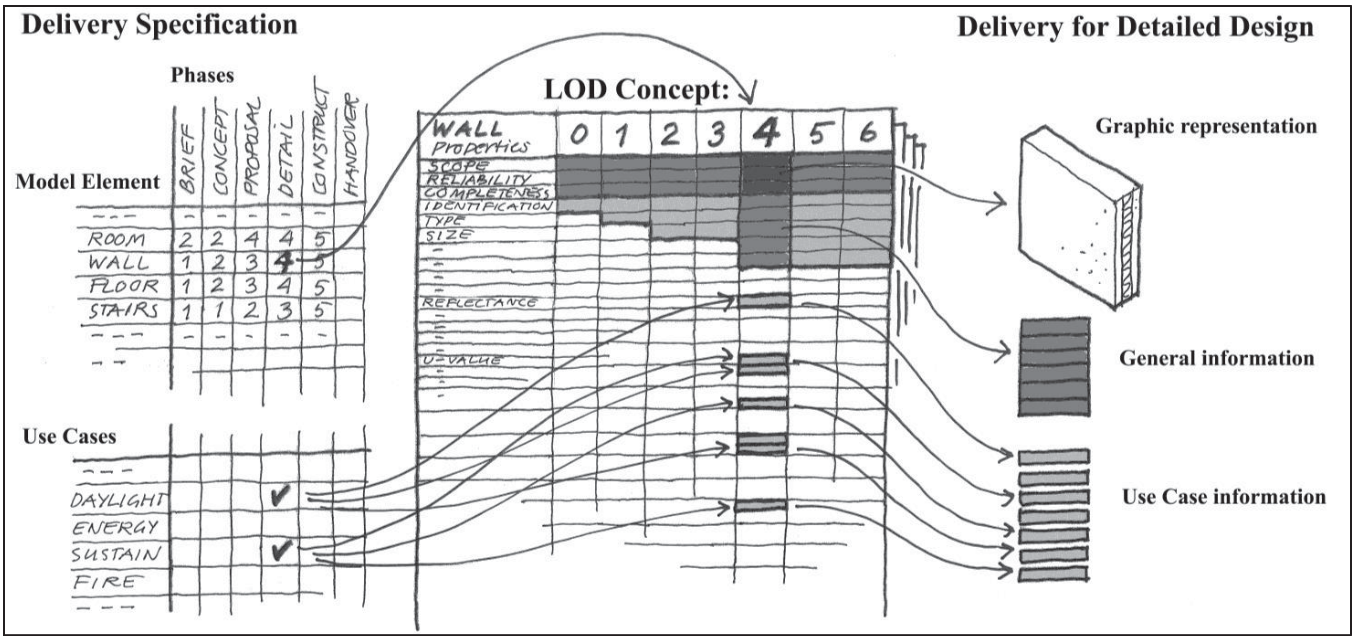


Figure 1. Modular approach of defining delivery requirements based on LOD selection for model elements and supplementing requirements with desired use cases.

7 CONCLUSIONS

In this study, we review several existing LOD concepts and conclude that addressing the completeness and reliability of deliveries along with use-case-specific requirements can provide a pragmatic approach for a LOD framework. This framework can act as a basis for future LOD solutions to harmonize the conceptual understanding of LOD definitions and, because it combines LOD definition requirements with IDM-based use case requirements, the solution is also highly modular.

The use of LOD is linked to the need for a pragmatic approach to agreeing on model deliveries, but the concept still requires human interpretation of graphical requirements to be translated into individual model-specific requirements. As the AEC industry matures further in relation to BIM modelling, it would be appropriate to focus more on IDM requirements – potentially fully integrating the LOD concept into IDM.

8 ACKNOWLEDGEMENTS

The authors would like to thank the bips organization and the members of DiKon for their fruitful and intense discussions on the development of Information Levels for the Danish AEC industry.

REFERENCES

AIA 2013a. Document E203™ – 2013 – Building Information Modeling and Digital Data Exhibit. US: The American Institute of Architects.

AIA 2013b. Document G202™ – 2013 – Project Building Information Modeling Protocol Form. US: The American Institute of Architects.

Berlo, L. van, Bomhof, F. & Korpershoek, G. 2014. Creating the Dutch National BIM Levels of Development (extended). Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering, 129–136.

BIM Acceleration Committee. 2014. New Zealand BIM Handbook - Appendix C - Levels of Development definitions. NZ: The Building and Construction Productivity Partnership.

BIMForum 2015. Level of Development Specification (Version 20). US: BIMForum.

bips 2007. 3D Working Method. Translated into English in 2007. Ballerup, Denmark: bips.

bips 2009. C102 e - CAD manual 2008, Instructions. Translated into English in 2009. Ballerup, Denmark: bips.

Boton, C., Kubicki, S. & Halin, G. 2015. The Challenge of Level of Development in 4D/BIM Simulation Across AEC Project Lifecyle. A Case Study. Procedia Engineering, 123, 59–67.

BSI 2013. PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling (March). UK: The British Standards Institution.

buildingSMART 2007. IFC2x Edition 3 Technical Corrigendum 1. Retrieved April 10, 2016, from http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.htm

buildingSMART Norway 2015. bSN Guiden - Prosessveiledninger. Retrieved October 19, 2015, from http://buildingsmart.no/bs-guiden/prosessveiledninger

Cuneco 2014. CCS Informationsniveauer (R0 ed.). Herlev, Denmark: bips.

DiKon 2015. Level of Information for Building Models - for selected building parts. DK: Digital Convergence. Retrieved from http://www.digitalkonvergens.dk/building-standards/model-delivery-specification/

Hooper, M. 2015. BIM Anatomy II - Standardisation needs and support systems. Lund University.

Koskela, L., Huovila, P. & Leinonen, J. 2002. Design Management In Building Construction: From Theory To Practice. Journal of Construction Research, 03(01), 1–16.

Lee, G., Eastman, C. M. & Sacks, R. 2007. Eliciting information for product modeling using process modeling. Data & Knowledge Engineering, 62(2), 292–307.

Mondrup, T. F., Treldal, N., Karlshøj, J. & Vestergaard, F. 2014. Introducing a new framework for using generic information delivery manuals. In Proceedings of the 10th European Conference On Product And Process Modelling In The Building Industry (ECPPM) (pp. 295–301).

NATSPEC 2013 BIM Paper NBP 001. AUS: Construction Information Systems Limited.

NBS 2015. BIM Toolkit. Retrieved March 20, 2016, from https://toolkit.thenbs.com/

See, R., Karlshøj, J. & Davis, D. 2012. An Integrated Process for Delivering IFC Based Data Exchange. Retrieved March 22, 2016 from http://iug.buildingsmart.org/idms/methods-and-guides/Integrated_IDM-MVD_ProcessFormats_14.pdf/view

TNO, BuildingSMART, Benelux & Stumico. 2014. BIM informatieniveaus. Retrieved April 10, 2016, from http://niveaus201402.nationaalbimhandboek.nl/

This page is intentionally left blank.

Paper D
Resource Utilization in Building Design: Reducing Variability

Resource Utilization in Building Design: Reducing Variability

Erik Falck Jørgensen

Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark

Niels Treldal

Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark

Rambøll Denmark A/S, Copenhagen, Denmark

Abstract

This paper examines problems faced by project managers in building design projects and suggests remedies. The study focuses on the social aspects of project management, agency and interaction with materiality in relation to norms and technologies. To examine the practice-based and socio-material perspectives, the study was carried out using the mixed-method approach of a quantitative survey and a number of qualitative interviews with project managers in a large engineering consultancy company. A range of criteria were used to identify project problems and elaborate on the kinds of remedies required. A cardinal instrument for project managers seems to be the shaping of communities, epistemic culture and ownership to reduce project variability. The study points out the organizational difficulties that arise when norms and strategic tools are introduced which do not support community building. Furthermore, the study indicates that, to avoid an increase in project variability, Building Information Modeling and other information technology initiatives must be implemented in communities which are strongly grounded.

Keywords: building design, communities of practice, construction industry, epistemic culture, epistemic objects, knowledge transfer, project management, socio-materiality, technology.

Introduction

Modelling the construction industry as a manufacturing process is believed to significantly improve its competitiveness because the manufacturing industry has outperformed the construction industry considerably in relation to productivity in recent decades (Kamara et al., 2007). Resource utilization is crucial if any manufacturing process is to be profitable, and variability in production must be reduced at all times to ensure stable performance (Hopp & Spearman, 2008). Lean principles and information and communication technology (ICT) are believed to support the reduction of variability in the construction industry just as much as in the manufacturing industry

(Koch & Friis, 2015; Koskela, 2000; Koskela & Kazi, 2003; Sacks et al., 2010). However, there are key differences between the mass production in manufacturing and the location of production activities in 'one-off' facilities in construction (Kamara et al., 2007). Furthermore, these 'one-off' facilities span from relatively straightforward single-family housing to highly specialized laboratories and hospitals. Every new project usually involves a new constellation of stakeholders, resulting in considerable challenges with shifting ICT setups, such as interdisciplinary data exchange platforms, information exchange requirements, and digital delivery requirements. Kamara et al. argue that the differences with manufacturing are mostly related to the product and that the processes are comparable, but the ever-changing projects and a considerably greater fragmentation in the construction industry challenge the stability of the social constellations of project teams even inside organizations. This social context is identified as a key barrier in the construction industry to implementation of ICT processes such as building information modeling (BIM). Such complexity and the conditions of implementation should be addressed more carefully if such ICT methods are to add value to projects (Miettinen & Paavola, 2014). As this study will illustrate, high levels of variability are still present in building design. For this reason, this paper will examine these social barriers that tend to block initiatives aimed at reducing the variability identified.

This paper explores how strategic initiatives in relation to project management, including the implementation of new processes and technology, should be targeted to meet these challenges. The paper will move forward in three steps. First, the methodological considerations that have guided the research are listed, supported by the pivotal theoretical considerations. Secondly, the empirical results of the projectare presented, which are partly quantitative and partly qualitative in an ethnographic and practice-based perspective. And finally, parallels to the theoretical landscape initially outlined are drawn, including exemplification and involvement of the empirical data along with a discussion of their significance.

Methodology

This study draws upon a mixed-method approach (Johnson et al., 2007; Kvale & Brinkmann, 2015) consisting of a quantitative survey and a number of qualitative interviews with project managers in a larger engineering consultancy company with approximately 3000 employees in Denmark, of whom approximately 750 work in the 'Building' unit. The quantitative survey was intended to get an overall view of challenges in managing the building design process. The survey was designed to include both descriptive and explanatory research (De Vaus, 2002, p. 22), firstly by identifying what project managers believe are the greatest challenges, and secondly by identifying the perceived knowledge and behaviour of project managers. The survey was carried out ultimo 2015 and will be discussed later in this paper. When the quantitative responses were analysed, inconsistency was observed. To clarify these responses, a smaller sample group was therefore selected for semi-structured interviews (Kvale & Brinkmann, 2015).

The interview data presented in this paper are fairly roughly transcribed. There is no indication of overlapping words, new beginnings, or the length of pauses, and vocal aspirations. Interruptions are usually not indicated. 'Latching' and prolonged syllables are not transcribed. Furthermore, the interview data has been translated from Danish into English. Nevertheless, we believe that the transcriptions are adequate for the level of analysis conducted here, and that this style of transcribing is easier to read. The interviews were carried out in the second half of 2016. Reflections on these qualitative interviews will be discussed later in this paper.

The results of the mixed-method approach enabled us to deduce the findings in this paper, which shows that it is beneficial to have multiple analytical perspectives on academic curiosity, especially when quantitative surveys are used.

Previous research on project management problems

Most research on problems faced by project managers has focused on the construction phase, and research on the specific problems faced by project managers in the design phase has been limited. Tilley (2005) summarizes this limited research, identifying poor management processes and poor relationships between participants as being the main reasons for poor industry performance. El Reifi & Emmitt (2013) made a survey of the UK construction industry and identified client aspirations and poor design management as key reasons for delays and budget overruns. Several other researchers have carried out similar surveys, but most have focused on external factors causing quality problems, and very few have investigated what might be the causes (or remedies) for poor design management in construction. In an earlier US survey, Arditi & Gunaydin (1998) found that problems in coordination, client requirements, and teamwork were the most important reasons for poor design quality while they ranked the designer's education as second lowest out of 17 possible factors. These results are very similar overall to the findings in this paper, which suggests that the building design industry is still facing the same problems as decades ago. Tilley (2005) and El Reifi & Emmitt (2013) indicate Lean Design Management as a remedy that can overcome both internal and external problems based on the rational focus of 'the old core values' of Lean Production philosophies, but they conclude that further research is needed to evaluate this effect. Miettinen & Paavola (2014) list a number of problems for which BIM was promoted as the solution, but conclude that the current implementation of such ICT solutions has had limited effect. Instead, they argue that ICT solutions must be implemented in the social context and carefully selected and managed, if successful implementation is to be achieved.

Variability in Building Design

Excessive variability is a chronic problem in construction (Koskela & Kazi, 2003). 'Variability' or 'uncertainty' is the possible deviation of an estimate, at the time of assessment, from the actual value (A Yassine et al., 1999), and Kraemer et al. conclude that it is important to understand and manage variability to achieve effective production management (Kraemer et al., 2007). BIM and lean principles are believed to have the ability to reduce product and process variability because they both focus on getting quality right the first time, and on reducing upstream flow variability and production cycle duration (Sacks et al., 2010).

From a BIM perspective, ICT challenges, such as deficient skills or machine, software, and communication breakdowns, are a considerable source of variability. The background variability of the ICT infrastructure should therefore be reduced (Koskela & Kazi, 2003). From a lean perspective, the combination of too much focus on deliverables (transformation of requirements to design) and too little focus on the flow of information and the generation of value is also a considerable source of variability, so changes in management focus are required (Pikas et al., 2015). The problem is that such knowledge has been available to the industry for decades and is, at least to some extent, already being addressed by engineering companies. Yet, as this study will show, high levels of variability are still present in building design. That is why this paper will examine the social barriers which could be part of the reason why variability in building design is still too high.

Knowledge Management and Practice

Building design can be considered a complex system which is often decomposed into a number of simpler subsystems that can be controlled independently, the sum of whose individual behaviours yields the performance of the original complex system (Ali Yassine & Braha, 2003). Decomposition is also intended to exploit opportunities for parallel execution, but one key challenge in decomposing the design process is that knowledge gets scattered among sub-teams and knowledge management becomes more complex. Moreover, most existing ICT solutions store data in a 'siloed' manner. This prevents and limits opportunities to capture critical knowledge of the connections between the silos and knowledge that is known only to specific team members (Yalcinkaya & Singh, 2016). Yalcinkaya & Singh further argue that the fragmented nature of the construction industry means that the success rate of managing such project knowledge is typically very low, and processes quite often end up being ad-hoc at the best.

So, the problem of knowledge management is particularly acute in practices where projects are complex and includes actors from several different disciplines. The challenge is to decompose siloed data and information to achieve the collaborative and shared intention of the project is therefore a matter of shaping communities that support and respect existing practices. The methodical premise for this study is therefore the practice-theoretical framework (Gherardi, 2012; Kemmis et al., 2014; Nicolini, 2012; Schatzki et al., 2000), in which the concepts of communities of practice (Lave & Wenger, 1991), objects (Nicolini et al., 2012), and socio-materiality (Carlile et al., 2013) underpin actors trajectories in practice. The field of practice theory describes the importance for human agency of having a shared purpose and how this affects the actors involved in a shared context. As Schatzki et al. put it, *'Activity is embodied and nexuses of practices are mediated by artifacts, hybrids, and natural objects, disagreements reign about the nature of embodiment, the pertinence of thematizing it when analyzing* *practices, the sorts of entities that mediate activity, and whether these entities are relevant to practices as more than mere intermediaries among humans'* (Schatzki et al., 2000, p. 11).

An organization can therefore be seen as an assembly of human actors acting in a community-like network in accordance with mutual guidelines and aiming at a shared purpose. For the individual, this objective may be more or less distinct depending on the organizational position. One key challenge for organizations is recruiting new employees who will fit into the organizational practice. It is this challenge of translating the organizational habitus and the myriad of social and disciplinary agencies that project managers have to deal with to create a stable community for the production of design.

Socio-materiality

In this paper, human agency and materiality should be understood in their widest senses (Carlile et al., 2013; Engeström, 1990; Knorr Cetina, 1999; Latour, 2005). Materiality is not just an expression of physically or metaphysically materialized entities, but an entanglement of social and material agency. It is what will be created by human and non-human actors in a transparent symbiosis which is interesting. As Carlile et al. write: *'What an organization learns is not the mere result of information processing or interpreting but of organizational members learning to do certain things through the use of objects, the training and use of the body, and engagement in certain practices. From a performative (or practice-based) perspective, organizational learning is a practice that is carried out in socio-material contexts, in particular ways. To know and to learn involves the material world (including the human body) as much as it involves the mind'* (Carlile et al., 2013, p. 2).

This paper's point of departure is the observation by Nicolini et al. (2012) that objects can serve different objectives in different phases of their life cycle. They also show how objects seen through different theories can serve different objectives. Boundary objects, for example, are used to transfer information in a more closed form, not necessarily involving consensus between actors and communities. In this state, they may serve a purpose depending how well the interfaces are defined. However, to start with, they will not motivate collaboration. Epistemic objects will motivate collaboration to a greater extent. Their open structure will require a dense and more mutually committed collaboration in communities (in which there is a shared understanding of the necessary knowledge) to transform objects to another level in the object's life cycle. Star (2010) reflects in a similar way that boundary objects are not intended to form consensus, but that, in a boundary infrastructure, some boundary objects will form more mutually dependent relationships than others. It is within the sum of all these boundary objects (which may be more or less committing) that collaboration may take place. Knorr Cetina (2001) describes epistemic objects as the materiality that motivates and ensures 'matters' to hold common objectives in practice. She focuses on the open structure of epistemic objects because this ensures the necessity of mutual commitment and shared engagement in epistemic culture. This paper will distinguish more loosely defined non-consensus-driven coordination supported by boundary objects and the more densely defined and mutually committed collaboration supported by epistemic objects by instantiating the coexistence of boundary objects and epistemic objects side by side.

The socio-material perspective used in this study indicates the unity created between actors, their disciplinary and social skills, and the multi-faceted technologies used to produce a shared imaginary construction. It is an important characteristic in the construction industry that this socio-material symbiosis can be recognized by practice and be transported, translated and transformed into a physical construction. This complex structure calls for communities of practice.

Communities

The concepts of ‘communities of practice’, ‘situated learning’ and ‘legitimate peripheral participation’ were formulated by Lave and Wenger (Lave & Wenger, 1991) and have since shown how much the shaping of groups means for human activities. This is valid in regards to acceptance of both professional and social skills. Through individual trajectories, communities are shaped to achieve a position in communities of practice through legitimacy. A community of practice is a dynamic state in constant change. Actors are led into practice through situated learning, where both disciplinary and social skills are conveyed through the apprenticeship principle. The notion of a community should be seen in contrast to other concepts such as a ‘network of practice’ (Brown & Duguid, 1991). A community of practice should be seen as a stronger shared commitment that builds upon mutually dependent relationships. A network of practice describes a situation where the participants have a common goal, but do not have the same interdependence. Star et al. (2003) explain that communities may consist of many subgroupings with major or minor overlapping concerns, sharing language, practices and technologies.

By acknowledging that mediation takes place in collaboration between groups, Wenger (1998) describes managers as ‘brokers’, who bridge between communities of practice in the network of practice. He also points to boundary objects as being the materiality which these brokers exchange. From the perspective of epistemic culture, however, mediation cannot occur solely through boundary objects, but requires closer relationships in the community of practice. This is why a project manager must balance between broking, where more loosely defined coordination is sufficient, and community shaping, where mutually committed collaboration is required. Another important aspect of communities is their temporary nature. Lave (2008) describes historical and conflictual impacts on the pathway which communities of practice have taken and might take. This explains why actors who have once been part of a fruitful collaboration tend to recreate a similar community – there is a negotiated agenda everyone knows and wishes to reproduce.

These notations towards practice social group formation are perceived in this paper as the glue needed to hold project teams together, based on the resources defined by the organization. As described later in this paper, the social dimension, and in particular mutual commitment, is what makes a project team a community of practice. How project managers balance organizational strategic norms/rules and create/ensure meaningful communities will be analyzed in the following after first identifying multiple perspectives on the problems faced by project managers.

Results and Analysis

The engineering company was selected based on the ability for the authors to gain in-depth access to strategic initiatives and the freedom to approach employees as required. Over the last four years, the company has introduced a range of ‘Project Excellence Life Cycle’ (PELC) activities with focus on 12 dedicated tools and guidelines, primarily based on templates in Microsoft Excel, in relation to themes such as benefit, stakeholder and risk management, complexity rating, front-loading, and decision gates. Furthermore, over the last 10 years, the company has incorporated BIM practices (centred on Tekla Structures, Progman MagiCAD, and Autodesk Revit) in most projects, at a total cost of about 1 million euros or more.

Findings from survey

To first get an overall view of the problems in managing the building design process, 149 potential project managers from the ‘Building’ unit of the company were invited to participate in a survey on their experience in executing design projects and the challenges they face. Of these, 1/3 were selected due to their involvement in large-scale projects in the company, while the remaining 2/3 were selected randomly out of around 390 employees registered in the company’s financial system as acting project managers. Since the pool included a large number of employees who were responsible for administrative projects or projects involving only 1-2 people, the survey started by asking such employees not to participate. About 10% of the employees in the ‘Building’ unit completed the survey, i.e. 77 project managers. They were believed to be representative of the project managers in that company unit.

The survey had 64 questions related to management knowledge and selected approaches, use of ICT, achieving good design quality, co-operation with external stakeholders, and finally their experience with current design and construction processes. A 5-point Likert scale was selected to capture the granularity of each opinion expressed by the participants. The scale ranged typically from either *not a challenge* to *most critical challenge* or from *highly disagree* to *highly agree*.

One problem with such surveys is the risk that participants might respond on the basis of what they think is expected of them as opposed to their actual perception. So the questions were designed to address challenges from different angles to reveal any inconsistency. Furthermore, participants were promised full anonymity and were asked for their name only at the end of the survey and in a non-obligatory manner.

It was notable from the results that project managers with only up to 3 years of management experience (n=12) responded quite differently from the others to key questions. So the responses from these 12 participants with limited experience were excluded from the results presented below to ensure a clear description of actual challenges.

Of the 65 participants, 51% had worked at a different company within the last 10 years and 75% of these believed they would have given similar or very similar responses if they had the same questions in the previous company. At least 30% of those who said they would have provided different answers also identified themselves as having worked at different types of company such as architects, clients or manufactures. For this reason, it is likely that the responses are representative of engineering companies in the construction industry in Denmark at least.

Key problems in creating good design quality

The participants were presented with ten statements on potential challenges. The statements were selected on the basis of initial discussions with selected project managers and they addressed problems which a company can solve by taking strategic initiatives. Participants were asked to evaluate the statements based on how urgent it was for the company to address the problems on a 5-point Likert scale. The responses to the ten statements are shown in Figure 1 sorted by average score.

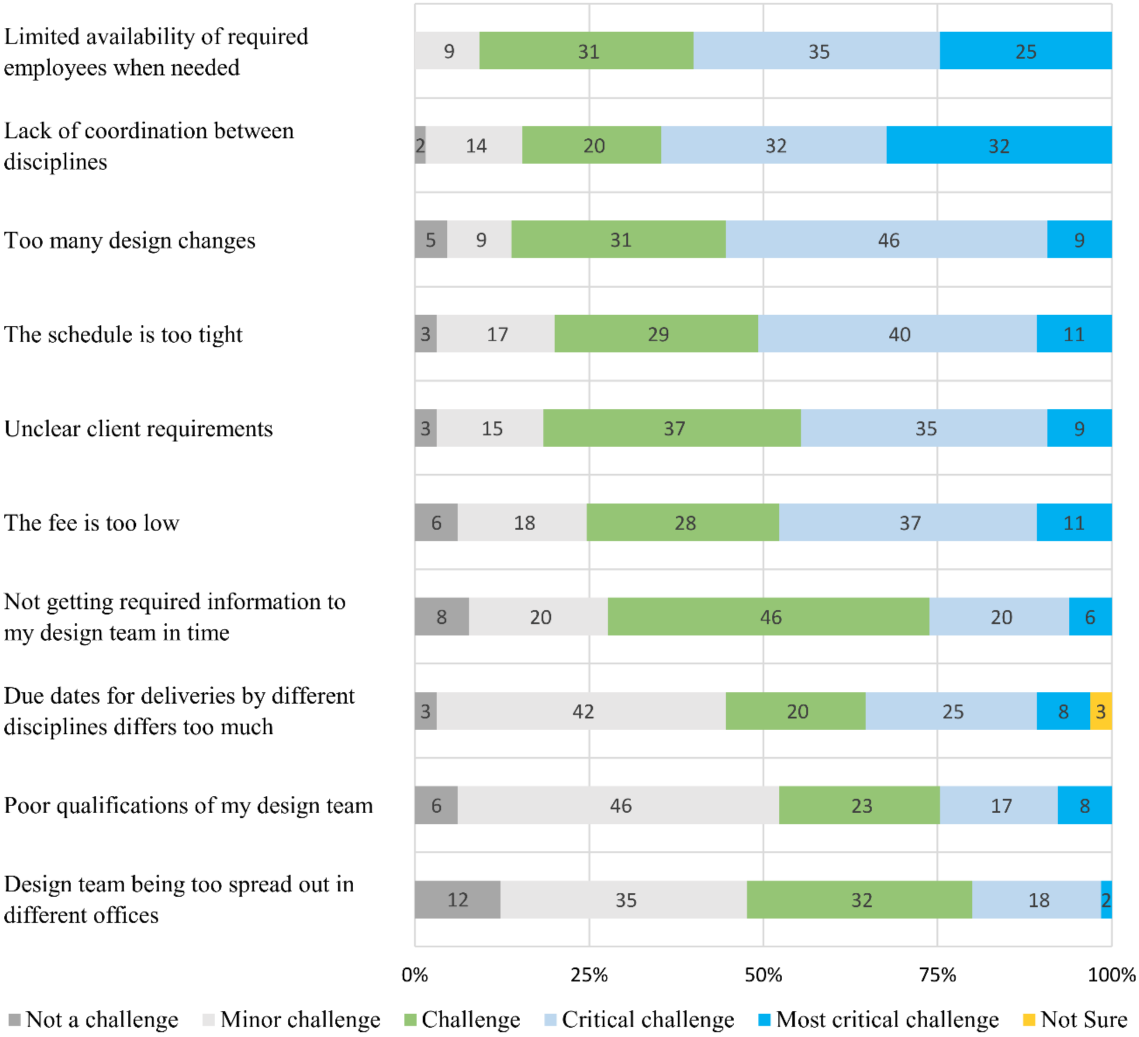


Figure 1. Responses to challenges in creating good design quality.

The three most significant challenges were related to the *availability of resources* and *coordination and changes*, closely followed by *tight schedules*, *low fees*, and *unclear* *client requirements*. Notably, *poor qualifications in teams* and *dispersed teams* were not considered as urgent to address.

Performance and Project Complexity

The participants were also asked for the financial performance of their latest project and only 14% of the participants had projects delivering a high financial return, while 34% responded that their performance was below the break-even point for the company. 75% of project managers dealing with high-complexity projects were in this last category. The profit margin of the company at around 5% is very similar to other Danish engineering companies and must be considered low for the complex technical services provided, so this indicates a considerable problem in balancing cost of especially complex design projects. More than 80% of the participants (for all complexity levels) believe they are paid sufficiently for extra work performed, as shown in Figure 2, and for this reason the problems of economic performance seems inherent in the way projects are executed.

The engineering company rates project complexity on a 20-point scale based on fee size, contract type, strategic importance, risk, and the stakeholders involved. Projects with a score of less than 10 are said to have low complexity, a score of 10-14 indicates medium complexity, and a score higher than 14 indicates high complexity. Most of the participants (60%) in the survey normally worked on projects with medium complexity, 21% normally worked on low-complexity projects, and 19% were mostly involved in high complexity projects. The responses from participants indicate very similar problems regardless of the complexity score of their typical projects with few exceptions. Project managers with high complexity projects believed they had more knowledge about management, better performing teams, and seemed more structured in their approach, but at the same time they experienced more problems at the construction site, significantly more rework due to a lack of coordination, and lower financial performance than participants with less complex projects. For this reason, there seems to be a clear relation between the level of complexity and the level of variability making current management methods even more problematic for complex projects.

Management Experience

The questions in relation to project experience illustrated in Figure 2 show quite clearly that the project managers are confident in their knowledge of how to manage projects because only 14% agree or strongly agree that they lack knowledge on how to better manage their projects and 88% also agree or strongly agree that they have a clear understanding of where projects are likely to go wrong. Yet they experience a range of problems on their projects: they postpone problems that should have been solved earlier (agreed or strongly agreed by 67%), they spend too many hours at the end of the design phase (agreed or strongly agreed by 77%), and they often underestimate the hours required for follow-up during construction (agreed or strongly agreed by 57%).

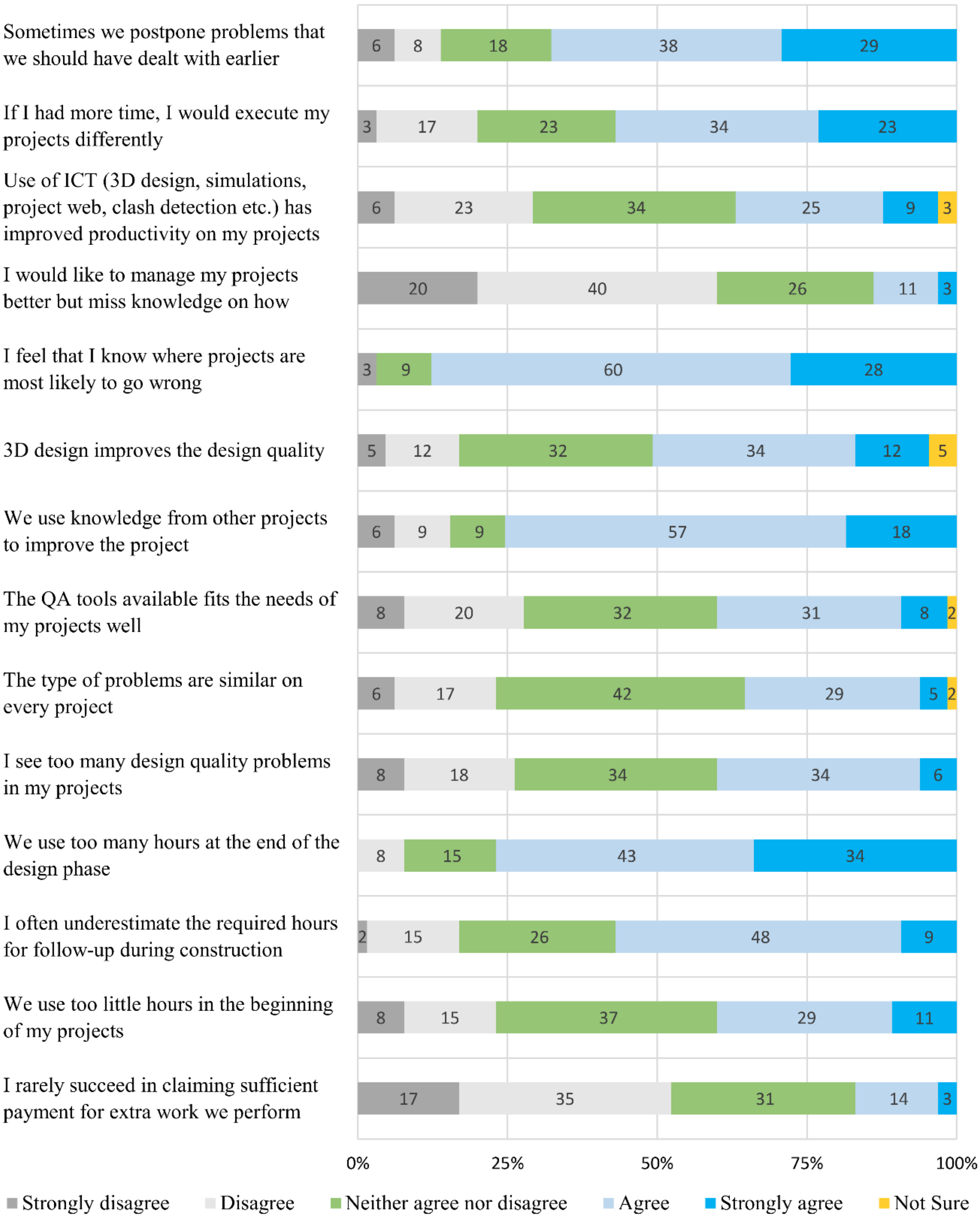


Figure 2. Selected responses in relation to project experience by participants.

There are too many design quality problems in many cases (agreed or strongly agreed by 40%) as seen in Figure 2. When asked specifically about challenges related to forecasting remaining work, as illustrated in Figure 3, last-minute changes and uncertainty about when information required will be delivered by clients or architects were critical or most critical problems for 63% and 55% respectively.

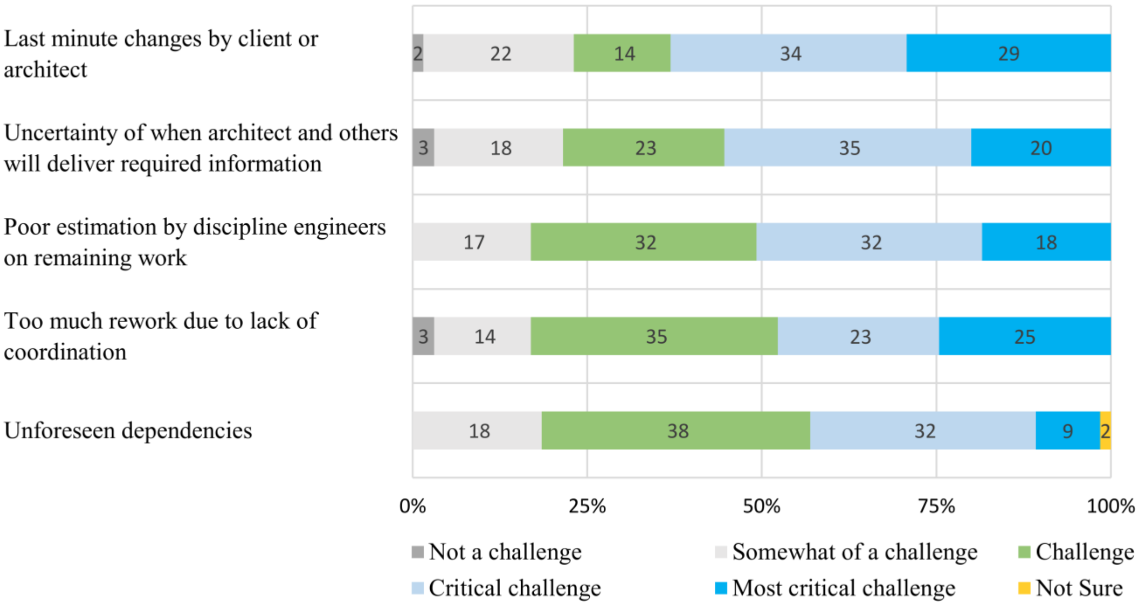


Figure 3. Responses to challenges on forecasting remaining work.

Responses expressing considerable concern about missing information, last-minute changes, limited coordination, and therefore considerable problem with design quality are in sharp contrast to the perceived understanding by project managers that they have sufficient knowledge about project management and know where their projects are most likely to go wrong. The problems seem closely related to management as opposed to the performance of individual design team members. Moreover, the results indicate significant variability in the design process when a lack of resources required, coordination, late changes, and delivery of information are seen as key problems.

Limited Value of BIM and ICT

In their projects, 76% of the participants often or constantly use BIM (referred to as 3D design in the survey), but only 46% agreed or strongly agreed that it improves the quality of design. Moreover, only 34% agreed or strongly agreed that Information and Communication Technology (ICT) in general has improved productivity on their projects. This indicates clear problems in utilizing technology that should have helped solve key problems, such as limited coordination, too many changes, and misaligned information exchange. Instead of reducing variability, there seems to be a risk that the technology implemented might instead be increasing the variability because utilization of new technology is resource intensive yet seems in the current cases often to provide only limited advantages.

Project Controls and Actions

When asked how projects are managed, participants indicate that they focus on hours spent by team members and on tracking of their deliverables. Only 23% use a look-ahead plan to discuss weekly progress. If deliverables are delayed, the most used strategy is to increase the utilization of the design team by either taking on more staff (used often or continuously by 45% of participants) or asking current team members to work longer (used often or continuously by 38% of participants). Attempts to reduce the scope or reorganize the schedule are used often or continuously by 35% and 16% of the participants, respectively. With high variability in the design process as described above, it seems like a considerable risk to use increasing resources as a key solution to tackle delays. If the design process was considered from a manufacturing point-of-view, the uncertainty of the delivery time of the design is likely to increase exponentially with very high utilization (Hopp & Spearman, 2008). As deadlines are usually fixed in construction, it seems likely that the quality of the design from proper coordination, quality assurance, etc. is very likely to be compromised in such cases.

Findings from interviews

To gain further insights from the responses from the survey, the company was asked for interview opportunities with a number of project managers. The top management of the company drew up a shortlist of project managers ‘recognized’ as being able to execute successful projects and representing different types of project in the ‘Building’ unit of the company. From this shortlist, five project managers were randomly selected to participate in semi-structured interviews. All the project managers had five years or more management experience and their typical projects had a complexity score above ‘medium’ according to the internal assessment score in the company. Two of the project managers came from the same department, the rest came from different departments in the ‘Building’ unit. They are all anonymized with common English names.

Ellinor (aged 55–60 years) has about 25 years of project management experience. She has more than 5 years of seniority in the company and more than 25 years in the construction industry. Osvald (aged 50–55) has about 10 years of project management experience. He has more than 10 years of seniority in the company and more than 25 years in the construction industry. Ellinor and Osvald usually manage projects with total costs of more than 10 million euros and also undertake large/complex projects of more than100 million euros. Both project managers are well-known to some of the largest clients of the company and acknowledged for their performance in the department.

Phillip (aged 55–60) has about 15 years of project management experience. For the last 5 years, he has managed large/complex projects with a total cost of more than 200 million euros. He has about 5 years of seniority in the company and more than 20 years in the construction industry. He is also well-known to some of the largest clients of the company. Billy (aged 45–50 years) has more than 5 years of project management experience. He manages projects in the medium segment, but is on the threshold of managing a more complex project. He has about 20 years of seniority in the company and in the construction industry. Allan (aged 35–40) has more than 5 years of project management experience and manages projects in the medium segment. He has about 10 years of seniority in the company and in the construction industry. Billy and Allan manage projects with total costs of more than 20 million euros.

General concerns in the survey responses

The responses to the survey showed a clear differentiation in how key challenges were rated. Limited availability of required employees when needed, lack of disciplinary coordination, and too many design changes were rated highest, whereas team qualifications and teams being too spread/dispersed were rated lowest.

It was these statements, in particular, that indicated that further insight was needed. Initially, the researchers had an expectation that problems would be related to translating strategic objectives into tactical instruments. The survey responses suggested that, although the company had focus on strategic objectives via the project excellence tools, project management executed projects focusing primarily on up-front operational activities and with limited focus on strategic or tactical considerations. The semi-structured interviews were therefore designed to focus on strategic, tactical and operational initiatives.

However, the interviews with the managers revealed that there could also be another agenda. The various interviews seemed to form a pattern suggesting that the human factor played a larger role than could be identified in the survey. A recurring theme in the interviews was the role that human agency played in managing design teams. The key challenges do not appear to be related directly to limited capabilities of individual design team members. Instead, there seem to be more fundamental challenges in how teams are organized and managed.

Awareness about communities

One of the recurring themes in the interviews was the problem of having a dispersed team. Phillip responded to this: *'I do not think you can make a large project together without being together. When we made [anonymized project], we gathered everyone [at the project site]. It was a prerequisite, otherwise the project would have gone wrong'* (Phillip 1:03:06). Similarly, Osvald said: *'We could not have done the project for [client] if we have had people at distant locations. The time factor plays a role, if you are insanely busy. Distance is an issue'* (Osvald 36:32). Allan elaborated: *'If I get assigned a HVAC team situated in another region, for example, then it is a decision I fight extremely hard to change. It costs a lot of money to coordinate across regions and daily contact cannot be achieved'* (Allan, 19:58). Asked if seeing people face to face makes a difference, he said: *'Human contact really means a lot to me'* (Allan 21:17). Ellinor responded to the same question: *'It means a lot! There are a lot of softer values in working together. It is simply easier to communicate with people once you have seen them'* (Ellinor 29:05). Billy put it very precisely: *'It is one of the things that are difficult for a project manager. If you have a dispersed team, you have to know those you do not have daily contact with really well. It is in the area close to you that things succeed'* (Billy 39:09).

Throughout the various interviews, the project managers each return repeatedly to the importance of the team and dense communities. Billy said: *'I spend all my energy getting the group to work. If you focus on the group, you can also see if it goes wrong'*

(Billy 35:45). Phillip said: *'You must have team spirit. You should just be able to go over and talk to them. You must know what it is they are working on'* (Phillip 1:03:06). Perhaps Oswald expressed it best: *'It is to build confidence between people in the project team. If one is drowning, then others need to step in and help'* (Oswald 33:10). The larger projects are, the more obvious it seems that the project team should preferably be co-located and integrated. In Phillip's case, he also wanted the other disciplines (such as architects and other designers) integrated, and so did Oswald and Ellinor on their large projects.

Another problem faced by project managers is schedule change, with projects being postponed for some reason or stopped. One of the strategic tools used by project managers is risk assessment. When a project manager outlines a risk assessment, this is done with an eye to the team they have. It can therefore be critical if the project cannot follow the planned start-up or process. This was described as one of the biggest problems. The battle to create a good team and a good community is sometimes made very difficult because employees cannot be out of work for long. Project managers were often at a high risk of losing the team they had painstakingly assembled for a project: *'When we have managed to establish the ideal team, then comes reality! From then on, we have to accept the team we can get. The best people for the job are rarely available all at the same time. It does not work like that!'* (Osvald 28:00). Similarly, Ellinor said: *'Our problem with resource management in the projects is that, if some project runs into trouble, then employees are taken from your project and put on the other project'*. This was followed up by her concern that, when an employee leaves a project for one reason or another, the project manager has to deal with the problem that important knowledge in the project may also disappear: *'When you have to replace someone, which can happen to anyone, then you have to be very careful how you do it, so as to ensure that the knowledge stays in the project when the person goes out the door'* (Ellinor, 7:56). Billy put it this way: *'From my allocation of resources, I can see whether the project is going well or badly. I have experienced that when changes happen along the way, then it [projects] end up performing more poorly'* (Billy, 47:26). Overall, this showed the importance of the project team and the close daily dialogue. When for some reason projects lose team members, this can harm the community and its accumulated knowledge. This was a cardinal issue for project managers in their assessment of the challenge of variability.

Awareness about digital technologies

Another recurring theme was problems connected with how digital technologies interact with actors and communities. In general, technologies are not in focus for the project managers, as long as they are invisible materiality that works and supports the production of data and information for the building design. Their concerns arise when technologies become visible materiality and require changed working methods or generate data and information in a new way. For example, they described challenges with the paradigm shift the company had gone through over the last decade in the form of 3D technology. As Billy put it: *'What I have experienced is that the [newcomers]* *would rather model in 3D and then do a 2D output of this, because they feel more secure using this working method. This is where there has come a gap between the old engineers and the new'* (Billy 20:34). He also thinks the newcomers are, at times, a little too eager to use the new 3D technologies: *'That's certainly what we learned, that it's really hard to manage people, and the time spent on 3D design—it expands itself!'* (Billy 20:20). It is important to clarify that Billy belongs to the generation that has worked extensively with 3D technologies in the company, and perhaps that is why he was able to say: '*There is nothing wrong with the technology in itself. It is just a question of how to get it going in the right way'* (Billy 22:00). Allan, who belongs to a generation that has had 3D technologies at close quarters through his education and early years in the company, put it slightly differently: *'I do not think 3D is the way that you get better projects. I just think with the right 3D competences, we can catch a whole lot more. The problem arises if there are people who we do not have under control'* (Allan 33:23). The other 'senior' project managers have a more distant relationship with technologies in general, since none of them have first-hand experience with 3D modeling, or for that matter, any other relatively new digital technologies in the engineering world. As Ellinor said: *'If we agree on the need to do a 3D model, then of course we do this. Because it's one of my talented colleagues who has suggested how we do it, I have complete confidence in this'* (Ellinor 24:27). Or as Phillip said: *'I go deep into the risks that may be when we start [using a program]. I spend a lot of time going in depth and get a strong gut feeling about whether it is implemented properly'* (Phillip 12:59). The fact that a project manager has no personal experience with 3D modeling causes some reluctance. The one who perhaps most clearly expressed this concern was Oswald: *'I have provocatively written in [internal pamphlet]. My next project will be made in 2D and no one must send mails. I know it's not going to happen, but it was my way to describe my world'*, and he completed his monologue with: *'It is the focus on technology that removes the focus from professional competency'* (Oswald 13:41). The gap between newcomers and old-timers on technology was also clear when Ellinor said: *'Some of what might be the challenge of [3D] technology is that you can make a lot of mistakes if you do not know what you're doing and it looks very complete'* (Ellinor 39:31).

The project managers' concerns are therefore divided. They know that new generations of engineers have been primarily trained in the use of 3D technologies, and project teams will include at least some relatively recently trained people, so this is a challenge project managers needs to relate to. As Elinor expresses it: *'When you want to use [digital technologies] as 'governing' tools, you must ensure that you cut down to the essence [and conduct] some sort of critical assessment of what will give value to the project'* (Ellinor 36:29). The project managers' aware attitude about technology supports the need to shape an epistemic culture with mutual commitment strong enough to absorb various technologies. If the project team does not appear strong and viable, with a suitable balance between newcomers, old-timers, disciplinary and social skills, project managers run the risk that the use of technology will increase variability.

Awareness about strategic tools

A third recurring theme was the problem of integrating strategic tools in project management. An extensive toolbox of strategic methods and systems has been developed to control and manage projects better. All project managers must apply and follow up on these methods and guidelines throughout the life of each project to comply with company standards. The strategic initiatives in the company, however, do not seem to support the needs of the project managers. These initiatives need a certain ‘plasticity’ if they are not to end up in a parallel world: *‘I really want to [use them] if I can see it makes sense. But not for the sake of the system or software – [only] if I can see that it provides a benefit for my project’* (Oswald 13:41), or as Ellinor put it: *‘Some of it tends to be a little controlling due to having too much focus on the bottom line’* (Ellinor 3:23). Later she added: *‘I follow those tools of course. But I will say, I also follow my own common sense and I speak with my very closely trusted employees’* (Ellinor 15:38). In general, there seems to be limited understanding for why the project managers need to spend so much time on these tools: *‘That whole toolbox is just growing and growing until we now have 12 tools, or something like that. In my world, it has become more cumbersome to start up a project. It’s hard to scale down that toolbox from large projects to small projects’* (Billy 4:52). Phillip expressed it as a concern about the workload and whether the outcome is commensurate with the effort: *‘We have a large number of tools that are running, and suddenly you have to spend your time as project manager keeping yourself updated on the many tools because the focus for the company will be on auditing whether one is using the latest version’* (Phillip 27:58). He added: *‘I disagree strongly with those things because they generate no value. Instead it should be a question of whether the people you hire are proficient enough’* (Phillip 27:19).

It all seems most accurately summed up in Oswald’s words: *‘No matter how many BIM models and systems we add, it is people who make it and we are not infallible, it [infallibility] does not exist’* (Oswald 46:18). The project managers’ statements argue that viability depends greatly on how well the project team has been shaped. There is very limited attention on community building in the strategic tools provided, which seems to be a clear barrier to the acceptance of tools intended to help the project managers. The less successful a project manager is in utilizing the ideal project team, the more problems will occur in the project at a later stage. This is probably why the limited availability of desired resources was rated among the greatest challenges in the survey because this is the key to developing a strong community. The solution to most other problems is found to rely on the ability of this community to collaborate and in this way reduce variability.

Discussion

There seems to be a key contradiction in the focus of the strategic initiatives developed by the company and the focus of project managers. The company focuses on explicit strategic initiatives, which are intended to limit variability from external sources and give limited attention to the social dynamic in project teams. The strategic initiatives focus on the scope, planning and process-related risks in the design work, and of course on the physical construction—all elements that directly affect the financial performance of the company.

The project managers, however, seem to conclude that the social context has even greater effect on the financial performance than these so-called external factors. They clearly acknowledge that the more team members are committed in helping and supporting each other, the stronger and more solid they are able to build their community. A project that is too network-oriented generates too much variability and too little commitment. Such a weak community will produce too many 'boundary objects' whereas the project interfaces require more consensus-driven and well-defined 'epistemic objects'. Project managers therefore try to ensure a comprehensive community of practice that contains a well-defined epistemic culture that can create exactly the required 'boundary infrastructure' consisting of discipline 'epistemic objects' and 'boundary objects' which can ensure a certain plasticity that allows various solution spaces and can achieve the necessary coherence.

It should be acknowledged that concerns about resource utilization based on historical and conflictual experience in shaping the future for human actor trajectories are vital for project managers. An awareness of organizing a team with both social and technical competence seems such a considerable factor for a successful project, that this focus should be addressed more specifically in strategic initiatives. At the same time, it is of great importance to acknowledge that organizations must ensure the inclusion and training of new employees in the company to ensure the continuous development and evolution of communities. In other words, communities are built on past experience but must allow for expansion to ensure the sustainable development of the company.

This focus on shaping communities also seems to be a key way to improve the implementation of ICT initiatives. The problem of limited productivity achievements indicates that BIM and other ICT initiatives are not in themselves able to shape communities. ICT initiatives are only likely to improve efficiency in communities that are already strong. That is why it seems vital that companies acknowledge that it is within strong communities that new technology can be implemented successfully.

The same seems to apply for most other strategic initiatives, such as the introduction of lean principles. If implementation is not integrated within the community, it is likely that it will exist in a parallel world and achieve far less success. The project managers describe this in the way they make use of the strategic tools provided by the company. They use their common sense and select only tools that they believe provide direct value, i.e. the tool must make sense for their community. In those cases where they feel obliged to include more tools, they see this as something 'extra', which lives parallel to the project, neither disciplining nor providing direct value. The company seems convinced that the explicit strategic initiatives are successful because they release more and more tools, but the project managers seem to have another perception. Where such strategic tools live, it would seem to be difficult for the company to understand what is happening.

Conclusion

It is understandable that senior management tends to look outwards and focus on the explicit framework or boundary conditions for projects which can clearly impact projects if not properly defined. Social relations seem, however, to be of greater concern for project managers in achieving project success because they clearly believe that a strong community and epistemic culture are the best ways to limit project variability. This paper has focused on such social relations and tried to assess the importance of community building. This is what project managers express in terms of as team spirit and collaborative design. Collaborative refers in this context to a spatially closer connection to ensure strong and committed communities. Conclusions about who to involve in such a community should depend on the relationship required between the project's participants. The community should not necessarily be limited by company borders because close collaboration with other stakeholders might be the key to project success. Although it is difficult to acknowledge conflictuality and history as having a significant impact on community building—perhaps more significant than most explicit factors—companies should put an effort in acknowledging the socio-material structures when allocating resources to a project.

Continuously introducing newcomers to company practices is also important so that the company can achieve a learning environment that will ensure stability in future projects. Companies should therefore focus on supporting project managers in getting 'stable' teams with the necessary mix of old-timers and newcomers that the project manager believe can make the project perform successfully. Moreover, a company must have an eye for the technological requirements of the projects. If a project does not consist of actors who have the necessary community skills, the implementation of new technology is not likely to be successful.

This paper is intended as a contribution to understanding the social dimension of project management in building design. At the same time, it is critical of organizational strategic decisions not rooted in the practices taking place within the company. Furthermore, the study contributes to solving the problem of the weak utilization of technology to support knowledge management and limit project variability.

References

Arditi, D., & Gunaydin, H. M. (1998). Factors That Affect Process Quality in the Life Cycle of Building Projects. *Journal of Construction Engineering and Management, 124*(3), 194–203. http://doi.org/10.1061/(ASCE)0733-9364(1998)124:3(194)

Brown, J. S., & Duguid, P. (1991). Organizational Learning and Communities-of-Practice: Toward a Unified View of Working, Learning, and Innovation. *Organization Science, 2*(1), 40–57. http://doi.org/10.1287/orsc.2.1.40

Carlile, P. R., Nicolini, D., Langley, A., & Tsoukas, H. (2013). How Matter Matters: Objects, Artifacts, and Materiality in Organization Studies. In *How Matter Matters* (pp. 1–15). Oxford ; New York: Oxford University Press. http://doi.org/10.1093/acprof:oso/9780199671533.003.0001

De Vaus, D. A. (2002). *Surveys in social research* (5th ed.). St. Leonards, N.S.W.,

Australia: Allen & Unwin.
El. Reifi, M. H., & Emmitt, S. (2013). Perceptions of lean design management. *Architectural Engineering and Design Management*, *9*(3), 195–208. http://doi.org/10.1080/17452007.2013.802979
Engeström, Y. (1990). When Is A Tool? Multiple Meanings Of Artifacts In Human Activity. In *Learning, working and imagining: Twelve studies in activity theory* (pp. 171–195). Orienta-Konsultit Oy.
Gherardi, S. (2012). *How to Conduct a Practice-based Study*. Edward Elgar Publishing. http://doi.org/10.4337/9780857933386
Hopp, W. J., & Spearman, M. L. (2008). *Factory Physics* (3rd Ed.). New York, US: McGraw-Hill Education.
Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research*, *1*(2), 112–133. http://doi.org/10.1177/1558689806298224
Kamara, J. M., Anumba, C. J., & Cutting-Decelle, A.-F. (2007). Introduction to Concurrent Engineering in construction. In J. M. Kamara, C. J. Anumba, & A.-F. Cutting-Decelle (Eds.), *Concurrent Engineering in Construction Projects* (pp. 1–11). London, UK: Taylor & Francis.
Kemmis, S., Wilkinson, J., Edwards-Groves, C., Hardy, I., Grootenboer, P., & Bristol, L. (2014). *Changing Practices, Changing Education*. Singapore: Springer Singapore. http://doi.org/10.1007/978-981-4560-47-4
Knorr Cetina, K. (1999). *Epistemic Cultures: How The Sciences Make Knowledge*. Cambridge, Massachusetts: Harvard University Press.
Knorr Cetina, K. (2001). Objectual practice. In T. R. Schatzki, K. Knorr Cetina, & E. von Savigny (Eds.), *The Practice Turn in Contemporary Theory* (pp. 184–197).
Koch, C., & Friis, O. (2015). Operations strategy development in project based production – a political process perspective. *Journal of Manufacturing Technology Management*, *26*(4), 501–514. http://doi.org/10.1108/JMTM-03-2013-0017
Koskela, L. (2000). *An Exploration towards a Production Theory and its Application to Construction*. *Construction*. Helsinki University of Technology. Retrieved from www.vtt.fi/inf/pdf/publications/2000/P408.pdf
Koskela, L., & Kazi, A. S. (2003). Information Technology in Construction: How to Realise the Benefits? In S. Clarke, E. Coakes, M. G. Hunter, & A. Wenn (Eds.), *Human Cognition Elements of Information Systems* (pp. 60–75). Information Science Publishing.
Kraemer, K., Henrich, G., Koskela, L., & Kagioglou, M. (2007). How construction flows have been understood in lean construction. In *Proceedings of 4th International Research Symposium (SCRI)* (pp. 121–132).
Kvale, S., & Brinkmann, S. (2015). *InterViews: learning the craft of qualitative research interviewing* (3. edition). Thousand Oaks, California: SAGE Publications Inc.
Latour, B. (2005). *Reassembling the Social: An Introduction to Actor-Network-Theory*. New York: Oxford University Press.
Lave, J. (2008). Epilogue: Situated Learning and Changing Practice. In A. Amin & J. Roberts (Eds.), *Community, Economic Creativity, and Organization* (pp. 283–296). Oxford University Press.
Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge: Cambridge University Press.
Leigh Star, S. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. *Science, Technology & Human Values*, *35*(5), 601–617.

http://doi.org/10.1177/0162243910377624
Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction*, *43*, 84–91. http://doi.org/10.1016/j.autcon.2014.03.009
Nicolini, D. (2012). *Practice Theory, Work and Organization. An Introduction*. Oxford, UK: Oxford University Press.
Nicolini, D., Mengis, J., & Swan, J. (2012). Understanding the Role of Objects in Cross-Disciplinary Collaboration. *Organization Science*, *23*(3), 612–629. http://doi.org/10.1287/orsc.1110.0664
Pikas, E., Koskela, L., Thalfeldt, M., Dave, B., & Kurnitski, J. (2015). Complexity in Designing Energy Efficient Buildings: Towards Understanding Decision Networks. In *Proc., 23rd Annual Conference of the International Group for Lean Construction* (pp. 213–222).
Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*, *136*(9), 968–980. http://doi.org/10.1061/(ASCE)CO.1943-7862.0000203
Schatzki, T. R., Knorr Cetina, K., & Savigny, E. von. (2000). *The Practice Turn in Contemporary Theory*. Routledge. http://doi.org/10.4324/9780203977453
Star, S. L., Bowker, G. C., & Neumann, L. J. (2003). Transparency beyond the Individual Level of Scale: Convergence between Information Artifacts and Communities of Practice. In *Digital library use: social practice in design and evaluation* (pp. 241–269). Cambridge, Massachusetts: MIT Press.
Tilley, P. a. (2005). Lean Design Management–A New Paradigm for Managing the Design and Documentation Process to Improve Quality. *Proceeding IGLC-13*, (July), 23–35.
Wenger, E. (1998). *Communities of Practice: Learning, Meaning, and Identity*. New York, US: Cambridge University Press.
Yalcinkaya, M., & Singh, V. (2016). A Visual Transactive Memory System Approach Towards Project Information Management. In *CIB W78 Conference 2016*.
Yassine, A., & Braha, D. (2003). Complex Concurrent Engineering and the Design Structure Matrix Method. *Concurrent Engineering*, *11*(3), 165–176. http://doi.org/10.1177/106329303034503
Yassine, A., Falkenburg, D., & Chelst, K. (1999). Engineering design management: An information structure approach. *International Journal of Production Research*, *37*(13), 2957–2975. http://doi.org/10.1080/002075499190374

Paper E - Agile Approach to Building Design Management

Agile Approach to Building Design Management

Niels Treldal[1], Jan Karlshøj[2]
[1]Ph.D. Candidate, Department of Civil Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby and Chief Specialist, Pharma Department, Ramboll Denmark A/S, DK-2300 Copenhagen S. E-mail: nitr@byg.dtu.dk
[2]Head of Section and Ph.D., Department of Civil Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby. E-mail: jak@byg.dtu.dk

Abstract
Interdisciplinary collaboration is much needed in the building design process, but the construction industry is still finding it difficult to adopt appropriate methods to achieve this. This paper proposes a theoretical framework for an Agile Project Management (APM) methodology as an alternative or supplement to other design approaches. The APM approach is based on agile Scrum methodology originating from information system development. Physical construction requires adherence to fixed deadlines, so the proposed APM methodology is also inspired by parts of the Last Planner System™. An evaluation from testing the methodology in three recently completed case studies is described. It concludes that the APM approach can result in better coordination and improved management of changes, but that the organization, structuring and facilitation of the design process are vital to its success. If these aspects are not well addressed, this can result in non-value-adding design iterations. Design teams noted that some agile principles were already in use in the current design process and it was concluded that the APM methodology adds needed structure to this current practice.

Keywords
Agile Project Management, Scrum, Building Design, Community of Practice, Last Planner System™

Introduction
In building design, interdisciplinary collaboration is needed to make the processes efficient and the product (the building) of good quality (Emmitt and Ruikar 2013). The research community is still discussing how such collaboration should be implemented and managed in building design processes, and numerous approaches have been proposed. Integrated Concurrent Engineering (Chachere et al. 2009), Lean Design Management (Tilley 2005), Collaborative Design Management (Fundli and Drevland 2014), and Integrative Design (Reed 2009) all attempt to frame the design process to support efficient collaboration. However, there seems limited consensus on what such approaches imply for the design process, and there is a limited theoretical framework for how they add value (Emmitt and Ruikar 2013; Jørgensen and Emmitt 2009; Koskela 2007). Koskela (2000) argues that it is a needed theoretical shift to principles of concurrent engineering (Anumba et al. 2007) which is emerging in design management, similar to what the construction industry experienced with the implementation of the lean philosophies most often called Lean Construction.

El Reifi and Emmitt (2013) finds that the adoption of such approaches in building design is still limited and conclude that lean-inspired approaches are most commonly used to focus on eliminating waste. The building design process is fundamentally different from construction and manufacturing, and this seems to hinder successful implementation of lean approaches in design. Bølviken et al. (2010) conclude that most basic lean strategies are only applicable to parts of the design process. It is the iterative and therefore changing nature of design which differentiates design from construction and manufacturing (Ballard 2000a), and waste in design is therefore more difficult to identify because some trial-and-error must be allowed.

This paper presents an evaluation of an approach using Agile Project Management (APM) principles as a contribution to understanding how the required theoretical and practical shift in design can be implemented, giving broader support for the needs of the design process. Based on lean philosophy, APM developed on the principle that changes are inevitable in the design process and that detailed up-front planning should therefore be limited (Cobb 2011). To the knowledge of the authors, there has been very little research on the application of agile approaches in building design and the general theoretical framework for the use of APM also seems limited. That is why a theoretical framework for the use and effect of APM is set out in this paper and the results from three case studies are discussed. The study was structured using a design science research approach, first identifying current needs in building design, and then constructing and evaluating a solution.

Building Design Management

For planning purposes, the building design process is often divided into a series of stages or phases corresponding to the traditional 'waterfall' planning method (Cobb 2011). Well-known examples are the seven stages of the UK RIBA *Plan of Work* (Ostime 2013) and the eleven principal stages identified in ISO 22263 (ISO 2008), four to six of which are related to design. Both solutions describe a step-wise design development approach, starting with briefing and conceptual design and ending with a fully detailed and technical design. The sequencing include similarities with *systems engineering* principles, but the systems engineering approach more specifically addresses the need to distinguish requirements development from design development (INCOSE 2015). In systems engineering, the design process has three steps: 1) *Requirements Analysis*, where the mission and design problem are identified and converted into functional requirements, 2) *Functional Analysis*, where functional requirements are decomposed and where interfaces are identified, and 3) *Synthesis*, where design solutions are developed based on the functional requirements and validated (Lightsey 2001). It has long been argued, however, that the concept of freezing the requirements at an early stage of design does not match the factors that drive requirement development to achieve client satisfaction (Othman et al. 2004). That is why Othman et al. propose a more dynamic approach to brief development in building design, one essentially very similar to agile approaches. Recent developments in systems engineering approaches acknowledge such problems and argue that, when balancing between waterfall and agile approaches, the expenses for modularity of the design should be weighed against the probable costs for requirements evolution (INCOSE 2015 p. 208).

The wicked nature of design

Building design can be considered a complex system in relation to product, process, and organization (Pikas et al. 2015). The complexity is due to the 'wicked' nature of the design process: there is often no optimal solution to the problems faced, and preconditions are defined in parallel with solutions (Bertelsen 2003; Lawson 2005). Bertelsen and Emmitt (2005) conclude that the client should also be seen as a complex system and argue that irrational behavior from such complex systems is to be expected. As a result, constant changes to requirements and planning are inevitable. Complexity in projects can significantly influence project performance (Sohi et al. 2016) and conventional planning principles based on the waterfall approach seem more and more limited in such complex and turbulent environments (Riedel et al. 2013). In response to these wicked and complex challenges, the idea of *design thinking* (Johansson-Sköldberg et al. 2013) has gained increasing attention as a way to understand and propose solutions by approaching the design process with a learning perspective. Seeing design thinking as a way of reasoning in a reflexive practice, Lawson (2005) argues that the design process should include three steps repeated in an iterative development process: 1) analysis, 2) synthesis, and 3) evaluation. The analysis and synthesis steps are similar to principles from systems engineering, but where systems engineering focuses primarily on verifying that solutions meet requirements, Lawson adds an evaluation step and concludes that the process should evolve in an iterative manner. The added step of continuous evaluation is seen as a learning step. Here, findings from the synthesis must be used to adjust the requirements from the analysis step, if they prove to be in contradistinction to achieving a solution to the design problem at hand. This concept is in line with the iterative problem-solving approach of Plan-Do-Check-Act described by Deming (1982). This idea of continuous improvement is what ultimately led to the development of lean principles (Liker 2004) and it is also a fundamental part of agile principles (Owen and Koskela 2006).

Bringing the various focus areas of the design development process together, Figure 1 shows the fundamental steps of the design process from both a systems and a continuous improvement perspective. As will be described later in this paper, agile approaches include both perspectives in a similar manner, and the map below is therefore a useful illustration of each incremental step in APM.

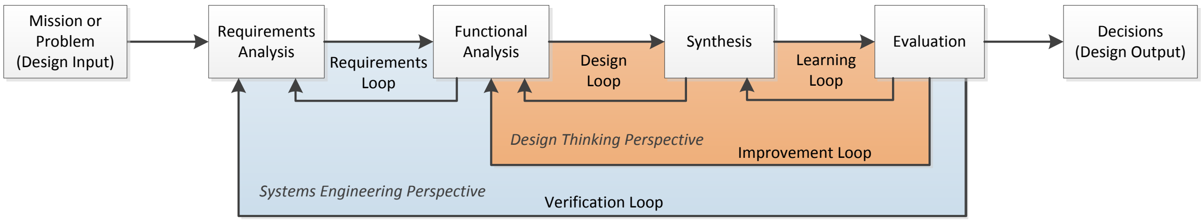


Figure 1. Map of the design process from both a systems and a continuous improvement perspective – based on (Lightsey 2001) & (Lawson 2005).

Planning in design

The Last Planner System™ (LPS) is a method used in construction to manage what Koskela (2007) describes as the three fundamental steps also required in concurrent engineering: 1) transforming the requirements to design, 2) ensuring an efficient flow of information throughout the process, and 3) maximizing value generation for the client while transforming. The key elements of LBS are scheduling assignments from a *Master Schedule* or a higher hierarchy into a *Look-Ahead Plan* or a lower level hierarchy in a visual and collaborative manner (Ballard 2000b). Each assignment is assessed on the basis of when it *should* be done, when it *can* be done, and when it *will* be done, and plans are adjusted on a weekly basis accordingly. Some initial attempts to use the principles of LBS in design have found that the concept has potential to improve the planning of the design phase (Hamzeh et al. 2009; Rosas 2013). However, Bølviken et al. (2010) argue that LPS is mostly useful if assignments are executed sequentially, and since much of the design process involves interdependent assignments (Knotten et al. 2015), there seems to be a misalignment between the LPS method and the planning needs of most design phases. In contrast, agile was developed as a response to such changing environments (Owen and Koskela 2006). Yet, it is essential to note that agile methods originate in software development where the end product is a virtual artifact. In building design, the end product is a physical artifact. Whereas software can be modified in further iterations and is often released with limited implications, it is paramount that the results from a building design process are correct before the information is used for construction because poor design quality is seen as a main cause of construction process inefficiency (Tilley et al. 2002). So there is a need to balance sufficient planning to meet critical milestones and a design process with an evolving scope. The range of planning possibilities can be categorized on a scale from a traditional plan-driven waterfall approach, through incremental and iterative approaches, and up to fully adaptive and agile approaches (Cobb 2011), as illustrated in Figure 2.

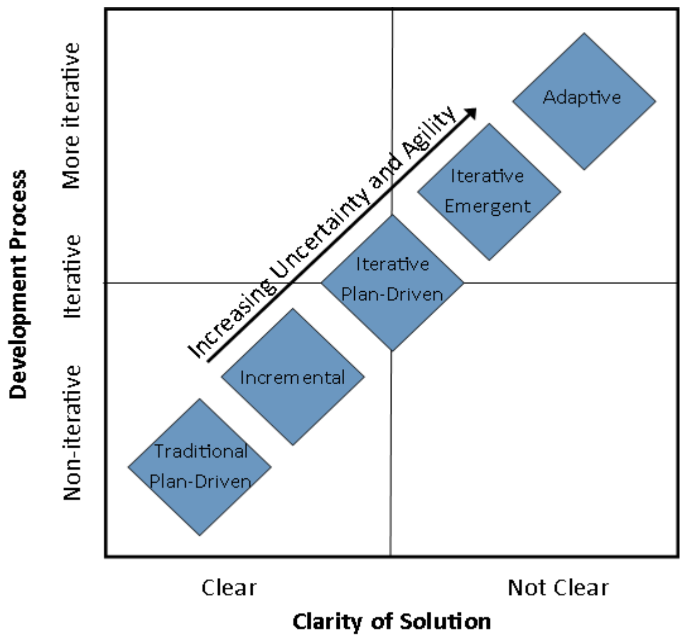


Figure 2. Planning approaches based on level of clarity and iterative development (Cobb 2011)

Boehm and Turner (2009) add design team competence, project criticality, dynamism of requirement development, team size, and team ability to manage chaos vs. order as other key criteria when balancing between plan-driven and agile approaches. The LPS method could be described as what Cobb calls an iterative plan-driven approach because the overall plan is fixed in a master schedule but findings from each iteration cycle will be used to improve the planning of upcoming iterations. The need in design seem in most cases to be towards a more adaptive and agile approach – depending on the nature of the project, as argued by Boehm and Turner.

Agile Project Management

Since the release of the Agile Manifesto (Beck et al. 2001), a number of iterative and incremental information system development methodologies have been associated with agile principles. Agile methods can be summed up by their ability to be *iterative* by continuously releasing results for evaluation, *incremental* by decomposing systems into distinct functionalities which can expand over time, *emergent* by innovating throughout the design process, and capable of empowering *self-organized* teams (Riedel et al. 2013). In recent years, agile principles have expanded outside the software industry in the form of Agile Project Management (APM). APM has been found to reduce the costs of having to repeat work due to misunderstood or changing client requirements, and in doing so, has improved project efficiency, stakeholder satisfaction, and the overall perception of project performance in a number of different industries (Pinto 2016; Serrador and Pinto 2015). By embracing change, APM is seen as an opportunity for improved, early and sustained value delivery, but it requires organizations to be more proactive than lean organizations (Owen et al. 2006). It should be noted that although APM is intended to limit up-front planning, it is found that substantial planning is done during execution, and agile projects therefore appear to do more planning overall than traditional projects (Serrador and Pinto 2015). The key differences with other planning and management approaches therefore are the combination of functionality-centric prioritization, continuous planning, and continuous learning.

Scrum as Agile Framework

One of the most widely used agile methods is called *Scrum* (Sohi et al. 2016). Other methods exist such as Extreme programming (XP), *Feature-driven development (FDD)*, *Dynamic Systems Development Method (DSDM)* and several more (Cobb 2011), but most are closely connected to the software development process, which makes them less applicable in other industries. Scrum can be considered a more generic framework for planning with a set of predefined steps and roles. Scrum originates in work by Takeuchi and Nonaka (1986), who promote a holistic method for new product development (Pinto 2016). The method has its name from the restarting of a rugby game following a minor infraction, which emphasizes its focus on team performance and an incremental development approach. The goal of each incremental step is to gradually create value by developing sub-features or elements in the overall project. These steps are called *sprints*, and are intended to last for short time periods of one to four weeks to ensure fast feedback on solutions. Numerous approaches to Scrum are described in the literature, but the research presented here includes the following elements:

Story Development

The fundamental basis of the Scrum method is a functional decomposition of the client's mission and needs into *user stories*, which in plain wording describe a desired functionality which *should* be available from the final design artifact. Stories can be grouped into *epics*, which represent a greater or overall functionality which is too extensive to design within one sprint. Once stories are verified, *features* can be defined which are needed in the end product to support the stories. Features can also be referred to as functional requirements, and can be further decomposed into tasks for individual design team members to solve. The development of stories and epics can be seen as parallel to the *requirements analysis* in Figure 1, and defining features can be seen as parallel to the *functional analysis* in the same figure.

Backlog Prioritization

Once defined, stories are listed in the project *backlog* along with their required features and tasks. Stories, features and tasks can collectively be described as assignments as they are all assigned to a specific design team member who is responsible for their completion. The backlog essentially contains all known work that needs to be completed. In collaboration with other stakeholders, the design team prioritizes assignments in the backlog so that the most important assignments which *can* be solved are placed at the top of the list, as illustrated in Figure 3. Continuous prioritization is desirable, but usually dedicated planning sessions are used to engage the entire team in also discussing dependencies and uncertainties, as well as generating better understanding of each other's tasks and problems.

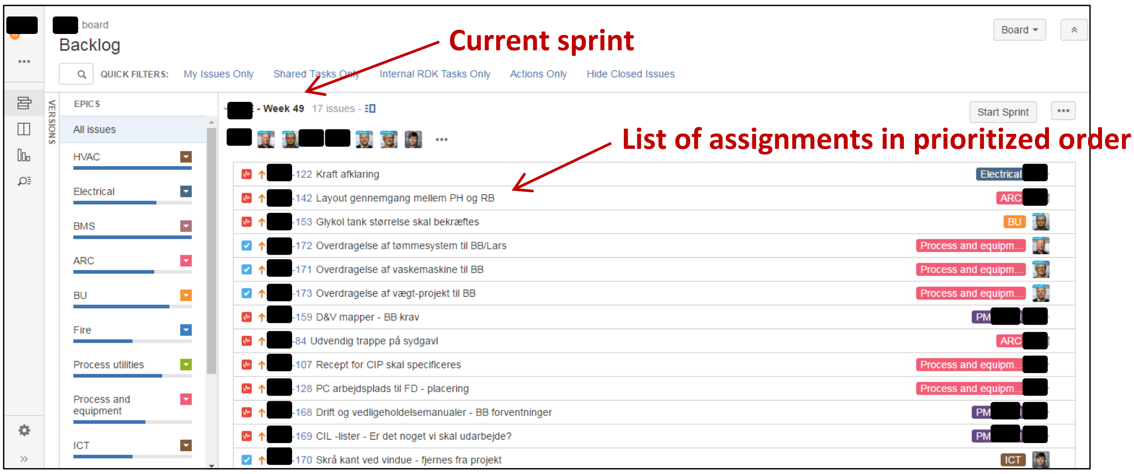


Figure 3. Example of the online backlog from case study B in which assignments are organized in sprints and are dragged either up or down to indicate priority (the assignments are in Danish and anonymized for confidentiality).

Sprint Planning

In the backlog, sprints are defined in relation to key milestones in the project, and assignments are then allocated to the sprints on the basis of the resources available within the design team. The essential point is that the team only commits to the number of assignments in each sprint that they believe *will* be solved. Once each sprint starts, a Kanban board with columns such as *To Do*, *In Progress* and *Done* is used to monitor the progress of assignments as illustrated in Figure 4.

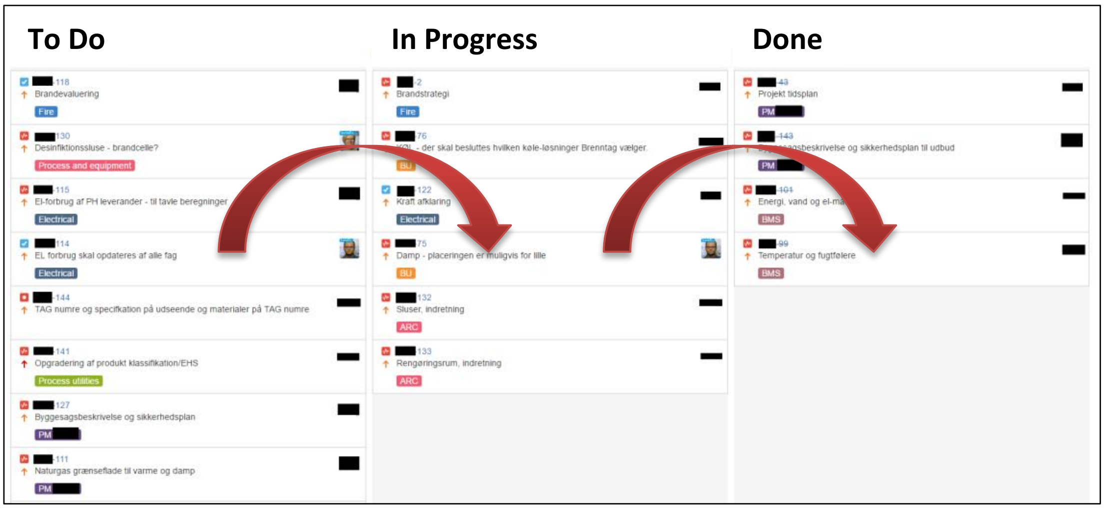


Figure 4. Example of the online Kanban board from case study B used to monitor the progress of assignments within an active sprint – including indication of transition steps (the assignments are in Danish and anonymized for confidentiality).

Stand-up Meetings

On a regular basis during each sprint, the design team should meet for a short 10-15 minutes stand-up meeting to update each other on the progress of assignments and any potential obstacles which need to be handled. The intention is to ensure that all team members have the prerequisites needed for their assignments and are on track in completing work. It is during each sprint that assignments are solved which incrementally synthesize functional requirements into design as also shown by the synthesis step in Figure 1.

Sprint Review and Retrospective

Following each sprint, a review meeting of the design team and other key stakeholders is held, in which the new additions to the design artifact are evaluated and verified against functional requirements. If adjustments are needed, the functional requirements are modified and new tasks are assigned. Furthermore, the completed sprint process is analyzed retrospectively to evaluate the performance. On the basis of the learning from the evaluation of both the performance and the design artifact, the assignments and priorities in the backlog are adjusted accordingly. This review and retrospective step can be seen as corresponding to the *evaluation* step in Figure 1, essentially making this map of the design process a direct representation of the fundamental steps in a Scrum approach to APM.

Meeting Project Milestones

Although Scrum and APM in general are found to improve projects in several aspects, Pinto (2016) points out a number of problems in the APM approach. These include: 1) the need for the intensive involvement of all stakeholders throughout the design process because feedback and prioritization must be done continuously; 2) scope creep and a never-ending series of changes requested by the users due to the limited upfront requirements defined; and 3) more difficulties in preparing business plans because it is difficult to predict at the beginning what the final design artifact will look like. The ability to commit to an overall time schedule and ensure design work to be finalized at specific milestones seems challenging in such pure agile approaches. As previously discussed, meeting specific milestones is a prerequisite in construction, which is why a methodology is proposed here which uses a combination of LPS and Scrum. The methodology is what Cobb (2011) describes as 'iterative emergent', as illustrated in Figure 2. In an iterative emergent process, high-level requirements, a master schedule, and an overall design framework are defined prior to starting design iterations. Learning from within the design process is used to adjust functional requirements, but within the framework set by the initial high-level agreements. This is to ensure that key milestones are met. In Figure 5, the steps from Scrum are aligned with this approach and compared to the steps of the traditional lean-based Last Planner System. As the figure indicates, LPS and the Scrum-based APM methodology share many similarities, but the process is considerably more iterative because functional requirements even at the *should do* level are adjustable.

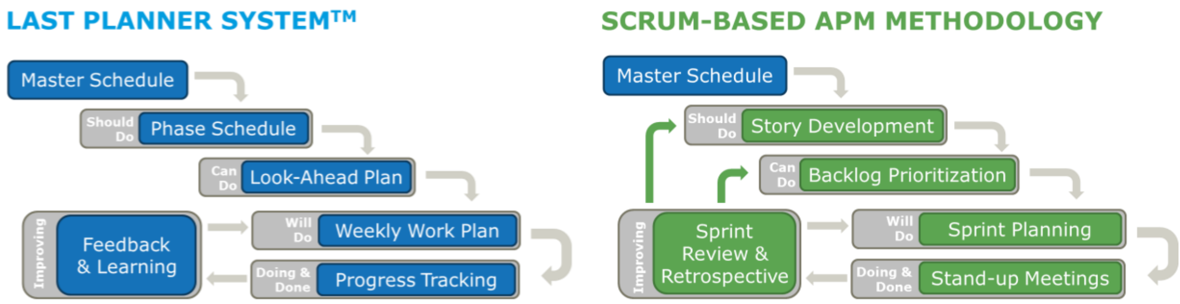


Figure 5. Traditional Last Planner System (Smith 2011) and the Scrum-based APM methodology used in this study

New Management Roles in Scrum

The traditional project management role of telling design teams how to perform is put aside in Scrum and, instead, value generation relies on the skills and training of the design team (Schwaber 2004). This is believed to give the advantage of an increase in value delivery because the entire design team takes part in shaping the project, as opposed to a traditional project in which the skills of the project manager are often decisive for project success (Cobb 2011). To do so, two distinct management roles are defined in Scrum, as described below.

Product Owner

The Product Owner is responsible to all stakeholders involved in the project, but must represent the 'outside' user's viewpoint in managing the functional requirements. It is the Product Owner who creates user stories and identifies the specific needs of the external stakeholders. It is also the Product Owner who leads the review discussions of the current design solutions after each sprint.

Scrum Master

The Scrum Master is responsible for managing the Scrum process by providing leadership and guidance in planning and prioritizing the tasks. The role is not to manage design team members, but to support them in making well-founded decisions and ensuring that they engage in the Scrum process. The Scrum Master must also monitor the sprint development process and lead the retrospective discussions on team performance after each sprint.

Creating a Community of Practice

To understand why Scrum has implications beyond *managing* the design process, it is interesting to see how team formation and performance is viewed from a social science perspective. Team formation and performance can be viewed within the practice theoretical framework (Nicolini 2012), in which the concept of *communities of practice* (CoPs) (Lave and Wenger 1991; Wenger 1998) is key to understanding what shaping of groups means for human activities. A CoP is a group of people who share a common practice or interest. A design team is not normally defined as a CoP because the participants are usually in a situation where they may have a common goal, but do not share the interdependence of a common practice. This situation is better described as a *network of practice* (Brown and Duguid 1991). This essentially describes how different CoPs are interlinked. Each individual CoP can be understood as a strong shared commitment built upon a mutually dependent relationship. In a building design project, each discipline represented could constitute a CoP, and the task of the project manager would be to get these different CoPs to collaborate. In recent years, the power of strong CoPs in organizations has been acknowledged because it has been found that CoPs are essential for the capture of tacit knowledge in organizations (McDermott and Archibald 2010), and that members of a CoP are better at profiting from each other's knowledge in problem-solving situations (Kietzmann et al. 2013). Building design projects have to manage the large amount of tacit knowledge which is essential for successful projects (Yalcinkaya and Singh 2016). This is why it would be of great interest to merge the various different CoPs in a design team into one shared or intermediate CoP, which is essentially what most of the integrated and collaborative design approaches previously described are trying to achieve. The existing communities might still co-exist, but the design team members should also sense membership of an intermediate CoP in which understanding of common ground and knowledge-sharing seems natural. The desired transition from a network of practice to an intermediate community of practice is illustrated in Figure 6.

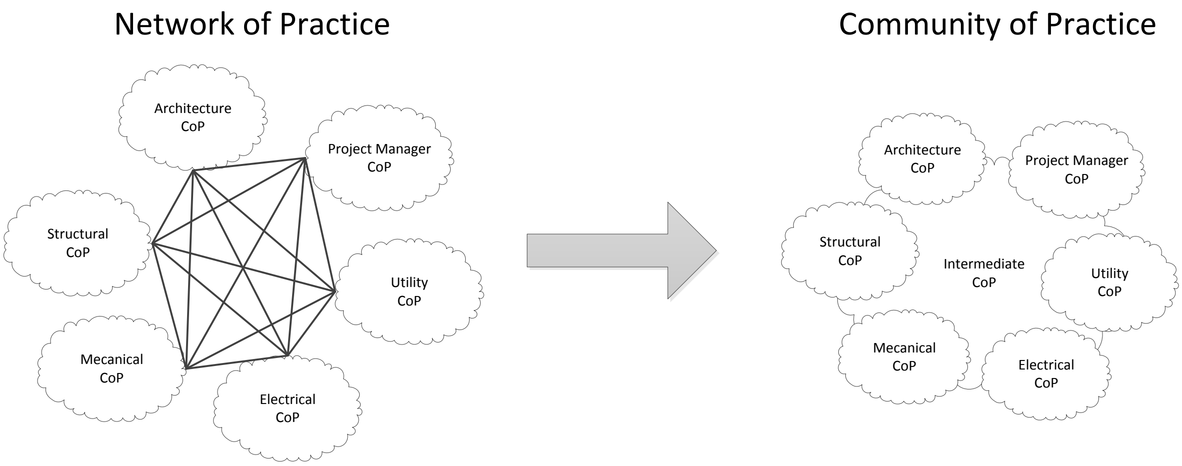


Figure 6. The quest in modern design approaches to merge design disciplines in different CoPs into an intermediate CoP to increase collaboration and knowledge-sharing.

Wenger uses the concept of 'brokering' to describe how cross-functional activities are managed between different CoPs and argues that '*the role of managers is often construed in terms of directing people, but it is worth noting that a good part of their activities have more to do with brokering across boundaries between practices'* (Wenger 1998 p. 108). Good brokers are able to make new connections across CoPs, facilitate coordination, and open new opportunities for meaning exchange. However, the job of brokering can be complex because '*it involves processes of translation, coordination, and alignment between perspectives'* (Wenger 1998 p. 109).

Scrum can be seen as a method for ensuring a strong intermediate community of team members originating in different CoPs and achieving common ground on the stories and tasks at hand using its embracing and visual approach. The role of the Scrum Master is parallel to Wenger's description of a broker who must try to play a mediating role between CoPs of different design disciplines and essentially create an intermediate design team community. The Product Owner has the role of connecting with people outside the intermediate design team community – primarily the client and external stakeholders – but should achieve this playing a similar broker role to connect the design team community with peripheral CoPs. In this way, Scrum is of interest as it specifically addresses the need to create strong communities and strong relationships with peripheral CoPs. This is the essential goal of most of the recently proposed design approaches, but Scrum addresses the need more explicitly by defining clear goals and roles specifically aiming at strong community development.

Methodology

The goal of the research presented here was to assess the effect of implementing the Scrum-based APM methodology described above in building design projects and to evaluate whether it has advantages over current design methods. Since project organizations and design results are unique from project to project in the construction industry, comparative analysis in this field is difficult. So in the current study, a design science research (DSR) approach was selected, in which the research artifact (the APM methodology) is evaluated by linking the problems in the surrounding environment to the actual research and grounding the research in the existing knowledge base (Hevner et al. 2004). Although this method makes comparison with other design approaches more difficult, it enables academic research to be better connected to practical problems (in this case, in the construction industry) and more clearly contribute to the knowledge base (Rocha et al. 2012).

The APM methodology was tested in three building design projects in the large Danish engineering company Ramboll with approximately 750 employees in its ‘Buildings’ unit. The three case studies made use of an agile online software tool called *JIRA* to support the APM methodology and to capture data for progress monitoring.

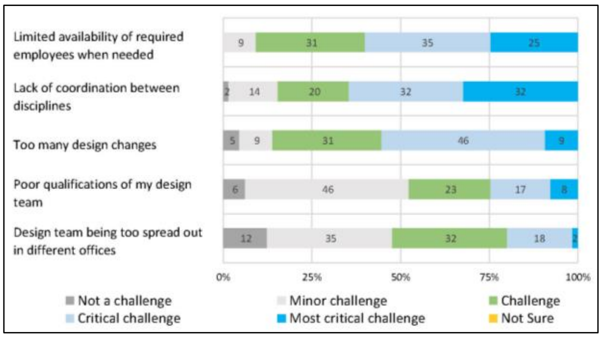
Grounding the research in the existing knowledge base is what Hevner et al. describe as the rigor cycle, and this is based on the above theoretical linking of APM to existing design management and social science theory. Linking the problems in the surrounding environment to the actual research is what Hevner et al. describe as the relevance cycle, in which business needs are used to evaluate the artifact. To identify the business needs, a survey was conducted among project managers in the engineering company to identify problems in current projects. The survey was carried out in late 2015.

The first author of this paper was involved in each of the case study projects, providing an introduction, configuring the software platform, and supporting the project management team in playing the agile roles throughout the case studies. Continuous evaluation and adjustments to the APM methodology were carried out on a bi-weekly or monthly basis in design meetings with the teams. The final evaluation of each case study was carried out as both quantitative and qualitative research in which selected design team members were asked to rate the effect of using APM based on the previously identified key problems. Semi-structured interviews (Kvale and Brinkmann 2015) were used to get design team members to further elaborate on their responses. The client in each project was also interviewed using semi-structured interviews. The case studies were carried out in 2016.

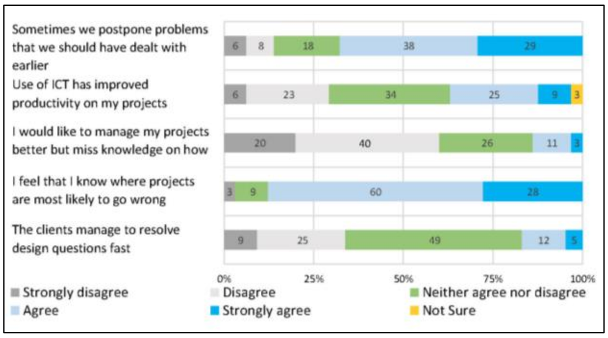
Survey on Design Management Challenges

To identify evaluation criteria for the implementation of the APM methodology, a survey was sent out to 149 potential project managers from the ‘Buildings’ unit of the engineering company in question. Of these, 65 project managers provided valid responses to the 64 questions asked about problems in building design. A 5-point Likert scale was selected to capture granularity in particular opinions expressed by the participants, and detailed findings from the survey have been published (Jørgensen and Treldal 2017). Of the 64 questions in the survey, 12 were selected to be used as key indicators for the evaluation process as the authors believed they represent the areas of most interest in relation to the agile process and the challenges of design. The original responses to these questions are shown in Figure 7.

What are key challenges in creating good design quality: (top three and bottom two)



Regarding your leadership and the clients you work for:



What are the key challenges forecasting remaining work:

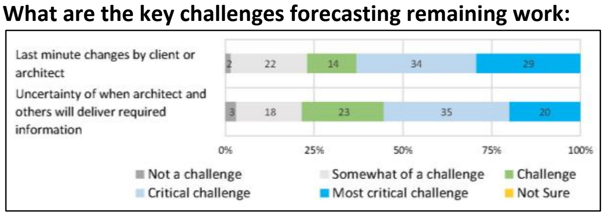


Figure 7. Responses from 65 project managers in the engineering company to 12 selected survey questions

As part of the survey, the project managers were asked to evaluate the implications of ten different challenges in building design. The top three and bottom two are included in Figure 7. The three most significant challenges were related to the availability of resources, lack of coordination, and too many changes. The qualifications of teams and the dispersal of teams were not considered urgent to address, but they were included here to monitor whether the APM methodology would affect them. Last minute changes by the client and uncertainty of deliveries from others were identified (out of five options) as most critical to forecast remaining work. Regarding their leadership, the project managers were challenged by problems being postponed too long and limited productivity effects from use of information and communication technology (ICT), such as 3D design, simulations, online document-sharing, e-mails, etc. On the other hand, they believe they have sufficient knowledge about how to manage projects and know where projects are likely to fail. In most cases, the clients also manage to resolve design questions fast.

Case Studies

The three case studies were selected because they all had a small and integrated design team, a relatively short design schedule, and close interaction with the client - elements that fit within the requirements for an agile approach. All three projects had private clients with limited up-front requirements, and part of the design team effort had been to develop a client brief as well as a conceptual design proposal. The case studies were monitored from either the start or the end of the preliminary design phase until the end of the detailed design phase, except that project C's design phase continued another two months after the monitoring period. The case studies are described in Table 1.

Table 1. Case study projects used in evaluation

	Construction Cost	Design Fee	Team members	Description	Monitoring period
Project A	€3,7M	€0,6M	10	Pharmaceutical company rebuilding part of a production facility	Jan-Jul 2016
Project B	€4,0M	€1,3M	10	Pharmaceutical company building a 100 m2 production extension	Jun-Dec 2016
Project C	€7,1M	€4,5M	25	Pharmaceutical company building a 300 m2 production extension.	Aug-Dec 2016

In all three cases, equipment suppliers were key stakeholders in the project. In project B, a sub-consultant to the client provided consultancy work on surrounding building structures. All other architecture and engineering services were provided by the engineering company monitored.

Research Artifact

To support the implementation of the APM methodology, the online tool *JIRA* was configured to match the needs of a building design process. JIRA allows for *assignment* (stories, features and tasks) to be configured individually for projects and presented in a backlog or a kanban board as illustrated in Figure 3 and Figure 4. In the three case studies, the design teams were introduced to the APM methodology, but allowed to define the assignment types required individually. From data analysis and evaluation of various assignments used, it was found that the teams needed the following assignment-types:

- Design Issues – representing stories of what each design discipline needed to complete to meet design targets and/or support other disciplines in meeting their design targets.
- Tasks – representing assignments which need to be resolved
- Clarification Issues – representing questions to the client or external suppliers
- Change Requests – representing identified scope changes which needed a client decision

In this way, the client was 'on-board' further than some Scrum approaches entitle, but there was a clear desire from both the project team and the clients to be able to continuously prioritize and monitor the dialog originating from sprint review meetings in response to the shifting priorities of the project. Due to strict legislation on drug manufacturing, pharmaceutical projects require close collaboration with the client to ensure compliance, so client involvement in such cases important.

The teams found it difficult to translate stories to a functional level and often stayed at either story or task level. Although teams were encouraged to skip traditional meeting memos and manage all tasks in JIRA, only project C did so to a large extent, so not all tasks were captured and managed in JIRA. All teams had a clear focus on capturing and monitoring stories and tasks with interdisciplinary implications, and these types of assignments were well represented in all cases.

If the case studies had not used the APM methodology, the project managers all agreed that they would have used a master schedule in Microsoft Project, design and client meetings with document memos in Microsoft Word, and action lists in Microsoft Excel to manage, plan and evaluate the projects. Using the APM methodology, they now also arranged one or more meetings to develop and define stories before starting work. On a five to six week basis, project A and (to some extent) project B held dedicated backlog periodization sessions where all assignments from JIRA were printed on small cards and put on a large black board for better visual planning with the discipline leads. Upcoming sprints were also listed on the board, and assignments were placed within sprints in prioritized order. New assignment were added with post-its and afterwards created in JIRA. One such session is pictured in Figure 8.

Figure 8. Backlog prioritization session on Project A with discipline leads

Figure 9. Stand-up meeting on Project B with design team

Sprints were aligned with the frequency of client meetings, which in most cases were weekly or bi-weekly. Client meetings were used for sprint reviews and evaluation of the design. In most cases, a 3D Building Information Model (BIM) was used to illustrate design solutions to the client so that solutions were released in the most engaging way as possible. Weekly design meetings were used to conduct a retrospective view on sprint development, and input from all meetings was used to continuously adjust the backlog content and priorities. Project B and (to some extent) project A held stand-up meetings with 2-3 day intervals between design meetings as pictured in Figure 9, but only in intensive periods of the design process. The project managers argued that it was difficult to find time because team members were busy or out of the office. The same argument was used by project C to explain their lack of stand-up meetings.

The project managers quite easily adapted to the role of the product owner, ensuring balance between requirements, feedback and story development. The scrum master role was more loosely defined. In project C, the assistant project manager took on the role, but did not spend much effort in engaging the design team. In projects A and B, no dedicated resources were available and the project manager tried to take on this role as well. In both cases, they complained afterwards about not having sufficient time for this role.

Projects A and B created a total of 171 and 173 assignments over the monitoring period, and project C created a total of 275 assignments. The resolving of assignments followed a reasonable steady path throughout the monitoring period in all cases as illustrated in Figure 9 for project B.

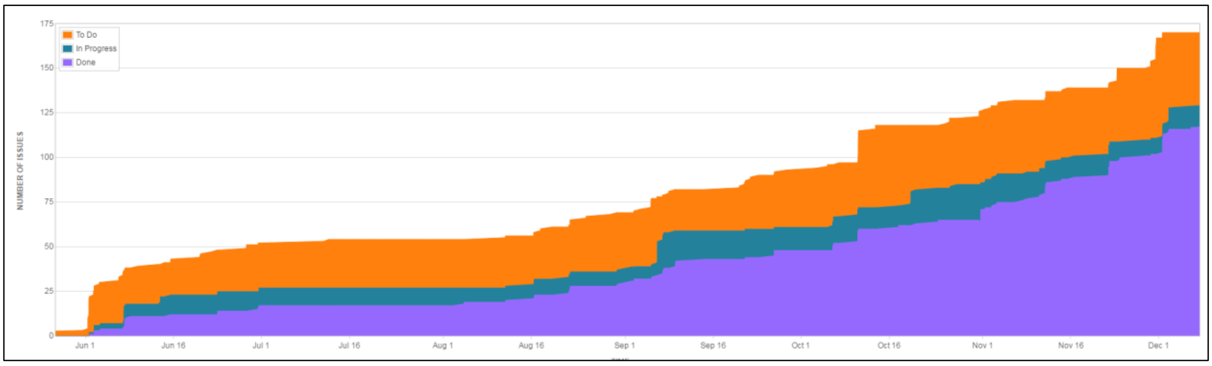


Figure 10. Cumulative illustration of assignments defined during the monitoring period of Project B. Orange represents assignments with *To Do* status, blue represents *In Progress*, and purple represents *Done*. The low increase in assignments at the beginning of the period was due to the summer holiday.

All three projects, however, had difficulty in meeting targets set for the number of assignments to be resolved in each sprint. The number of assignments resolved in each sprint relative to the number of assignments created is a key metric in LPS and defined as *Percent Plan Complete (PPC)* (Ballard 2000b). In Scrum, the same metric is defined as the project *velocity*, and in both cases the intention is to monitor team performance and its self-assessment ability. In other research using a collaborative approach to LBS in building design, average PPCs of 41% and 81% have been achieved (Fundli and Drevland 2014). It was not possible to achieve such PPC levels in the three case studies. The average PPC was 20-24%, as illustrated in Figure 11.

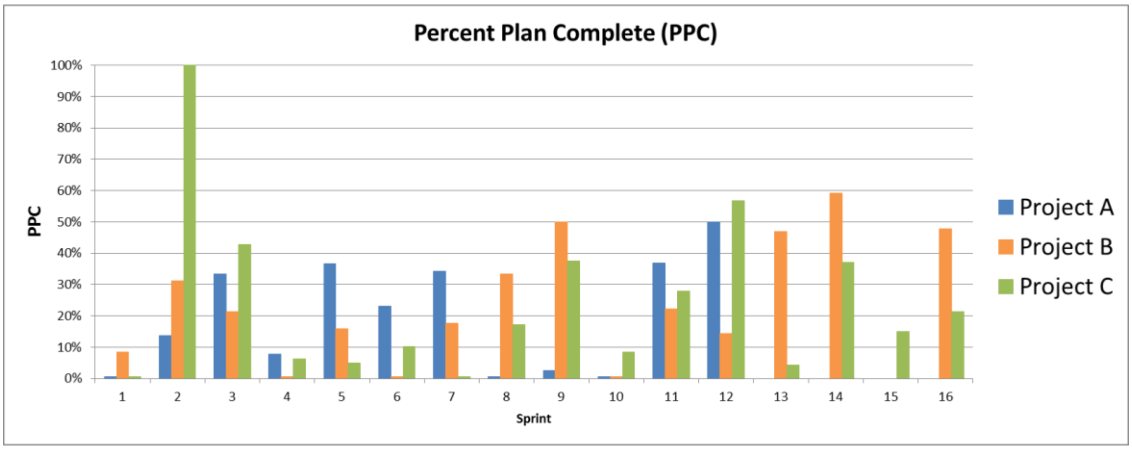


Figure 11. PPC calculated for each sprint over the period of each case study.
Project A had a total of 12 sprints, while projects B and C both had a total of 16 sprints.

The project managers argued that the low PPC was due to several stand-still periods in each project, during which the projects were put temporarily on hold due to internal client concerns about the project business cases. Project A, for instance, was stopped three times for more than a month each time. Another key reason given for the low PPC was the lack of necessary information from client or equipment suppliers. In particular Project B and C suffered from this problem because the equipment suppliers in both cases were contracted by the client with deadlines set later than the design team delivery dates. Furthermore, Project B had a change in project manager after sprint number 9, which resulted in a clear loss of momentum in story building and backlog prioritization, which took several weeks to catch up.

All three project managers concluded that each of the case studies was completed with more difficulties than usual. On the other hand, the design team members concluded that having a lot of changes is an integral part of the kind of projects they work on, and this was no different in the three case studies. Such a changing environment made it possible to fully test the ability of the APM methodology to adapt to change, so the case studies seemed suitable for evaluation.

Evaluation

To evaluate the APM methodology, five or six members of each design team were selected for a survey and interviews. The client in each project was also interviewed. Interviewees are listed in Table 2. When interviewees are referenced in the following, the abbreviations in brackets are used.

Table 2. List of interviewees from case studies

Project A		**Project B**		**Project C**	
Role in project	Years of experience in this role	Role in project	Years of experience in this role	Role in project	Years of experience in this role
Client [C-A]	1	Client [C-B]	1	Client [C-C]	3
Project Manager [PM-A]	16	Project Manager 1 [PM1-B]	5	Project Manager [PM-C]	5
Architect [A-A]	25	Project Manager 2 [PM2-B]	20	Assistant PM [APM-C]	8
Electrical Engineer [EE-A]	9	HVAC Engineer [HE-B]	4	Design Manager [DM-C]	6
HVAC Engineer [HE-A]	10	BMS Engineer [BE-B]	16	Electrical Engineer [EE-C]	9
Piping Engineer [PE-A]	3	Piping Engineer [PE-B]	3	Piping Engineer [PE-C]	10
Process Engineer [PRE-A]	30				

In the survey, all the design team members selected – including project managers – were asked to rate the 12 questions previously described twice. First, they were to rate the questions on the basis of their individual past experience during other similar projects, and secondly, on the basis of their experience during the case study in which they had just participated. The intention was to capture the effect on their experience of the use of the APM methodology. Improvements were calculated as the average difference for each case study between the 5-point rating of previous experience and experience during the case study. Results are presented in Figure 12 with the highest average improvement at the top.

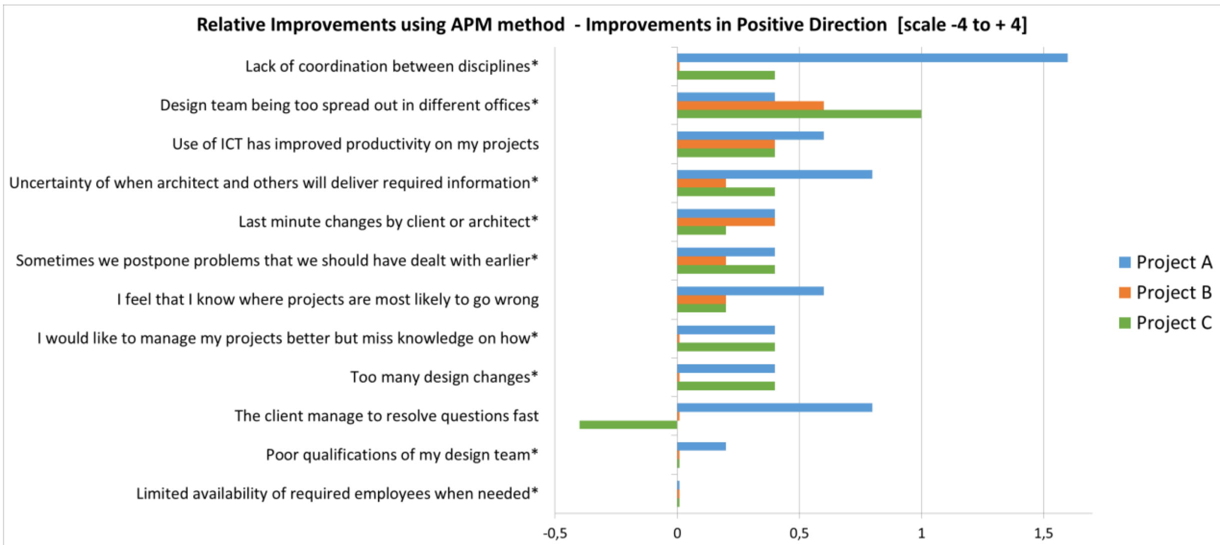


Figure 12. Average differences in the rating of key questions by design team interviewees in terms of their experience in previous projects and their experience in the case study they took part in. An * indicates questions where a decrease between previous experience and now on the 5-point rating of the question is an improvement.

In general, project A experienced the most positive improvements, while project B experienced fewest, yet all positive. Project C experienced one question where the APM methodology had a negative impact on the project, which was in relation to the ability of the client to resolve questions fast. Difficulties in getting the client organization sufficiently engaged in providing feedback on Project C made some design team members feel that the continuous communication required could overload some clients. In general, all the design team members believed the methodology provided clear value to the projects, but two team members on project B concluded that the methodology did not add sufficient value in the way it was executed on project B to be worth using on new projects.

As illustrated, improvements in coordination and the functioning of spread out design teams were rated highest, though project B experienced no improvement in coordination. The improvements in the contribution of ICT were attributed to JIRA being a better communication platform than e-mails and traditional meeting memos. A positive effect was also detected in most other cases, such as on-time delivery of information, the impact of changes, as well as better understanding, prioritization and knowledge of the project and management requirements. There was little or no change in the problems of poor qualifications in the design team and the availability of resources when needed. With regard to qualifications, this was actually positive because the APM methodology puts more responsibility on the team, which might be expected to make this problem worse. In relation to resources, it was argued that the resource planning was based on the master schedule and not lower level planning and was therefore not impacted by the APM methodology. In general, most improvements were smaller than might have been expected from introducing the APM methodology with dedicated management approaches to tackle the above problems and some observations on this are made below.

Plan-Driven or Agile

The traditional phase models tend to promote the use of a plan-driven waterfall approach to design, but in the interviews the design team members said they considered the design process to be relatively agile already – at least in their industry sector of construction:

> ‘Continuous releasing of design has been used before, such as 30%, 60%, and 90% reviews.’ [PM-A]

> ‘[Before the APM methodology] we also made designs in several small steps. They were used to explain to the client when the last responsible moment for decisions of specific information was needed.’
> [DM-C]

The structured approach to agile is what seems to have been missing. The change of mindset in the design teams in implementing the APM methodology, on the other hand, seems to have been less of a challenge and the selection of the APM methodology seems applicable on this basis. The foundation of balancing the approach to ensure that milestones were met was also confirmed by project managers:

> ‘In the balance between agile and waterfall, we need a combination, because we have fixed deadlines and risk getting some information too late using a pure agile approach with uncertain output.’ [PM-A]

The APM methodology selected in the case studies for this reason seems to add needed support to the current practice. Nevertheless, some fundamental difficulties using the methodology were identified and should be considered for future implementation.

Communication and Client Involvement

All three clients were very satisfied with the methodology and would recommend using it on new projects. All three gave similar feedback to that given below:

> 'It is great to follow the process. Everything is gathered in one system, and I can get an overview of the project fast. […] It is a good way to structure work and to track its progress.' [C-B]

However, neither the clients nor the design teams were satisfied with the communication achieved. One design team argued that there was a lack of requirement input and that feedback on solutions from the clients was often delayed for weeks. They said:

> 'The client was not so experienced and the organization behind [our client] did not provide sufficient support. Everyone has to play on the same team in relation to this new dynamic process because it will be a show-stopper for the work flow required if not all [stakeholders] are geared for the task and engaged. […] Common principles which everyone follows need to be in place from the beginning.' [DM-C]

The clients agreed with this:

> 'I can get behind on answering questions because I am the only one answering them. If my organization had had more time, it would have improved the flow in JIRA.' [C-B]

> 'It was difficult to get the right response from deep inside [our] organization.' [C-C]

As previously explained, the APM methodology puts considerable obligations on the client to be engaged throughout the design process due to the need for continuous feedback and clarification. Although the clients were represented by one or more dedicated project managers and supporting staff in all three cases, it was very difficult for the dedicated managers to get the feedback needed from the rest of their organizations fast enough. In projects B and C in particular, this was clearly the key hindrance to the desired progress, and it led to a lot of frustration among the team members, which is also reflected in the small amount of improvement experienced.

A similar concern was raised in relation to sub-consultants and equipment suppliers not taking part in the APM process, but interacting with the design team in a traditional manner with meeting memos and e-mails. These stakeholders were not involved due to client reluctance to manage the contractual interfaces, but this led to similar frustration in the design team. Nevertheless, the clear and visual communication with the APM methodology and use of JIRA also gave clear advantages:

> 'Coordination has improved significantly and clarification is clearer. […] Problems do not go away, but it is good that the communication is visual.' [PRE-A]

> 'One system gathering all information [on assignments] is great. Much easier with direct communication in JIRA, rather than emailing. Great interaction. Easy to see history of assignments.' [C-A]

Both teams and clients, however, also emphasized the importance of well-defined assignments because misunderstandings did lead to delay in solving assignments in some cases.

Limited Community Building

The challenges of online communication emphasized the importance of the physical meetings because the online platform is clearly not able to transfer sufficient meaning on content and constraints:

> 'One thing is the digital environment, but the physical backlog prioritization meetings help to make it more tangible. Some might distance themselves from JIRA, but in the physical meetings they were engaged and started taking responsibility.' [PM-A]

Although the effort as Scrum Master was limited, the project manager in project A managed to get the team engaged sufficiently to experience the team becoming better self-managed, leaving room for him to play a more facilitating role:

> 'The involvement of each team member encourages them to actively follow up on their own activities. Now the team members can solve the problems on their own. So, I felt they were more self-managed and I could use more time on managing the framework around the project.' [PM-A]

> 'Understanding what others are doing is very powerful. […] Interfaces are clearly highlighted and resolved. However, it is important to have someone who manages, sends reminders, and follows up.' [PE-A]

In the other projects, this was clearly less successful. It seems to be connected to the lack of communication with other stakeholders and the limited engagement in the Scrum Master role:

> 'It seems like we did not adapt fast enough to using the methodology. It improved towards the end with more aggressive follow-up. […] I [normally] spend too much time on managing assignments. This makes it easier, but there is a cultural challenge in getting people to use the methodology.' [PM2-B]

> 'There was a clear lack of motivation on the project, which was linked to the lack of communication with the client and the equipment supplier.' [EE-C]

Positive tendencies were also experienced, indicating a clear relationship between the ability to create a strong community and the ability to overcome problems in each project. Creating ownership and common ground was of importance to ensuring the community:

> 'The more ownership each discipline [team member] feels over the project, the more [problems] are solved during the project. The power is also that people get more ownership because it is their *own* assignment, and not an assignment from a project manager.' [PM1-B]

> 'The process was more transparent. It worked well for internal project coordination, but not with client communication.' [DM-C]

> 'The approach motivates more collaboration.' [A-A]

From the feedback, it seems clear that the project managers underestimated the effort required to create a strong community by not putting sufficient effort into the Scrum Master role. They all concluded that this was a valid lesson learned and that, next time, they would put more focus on this from the beginning.

Missing Sprint Goals and Feature Level

The limited positive effect of the APM methodology on the impact of changes was also not as expected. All three projects were challenged by shifting master schedules, but the teams also seemed to have difficulties in prioritizing assignments between sprints, which made the planning sessions more confusing and therefore less adaptable to change. In the first few sprints, the goal of each sprint was relatively clearly defined, e.g. "identify the best layout for building services routing" or "identify the best layout of production space", but as the design progressed and more and more assignments had not been solved on time, the backlog started to contain too many outstanding assignments, which blurred the following sprints.

Moreover, the design teams often skipped the breakdown of stories into functional requirements (features) before commencing work. This made it difficult to evaluate the solution from each sprint, because the team had only the loosely defined stories and the client brief to base the evaluation upon. This made both planning and evaluation more difficult:

> ‘We need better defined [sprints] to plan work efficiently. A [sprint] must be defined on the basis of quality requirements for the solution. This will also make it easier to allocate assignments [to sprints].’ [PM-C]

> ‘Next time, I would like to spend more time in the early stages to define features.’ [APM-C]

This seems to be related to eagerness from both the clients and the design team to jump straight into design of solutions:

> ’The client would like us to start straight away [with solutions]. The clients want to know fast what they will get. […] It is also one of the greatest problems with engineers that they start making solutions from the beginning. […] If the clients have more experience, they are more aware [that they should not ask for solutions at the beginning].’ [PM2-B]

In all three case studies, the design teams took part in developing the client brief, which contained multiple functional requirements. However, as the design evolved, less and less attention was given to the content of the brief because the client requirements and developed solutions changed so fast that it was difficult to keep track all the way back to the original brief. This left the case studies with limited abilities for structured evaluation and the interviewees expected that the continuous learning process would improve significantly if the evaluation process could be conducted in a more structured way.

Managing Change

All three case studies experienced numerous changes during the design process. Project A was restarted three times, and each time large changes were introduced to match new budgets. Project B had the contract renegotiated twice, and the design fee tripled as the client requested the engineering company to take on more and more services. Project C received new requirements for the equipment that needed to be installed every month and redesigned the facility more than five times as a result. Despite such challenges, the projects ended with a satisfactory result in all cases:

> ‘Despite all the challenges, I see the project to a large extent as a success. We managed to get the deliverables ready on time and reasonably within cost. A clear list of decisions and deliverables and the tools implemented were very important for this.’ [C-C]

Although some design team members saw changes as frustrating, most accepted them as normal in this kind of project:

> ‘Changes are not a problem. They improve projects’ [PM-C]

> ‘Our projects are packed with changes, and we must adapt our processes on a continuous basis. The APM methodology supports this.’ [DM-C]

On the other hand, not all changes seem to have been beneficial for the projects. Part of the frustration among some team members was related to changes which they believed could have been avoided by better involvement from external stakeholders:

> 'The design team tried to align the design with client expectations with continuous releases, but the external equipment supplier started work later than us, and when they started, their design assumptions proved to be wrong.' [APM-C]

The three case studies give clear indications that the clients did become aware of many challenges up-front and also tried to address them. The way the projects were organized, however, did not allow for assignments to be solved fast enough, and iterations continued for too long. At the same time, it seemed that the design teams and the clients discovered far more design challenges in the in-depth discussion on design releases than in previous projects. This left the teams with a feeling of having identified more assignments than on previous projects hence having produces a better result. Monitoring of the construction phase would be required to evaluate the final quality and this was not possible in the current research.

Discussion

The evaluation of the proposed APM methodology confirms several assumptions on the effect of using an agile approach. The case studies experienced many changes due to both internal and external factors. The need for an approach that can address such a changing environment seems therefore valid. It was argued that agile principles were already in use in such design processes, and the contribution of the APM methodology would therefore primarily be to provide more structure to the process. More structure seems clearly needed, because the current design approach does not address the need for a collaborative, dynamic and changing planning process. From the evaluation, three elements were identified as impacting the results; they are related to the organization, the structuring, and the facilitation of the design process.

Creating an Agile Organization

It is essential that all key stakeholders are aligned with the agile approach, which means that they are involved and align their work continuously on the basis of the dynamic planning conducted. The influence of the process on organizations must extend further than key stakeholders. This was particularly clear with the client organizations, where an in-depth stakeholder analysis would have revealed that input from many areas of the client organization was required on a continuous basis. This means that, if the APM methodology is to be effective, all stakeholders with assignments which are mostly interdependent must be part of the APM approach and engaged in the intermediate community created. The reluctance of the clients to allow such involvement suggests there is a gap in the necessary understanding of the relationship between agile desires and stakeholder engagement.

Structuring the Design Process

Although they followed most of the steps in the map of the design process in Figure 1, the design teams found it difficult to conduct the functional analysis. Kiviniemi (2005) argues that this is very likely to result in unintended scope creep, and he proposes a method to define and structure requirements at a functional level in a way that allow for direct linking to the design solutions. Kim et al. (2015) find that, although commercial solutions now exist to support this need, it is still very difficult to keep the requirements up to date as changes are introduced. Kim et al. conclude that the continuous updating of requirements needs much closer mapping between requirements and user activities, adding an extra layer of complexity. It seems to be a key challenge in construction that functional requirements are so difficult to manage, and this means the improvement process is less structured and therefore generates less value. Increased focus on how to define clear functional requirements should for this reason be a vital requirement for the industry. The validity of the defined map for the design process in Figure 1 seems in this regard to still clearly match the needed steps of the desired APM methodology.

It might be expected that, as the design process progresses, there would be less need for agile methods and more plan-driven approaches would be beneficial as the clarity of solutions improves. This was not the case in any of the three case studies. New changes were introduced throughout the design process and, although some could have been avoided, most design team members believed it was the nature of such projects, due to their high complexity, and that they should therefore be accepted. In such cases, it is essential that the APM methodology is used throughout the design phases. In other cases, the APM methodology might be more useful at the beginning of the design process and, as solutions are clarified, a more plan-driven and stable approach could be introduced. However, the discussions throughout the case studies and the final evaluation makes it quite clear that it is very difficult to assess when solutions are finally clarified due to the range of external factors affecting such projects.

Facilitating the Design Process

The ability in project A to achieve a somewhat self-managed team clearly improved the project. This was not achieved well in project B, and the project's improvement scores were also significantly lower. It is well known that an inefficient Scrum Master is a clear drawback for the implementation of agile methods (Schwaber 2004), but it is interesting that the effort put into the role in projects A and B was not observed to be very different. The project manager in project A involved the team more and completed more planning sessions, but he spent far less time on follow-up than the project managers in project B. This confirms that the APM methodology requires more planning and engagement, but the effort clearly adds value to a project.

The low PPC score experienced in the current study compared to e.g. the results by (Fundli and Drevland 2014) indicate that elements in their method framed as Collaborative Design Management (CDM) could be of interest to include in the APM methodology. Bølviken et al. (2010) describe that CDM adds (among other) a *Decision Plan* and a *Dialog matrix* to LPS along with focus on six preconditions for sound design tasks. The inclusion of such focus on the decision making process would add clear value to the APM method and should for this reason be considered in future implementation.

In general, iterations in design can be described as either positive or negative depending on whether they generate additional value or not (Ballard 2000a). If the organization, structuring and facilitation of the design process are not handled as discussed above, the findings in the research clearly describe that the APM methodology runs a high risk of negative iterations. Yet, with the right effort clear value can also be achieved justifying the effort required.

Conclusion

The use of the APM methodology improved understanding and common ground, which in most cases resulted in better coordination and better management of changes, both previously identified as key challenges in building design. Increased team member involvement resulted in better team performance, and continuous backlog prioritization ensured that nothing was lost or ignored, which is believed to have resulted in fewer mistakes and improved quality. Finally, empowering the team members did not seem to endanger flow or value generation; on the contrary, the project manager found it improved the ability to monitor project progress. The effect, however, differed considerably in the three case studies in relation to the key questions used for evaluation, and the improvements were generally lower than expected, especially in relation to the impact of changes. Clear value generation was identified in most cases using the APM methodology, but the three elements of organization, structuring and facilitation of the design process are vital to the success of the APM methodology. They were not addressed well in all the case studies, and this clearly increased the risk of too many negative design iterations.

Acknowledgments

The research reported in this paper was funded by Innovation Fund Denmark and the engineering consulting company Ramboll Denmark.

References

Anumba, C. J., Kamara, J. M., and Cutting-Decelle, A.-F. (2007). *Concurrent engineering in construction projects*. Taylor & Francis, London, U.K.

Ballard, G. (2000a). "Positive vs. Negative Iteration in Design." *Proc., 8th Conference of the International Group for Lean Construction*, Brighton, U.K.

Ballard, H. G. (2000b). "The Last Planner System of Production Control." The University of Birmingham.

Beck, K., Beedle, M., van Bennekum, A., Cockburn, A., and Fowler, M. (2001). "Manifesto for Agile Software Development." <http://agilemanifesto.org> (Feb. 24, 2017).

Bertelsen, S. (2003). "Complexity – Construction in a New Perspective." *Proc., 11th Annual Conference in the International Group for Lean Construction*, Virginia, U.S.

Bertelsen, S., and Emmitt, S. (2005). "The Client as a Complex System." *13th International Group for Lean Construction Conference*, Sydney, Australia, 73–79.

Boehm, B. W., and Turner, R. (2009). *Balancing agility and discipline : A guide for the perplexed*. Addison-Wesley, Boston, MA.

Brown, J. S., and Duguid, P. (1991). "Organizational Learning and Communities-of-Practice: Toward a Unified View of Working, Learning, and Innovation." *Organization Science*, 2(1), 40–57.

Bølviken, T., Gullbrekken, B., and Nyseth, K. (2010). "Collaborative Design Management." *Proc., 18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel, 103–111.

Chachere, J. M., Kunz, J., and Levitt, R. (2009). *The Role of Reduced Latency in Integrated Concurrent Engineering*. *CIFE Working Paper*, Stanford, CA.

Cobb, C. G. (2011). *Making Sense of Agile Project Management: Balancing Control and Agility*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Deming, W. E. (1982). *Out of crisis*. Massachusetts Institute of Technology, Cambridge, Mass.

Emmitt, S., and Ruikar, K. (2013). *Collaborative design management*. Routledge, London, U.K.

Fundli, I. S., and Drevland, F. (2014). "Collaborative Design Management – A Case Study." *Proc., 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway.

Hamzeh, F. R., Ballard, G., and Tommelein, I. D. (2009). "Is the Last Planner System Applicable To Design? a Case Study." *Proc., 17th Annual Conference of the International Group for Lean Construction*, Taipei, Taiwan, 407–416.

Hevner, A. R., March, S. T., Park, J., and Ram, S. (2004). "Design Science in Information Systems Research." *MIS Quaterly*, 28(1), 75–105.

INCOSE. (2015). *Systems engineering handbook a guide for system life cycle processes and activities*. (D. D. Walden, G. J. Roedler, K. Forsberg, R. D. Hamelin, and T. M. Shortell, eds.), John Wiley & Sons, Inc., Hoboken, New Jersey.

ISO. (2008). "Organization of information about construction works - Framework for management of project information." *ISO 22263*, Geneva, Switzerland.

Johansson-Sköldberg, U., Woodilla, J., and Çetinkaya, M. (2013). "Design Thinking : Past, Present and Possible Futures." *Creativity and Innovation Management*, 22(2), 121–146.

Jørgensen, B., and Emmitt, S. (2009). "Investigating the integration of design and construction from a lean perspective." *Construction Innovation: Information, Process, Management*, 9(2), 225–240.

Jørgensen, E. F., and Treldal, N. (2017). "Challenges of Variability and Resource Management in Construction Design Projects." *Proc., 5th International Workshop - When Social Science meets Lean and BIM*, Aalborg, Denmark, 117–128.

Kietzmann, J., Plangger, K., Eaton, B., Heilgenberg, K., Pitt, L., and Berthon, P. (2013). "Mobility at work A typology of mobile communities of practice and contextual ambidexterity." *Journal of Strategic Information Systems*, Elsevier B.V., 22(4), 282–297.

Kim, T. W., Kim, Y., Cha, S. H., and Fischer, M. (2015). "Automated updating of space design requirements connecting user activities and space types." *Automation in Construction*, Elsevier B.V., 50(C), 102–110.

Kiviniemi, A. (2005). "Requirements management interface to building product models - CIFE Technical Report #161." Stanford University, USA.

Knotten, V., Svalestuen, F., Hansen, G. K., and Lædre, O. (2015). "Design Management in the Building Process - A Review of Current Literature." *Procedia Economics and Finance*, Elsevier B.V., 21(2212), 120–127.

Koskela, L. (2000). "An Exploration towards a Production Theory and its Application to Construction." *VTT Publications 408*, Technical Research Centre of Finland.

Koskela, L. (2007). "Foundations of Concurrent Engineering." *In Concurrent Engineering in Construction Projects*, J. M. Kamara, C. J. Anumba, and A.-F. Cutting-Decelle, eds., Taylor & Francis, London, UK, 12–29.

Kvale, S., and Brinkmann, S. (2015). *InterViews: learning the craft of qualitative research interviewing*. SAGE Publications Inc., Thousand Oaks, California.

Lave, J., and Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press, Cambridge.

Lawson, B. (2005). *How Designers Think: The Design Process Demystified*. Architectural Press, London, UK.

Lightsey, B. (2001). *Systems Engineering Fundamentals*. Defense Acquisition University Press, Fort Belvoir, Virginia.

Liker, J. K. (2004). *The Toyota way : 14 management principles from the world's greatest manufacturer*. McGraw-Hill, New York, NY.

McDermott, R., and Archibald, D. (2010). "Harnessing Your Staff's Informal Networks." *Harvard Business Review*, (March).

Nicolini, D. (2012). *Practice Theory, Work and Organization. An Introduction*. Oxford University Press, Oxford, U.K.

Ostime, N. (2013). *Handbook of practice management*. RIBA Publishing, London, UK.

Othman, A. A. E., Hassan, T. M., and Pasquire, C. L. (2004). "Drivers for dynamic brief development in construction." *Engineering, Construction and Architectural Management*, 11(4), 248–258.

Owen, R., Koskela, L., Henrich, G., and Codinhoto, R. (2006). "Is agile project management applicable to construction?" *Proc., 14th Annual Conference in the International Group for Lean Construction*, Santiago, Chile, 51–66.

Owen, R. L., and Koskela, L. (2006). "An Agile step forward in project management." *Proc., 2nd Specialty Conference on Leadership and Management in Construction*, Grand Bahama Island, Bahamas, 216–224.

Pikas, E., Koskela, L., Thalfeldt, M., Dave, B., and Kurnitski, J. (2015). "Complexity in Designing Energy Efficient Buildings : Towards Understanding Decision Networks." *Proc., 23rd Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, 213–222.

Pinto, J. K. (2016). *Project Management : Achieving Competitive Advantage*. Pearson Education, Boston, US.

Reed, B. (2009). *The integrative design guide to green building : redefining the practice of sustainability*. Wiley, Hoboken, N.J.

El Reifi, M. H., and Emmitt, S. (2013). "Perceptions of lean design management." *Architectural Engineering and Design Management*, 9(3), 195–208.

Riedel, R., Jentsch, D., Horbach, S., Ackermann, J., and Müller, E. (2013). "Agile Planning Processes." *Advances in Production Management Systems. Sustainable Production and Service Supply Chains*, 414, 143–150.

Rocha, C. G., Formoso, C. T., Tzortzopoulos-Fazenda, P., Koskela, L., and Tezel, A. (2012). "Design science research in lean construction: process and outcomes." *Proc., 20th Annual Conference in the International Group for Lean Construction*, San Diego, California.

Rosas, E. (2013). "Integrating the Design Structure Matrix and the Last Planner System Into Building Design." *Proc., 20th Annual Conference in the International Group for Lean Construction*, San Diego, California, 389–398.

Schwaber, K. (2004). *Agile project management with Scrum*. Microsoft Press, Redmond, US.

Serrador, P., and Pinto, J. K. (2015). "Does Agile work? - A quantitative analysis of agile project success." *International Journal of Project Management*, Elsevier Ltd. APM and IPMA., 33(5), 1040–1051.

Smith, A. (2011). "Agile and Lean Applied to Construction." *Ennova*, <http://ennova.com.au/blog/2011/09/agile-lean-compared-applied-construction> (Jan. 20, 2017).

Sohi, A. J., Hertogh, M., Bosch-Rekveldt, M., and Blom, R. (2016). "Does Lean & Agile Project Management Help Coping with Project Complexity?" *Procedia - Social and Behavioral Sciences*, 226, 252–259.

Takeuchi, H., and Nonaka, I. (1986). "The New New Product Development Game." *Harvard Business Review*, (January).

Tilley, P. a. (2005). "Lean Design Management — a New Paradigm for Managing the Design and Documentation Process To Improve Quality ?" *Proc., 13th Annual Conference in the International Group for Lean Construction*, Sydney, Australia, 23–35.

Tilley, P. A., McFallan, S. L., and Sinclair, R. G. (2002). *Improving Design and Documentation Quality*. Highett, Australia.

Wenger, E. (1998). *Communities of practice : learning, meaning, and identity*. Cambridge University Press, Cambridge, U.K.

Yalcinkaya, M., and Singh, V. (2016). “A Visual Transactive Memory System Approach Towards Project Information Management.” *Proc., 33rd CIB W78 Conference*, Brisbane, Australia.

This page is intentionally left blank.

Paper F -
Using BCF as a Mediator for Task Management in Building Design

USING BCF AS A MEDIATOR FOR TASK MANAGEMENT IN BUILDING DESIGN

Niels Treldal [(1) (2)], Hussain Parsianfar [(2)], Jan Karlshøj [(1)]

(1) Technical University of Denmark, Lyngby, Denmark
(2) Rambøll Danmark A/S, Copenhagen S, Denmark

Abstract
buildingSMART has adopted the BIM Collaboration Format (BCF) to improve interoperability in the field of process information exchange. The original scope of BCF was linked to a need to communicate BIM-related tasks, but a further expansion of the BCF format should be considered to add additional support to industry requirements for task management. The research described in this paper was based on literature studies of industry needs and evaluations of the current BCF specification and its implementation in software, and it identified some challenges in the current state of BCF. Based on these findings, we propose an information system consisting of decentralised model and task servers using both BCF and IFC. Using IDM Part 2 as an example, we further propose an architecture to expand BCF.

1. Introduction

Building design is complex, not only because of complexity within one domain, but because of interdependencies between all three domains: product, process and organisation [1]. Building Information Modelling (BIM) [2] is a response to reducing product complexity while management approaches such as Lean Construction [3], Integrated Concurrent Engineering [4] and Agile Scrum [5] address process and organisational complexity. Task management, which is the focus of this research, is essential in such management approaches in combination with flow and value management [6]. Information exchange is crucial in all of these management approaches and buildingSMART addresses this need by providing standards to improve interoperability in the exchange of building information. From its beginning in the 1990s, buildingSMART focused primarily on supporting the product domain by developing the Industry Foundation Classes (IFC). The IFC specifications was intended to capture object-oriented building information and, over the years, the IFC specifications grew to include some process-related information. Today definitions for actors, time, approvals and action management are all included in the specifications [7].

1.1. The BIM Collaboration Format (BCF)

Combining product and process information in one data model generated a range of practical issues when exchanging this large data model as a bulk data transfer [8]. So in 2010, the software companies Tekla and Solibri came up with the proposal of an XML schema for the BCF format. The BCF format is an open file format that introduces workflow communication capability and can be connected to IFC models.

BCF contains information about a task (called a *topic* in BCF) including status, type and assignee, any comments related to the task, and references to related objects in an IFC model. It can also include information on the camera position/viewpoint location of the authoring tool as well as a snapshot of that view. In 2014, bcfXML v2 was released and adopted by buildingSMART [8]. This version included the option to append documents and elements of a data model (BIM snippets) as well as an option to include more viewpoints and snapshots [9]. The BCF format is independent of the IFC specifications, and enumerations for topic type, status, priority, etc. can be predefined by using an extension schema.

In real projects, hundreds if not thousands of BCF files are necessary for communicating tasks, and managing these as individual files can be difficult [10], [11]. To address this challenge, a specification for a BCF web service called bcfAPI v1 was developed along with the release of bcfXML v2. The specification defines a RESTful API, which allows a BCF server to automatically synchronise BCF tasks with others. Apart from an ability to define users more accurately (e-mail identification), the scopes of bcfAPI v1 and bcfXML v2 are identical, and the only difference is the way BCF tasks are exchanged. In the following, bcfXML v2 will be addressed in the comparisons carried out, but similar results would apply if bcfAPI v1 had been used as the communication format.

1.2. Process information spectrum

The original scope of BCF is linked to a need to communicate BIM-related tasks such as clash detection findings and other coordination issues. However, there are many other types of process-related activities in architectural, engineering and construction (AEC) projects, including the management of contract and user requirements, cost and risk management, interface coordination, site registration, etc. For this reason, buildingSMART and other organisations are also engaged in developing standards like IDM Part 2 [12] to define and manage contractual agreements and the Danish U106 Digital Defect Registration [13] to define and assign defects during construction. A review of these standards reveals that they share many aspects: they all address a specific task, include the creator and assignee, manage its status, and track the development of the task. Moreover, they also address the individual focus points such as BIM linkage in BCF, workflow definitions in IDM Part 2, and location information in U106.

Many tasks in construction are related, which results in the complexity referred to previously, but tasks can also evolve. For example, a clash might just be a task between two designers, but if the problem cannot be solved by changing the current design, the task might escalate to involve the client and even result in cost or time overruns affecting contractual issues. In this case, both BCF and IDM Part 2 are required to fully capture the process information involved. From an interoperability perspective, it is a challenge that multiple standards must be used in parallel because information might be lost in the conversion, and from an implementation perspective, it is time consuming for software vendors if they are required to support multiple formats for similar functionality. In the light of these observations, it would be valuable to explore the possibility of harmonising standards related to capturing process information within management of tasks.

1.3. Study goals

The goals of this research were firstly to identify requirements for task management focusing on building design; secondly to assess the current implementation of BCF in available software to identify its current potential to capture process information; thirdly to compare BCF and IDM Part 2 to understand similarities and differences; and finally to evaluate the potential of expanding the BCF format to embrace a greater part of the spectrum of process information to support comprehensive task management.

2. Methodology

The research in this paper involved reviews of the literature and existing standards, and theoretical solutions are proposed on this basis. The research focused on building design, but most of the findings are applicable throughout the lifecycle of AEC projects.

2.1. Identifying requirements

To identify requirements for task management, the literature on current experience with AEC collaboration tools was reviewed and requirements specifically for task management were extracted. Findings in the literature selected were based on various approaches, such as interviews, implementation attempts, and research of existing tools. The findings are, therefore, believed to constituting a representative view of the industry needs including those not met by existing tools.

2.2. Review of bcfXML v2 exported by current software solutions

To review the content and quality of bcfXML information currently being shared, we made a structured review of the BCF packages exported from seven widely used tools supporting BCF. Each BCF package was created based on the same IFC model and a set of similar information was defined in each software solution to make it possible for their export capabilities to be properly compared. The content of each BCF package was reviewed in a text editor and compared to the bcfXML v2 specification. These findings were then compared to the industry requirements identified.

2.3. Comparison of BCF and IDM Part 2

To compare the BCF specification with the specification for IDM Part 2, we defined a list of the functionalities of the two standards and each specification was then evaluated based on these functional requirements. The purpose of this comparison was to provide a better picture of the areas where the two standards overlap and the areas where they differ.

2.4. Proposal for expanding the BCF specification

Finally, we used our findings and the findings from similar research to develop a theoretical proposal on how process and product information could be managed and exchanged within the framework of building design and how the BCF specification could be expanded to support this concept.

3. Requirements for a task management tool

The literature on systems to support the management of product, process and organisation complexity often defines such systems as collaboration tools. Table 1 identifies requirements in the literature that specifically target the task management part of collaboration tools. Requirements are grouped into categories of general requirements, requirements for what information is to be transferred, requirements for how workflows should be managed, and requirements for how tasks should be defined and related.

Table 1: Requirements for a task management tool

General	Information Transfer	Workflows	Task Management
• Improve understanding of project dependencies and impact of decisions [14], [15] • Support transparency [14], [16] • Provide overview, history, filtering, and any device accessibility [14], [15], [17], [18], [19] • Improve data management [14], [15], [20],[18], [17], [19] • Easy to use [14], [15], [20], • Support BIM model coordination [15], [20], [18], [17] • Include continuous system support and development [14], [20], [18], [17], [19] • Allow for integration with other tools such as simulation or visualisation tools [18] • Include social networking integration [14], [15]	• Manage client decisions and client comments on project materials [14], [20] • Manage comments on design from other disciplines [14] • Document agreements and manage tasks agreed with the client [14] • Manage deviation reports and enquiries from the contractors [14] • Visualise interdisciplinary interfaces, and warn of potential negative impacts [14], [15], [17], [19] • Manage communication based on the BIM design at hand [14], [15], [20], [18], [19] • Manage interface coordination and level knowledge [14] • Managing what is not within the BIM model [14], [17], [19]	• Manage user rights, roles and responsibilities [14], [20], [17], [19] • Provide guided and structured workflow [14], [15], [20], [19] • Allow for workflows to be adjusted [20] • Support for quality assurance [14] • Allow for agreeing on processes that support the needs of each discipline [14], [20] • Support automated workflows [14]	• Ability to define categorisation of the tasks [14] • Ability to define prioritisation [14], [17] • Ability to relate to deadlines and phases [14], [15], [17] • Support better design scheduling [14], [15] • Manage responsibility for BIM information [14], [20], [17]

The review identified the importance in task management of capturing and saving the history of decisions, agreements, comments and questions. Tasks should be able to link to deadlines, phases and/or schedules, link to the BIM model, support data management, and link to other tools including social networking. The ability to refer to issues in documents or a specific point on the construction site is also desirable. Structured and yet adjustable workflows, user rights and roles must be supported, management activities should be automated, and it should be possible to categorise and prioritise tasks. The management tool itself should be able to visualise the information to improve understanding, leverage knowledge, and support transparency. The tool must also be easily accessible, easy to use, and be continuously supported and developed to support individual projects.

4. Evaluation of current BCF implementation

To assess the current implementation of BCF in tools that support task management, exported BCF XML files from seven selected tools were analysed and compared to the requirements in the bcfXML v2 specification [21]. The following tools were selected: BCFier, KUBUS BIMCollab, Trimble Connect, Solibri Model Checker, DDS Viewer, BIMTrack and Revizto. A summary of the results is shown in Table 2.

Table 2: Summary of results from bcfXML v2 exports – displaying missing, incorrect, supported and not supported content

Software (version)	**BCFier** (2.0.2.0)	**BIMCollab** (2.5)	**Trimble Connect***	**Solibri** (9.6.12)	**DDS Viewer** (12)	**BIMTrack** (1.3)	**Revizto** (4.1.35834)
File: bcf.version							
File: project.bcfp		**Not exported**		**Not exported**	**Inconsistent implementation:** GUID not used	**Not exported**	**Not exported**
File: markup.bcf							
Header	**Optional but not supported:** IfcProject, IfcSpatialStructureElement,IsExternal, Filename, Reference	**Not supported**	**Optional but not supported:** IfcSpatialStructureElement,IsExternal, Filename, Date, Reference	**Optional but not supported:** IfcSpatialStructureElement,IsExternal, Filename, Date, Reference	**Not supported**	**Not supported**	**Not supported**
Topic	**Mandatory but not supported:** CreationDate, CreationAuthor **Optional but not supported:** TopicType, TopicStatus, ReferenceLink, Priority, Index, Labels, ModifiedDate, ModifiedAuthor, AssignedTo	**Optional but not supported:** ReferenceLink, Labels	**Optional but not supported:** Index, AssignedTo **Inconsistent implementation:** Title - Description is placed in Title Labels - IssueID in tool placed in Labels	**Optional but not supported:** ReferenceLink, Priority, Labels	**Mandatory but not supported:** CreationAuthor **Optional but not supported:** Priotiry, Labels, ModifiedAuthor	**Mandatory but not supported:** CreationDate **Optional but not supported:** ReferenceLink, Labels, ModifiedDate, AssignedTo	**Optional but not supported:** Topictype, ReferenceLink, Priority, Index, Labels, ModifiedAuthor
BIMsnippet	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**
DocumentReference	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Optional but not supported:** IsExternal	**Not supported**
RelatedTopic	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**
Comment	**Optional but not supported:** ReplyToComment, ModifiedDate, ModifiedAuthor	**Mandatory but not supported:** Status **Optional but not supported:** VerbalStatus, ReplyToComment, ModifiedDate, ModifiedAuthor	**Mandatory but not supported:** Status **Optional but not supported:** VerbalStatus, Viewpoint, ReplyToComment, ModifiedDate, ModifiedAuthor	**Mandatory but not supported:** Topic **Optional but not supported:** ReplyToComment, ModifiedDate, ModifiedAuthor	**Optional but not supported:** ReplyToComment, ModifiedDate, ModifiedAuthor **Inconsistent implementation:** Viewpoint – Comments reference under viewpoints, should be other way around	**Mandatory but not supported:** Status **Optional but not supported:** VerbalStatus, Viewpoint, ReplyToComment, ModifiedDate,	**Not exported**
Viewpoints			**Not supported**				**Not supported**
File: Visualization information (.bcfv)							
Components	**Optional but not supported:** Color **Inconsistent implementation:** Selected - Selected objects are not set to Selected=True, Visible - Used only when Visible = False	**Optional but not supported:** Color, OriginationSystem, AuthoringToolId **Inconsistent implementation:** Selected - Used only when Selected = True, Visible - Hidden objects are not set to Visible = False	**Optional but not supported:** Color, OriginationSystem, AuthoringToolId	**Optional but not supported:** Color	**Optional but not supported:** Color, AuthoringToolId **Inconsistent implementation:** Selected - Selected objects is not set to Selected = True, Visible - Hidden objects are not set to Visible = False	**Not supported**	**Not supported**
OrthogonalCamera							
PerspectiveCamera							
Lines	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**
ClippingPlanes	**Not supported**				**Not supported**	**Not supported**	**Not supported**
Bitmap	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**	**Not supported**

- (red) One or more required elements and/or attributes missing
- (orange) Inconsistent use of one or more elements and/or attributes
- (green) Elements and attributes supported in accordance with bcfXML v2
- (white) One or more optional elements and attributes not supported

* Version not available. Latest BCF export from the website: 28-06-2016

The review in Table 2 shows the rather inconsistent implementation of BCF in the tools selected. No tool is able to export a BCF file fully in accordance with the current bcfXML v2 specification, and elements and attributes available in the tools are not always exported.

Lack of implementation of non-optional attributes is seen in relation to *Topic*, where *CreationDate* and *CreationAuthor* are not exported in some cases, and in relation to *Comment*, where *Status* and related *Topic* are not supported in some cases. Incorrect implementation of attributes is seen in relation to *Components* where there is limited consistency in the methods of defining selected and visible objects, and in various other areas where attributes are not defined in accordance with the specification. Limited implementation of optional attributes is seen in relation to the *Header, BIMSnippet, DocumentReference, RelatedTopic, Lines,* and *Bitmap*. In several cases, the limited implementation is due to a lack of support for such functionality in the tools, but in many cases the functionality is supported in the tools but is still not exported. For example, viewpoints are not exported from Trimble Connect or Revizto although these are defined in the tools, and components are not defined from BIMTrack or Revizto even when selected here. The inconsistent implementation generates uncertainty in information exchange options because the different tools interpret BCF files differently. In almost all cases, round-tripping a BCF file through more than one tool will also result in loss of information due to the inconsistent implementation.

4.1. Support of industry needs by BCF

If we compare these findings with the industry needs in Table 1, most of the current implementations support a range of the general needs, such as information capturing of decisions, comments, and linkages to BIM design. However, more consistent implementation will be required to comply with needs such as assignment to a person (workflows), categorisation, prioritisation, labelling, relationships and document-linking (data management). The need for integration with other tools is partially supported by allowing for system-specific identification and open information exchange. Linking to deadlines, phases and/or schedules and referring to issues in documents or a specific location on the construction site are currently not supported. Similarly, the need to manage workflows, including user rights, roles and responsibilities, is only partially met in the current specifications. In the light of these findings, the BCF specification needs to be expanded if it is to fully support the needs of the industry. As an alternative, the functionality required could be implemented in task management tools, but interoperability in process information exchange would remain limited. For this reason, the following sections will elaborate on the potential for expanding the BCF format.

5. Comparison of BCF and IDM Part 2

IDM Part 2 specifies a methodology and XML format for describing coordination actions between actors in the construction industry [12] and is currently being used most intensively in the Netherlands under the name VISI to manage contractual agreements [22]. It has similarities to BCF, but IDM Part 2 also addresses predefined workflows, conditions, user rights, roles and organisations – features missing from the BCF format as described above. IDM Part 2 uses an extension schema to include an ability to predefine transactions and the messages required to support them. The extension schema can also be used to predefine most other attributes of the specification, and the intention therefore is to define process information more rigidly than was intended for BCF.

Table 3 compares the specifications of the two standards and identifies similarities and differences in BCF and IDM Part 2. The comparison shows that the two standards have many similarities, with workflow support in IDM Part 2 and BIM support in BCF being the main differences. However, neither standard is superior to the other when their abilities are compared with the requirements identified in Table 1. The requirements list both predefined workflows and BIM support as needed, along with a number of the elements and attributes that are present in one or other of the two standards. This suggests it might be best to try for a harmonisation of the two standards rather than selecting either one.

IDM Part 2 is based on organising transactions and messages in predefined or at least hierarchical order. This can be valuable in documenting agreements, but it runs the risk of making everyday tasks overly complicated to define. In this light, it is better to use the BCF specification as the starting point for a harmonisation, and to use the principles from IDM Part 2 to add additional methodology and attributes.

When parts of IDM Part 2 are implemented, the hierarchical relationships required by the specification should be avoided because they do not match the needs in other design activities. Instead, the focus should be on adding missing attributes and support for defining hierarchical relationships on top of the crosswise relationships.

Table 3: Comparison of the specifications for bcfXMLv2 and IDM Part 2: 2012

Functionality	**bcfXML v2**	**IDM Part 2: 2012**
Identification	GUIDs	Custom IDs
Extension schemas	Only enumerations for topic type, topic status, topic label, priority, users and snippet types	Extensive schema for entire specification incl. enumerations, workflows, user and roles, conditions etc.
Ease of use	Simple XML structure	More complex XML structure with several relationships required
User Management	Managed only by names	Unique users can be linked to roles and organisations
Topic Definition	ID, Title, Description, References, Priority, Labels, Index	Similar to BCF, but no priority or labels can be assigned. Topics can be predefined as required transactions or messages.
Workflow	Only a assigned user can be defined	Can be predefined with fixed workflows, statuses, conditions, roles and responsibilities
Task relationships	Simple crosswise 1:1 relationships	Hierarchical relationships but not crosswise relationships
Status	Simple status and date stamp	Status, state, send and received log and date stamp
Comments and notifications	Only comments supported	Comments supported as elements, notification requirements only as a Boolean value
Document support	Support for documents management internally or externally.	Support for documents management externally. Richer metadata compared to BCF.
Data exchange support	With snippets parts of any structured data can be exchanged	Only document support
BIM and viewpoint support	Direct linkage to IFC models and IFC objects and support for viewpoints	Not supported

6. Proposal for an information system for building design

To meet the information exchange needs to support task management, we have defined a proposal for an information system that captures and exchanges both product and process information. Centralising the management of process information on a task management server has proven valuable in relation to providing a quick overview on the status of a project and allowing for continuous commenting [11]. The idea of using a task management server is aligned with the previously described reasons for developing the bcfAPI web service to avoid BCF file exchange. However, researchers have also concluded [11] that it is a challenge to manage confidential information from different companies on a central server and have suggested a decentralised approach to overcome this problem. In recent years, a similar challenge has been discussed in the field of management of product information on model servers. Here, research has shown that a decentralised solution is more appropriate with model servers used only as reference models to one another [10], [23]. The conclusion is that there is only a limited need to edit work originating from other parties due to an already sharp split of responsibility. Harmonising the range of IFC interfaces in the different software tools to allow for error-free interoperability during editing and round-tripping of product information therefore still seems too resource-intensive to be attractive to the AEC industry.

Managing process information differs to some extent from managing product information because different parties need to be involved in process-related activities across different platforms as identified in Table 1. Specific users will need access to more than one server to manage different types of tasks – often using individual tools for each specific activity. Workflows and user rights on each platform or server might restrict different users in what they are allowed to do, but users from different domains need to be engaged in most activities. However, securing full interoperability between the different types of process activities and task servers seems of limited value as long as information is available for reference, e.g. to generate an overview of the project status or to generate new tasks based on existing ones. This is similar to the setup for model servers promoting the need for a decentralised server setup also for task servers.

In such a setup, the tools to manage process activities could be directly focused on carrying out a specific process activity and complying with the requirements in Table 1 of being easy to use and including guided workflows and leverage knowledge. The tools could use BCF to communicate with their dedicated server and, where a tool needs information on tasks from others servers, they could use BCF to query other servers for the information required.

A proposal for a setup with decentralised model servers and task servers is illustrated in Figure 1.

Each of the process activities is handled by one or more tools communicating with one or more task servers. Each task server can contain its own user management setup, workflow definitions and document storage to function independently. Preferably, the bcfAPI will be used to exchange information with the different tools and link the different servers to act as a coherent information system.

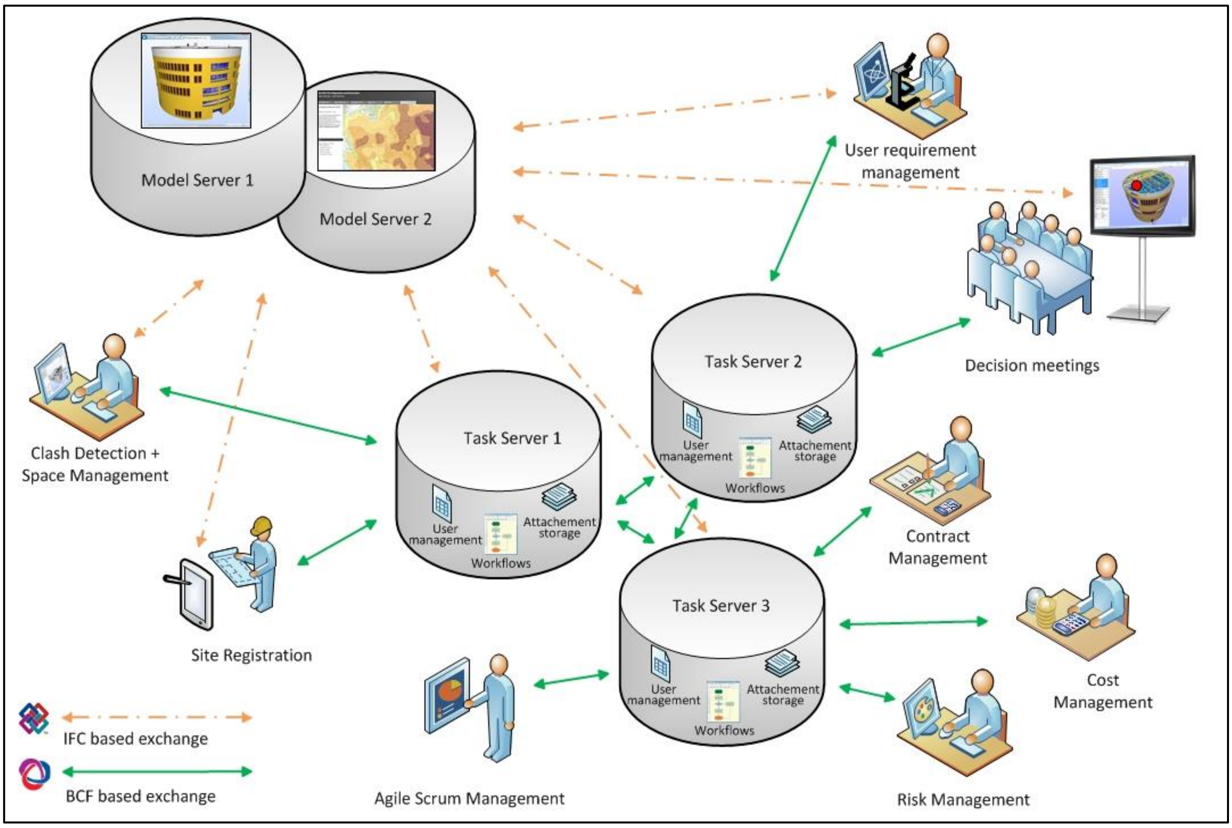


Figure 1: Proposal for information management and exchange in building design

Product information is collected, preferably using IFC exchange, from one or more model servers, as already proposed elsewhere [10], [23]. If required by the client or others, predefined workflows, required users and other conditions could be exchanged by implementing elements from IDM Part 2 in BCF to ensure consistent workflows across different platforms.

Should a project manager need e.g. to evaluate the overall project status or investigate why a certain area of a building or type of building component is causing problems, he or she will use a tool that, either by itself or via a task server, queries the other task servers to collect the task information required. To support such a setup, it would be preferable if the BCF specification used URIs (e.g. *https://server.com/bcf/projects/F445F4F2-4D02-4B2A-B612-5E456BEF9137/topics/B345F4F2-3A04-B43B-A713-5E456BEF8228*) instead of just GUIDs (e.g. B345F4F2-3A04-B43B-A713-5E456BEF8228) to identify not only the unique tasks but also the location of the task. This would ensure that any system would know exactly where the original task is located and should be updated, if required. It would also be beneficial if bcfAPI could be expanded to include standardised query calls, e.g. to present every task on a server that addresses a specific IFC object or contains a specific word in its title or description.

Practical implementation will be required to further evaluate how well BCF supports the proposed setup, but we did not identify any other aspects of the current BCF specification that would require adjustments for the setup to be supported.

7. Potential expansion of the BCF specification

One main advantage of the BCF format is its simple structure, which makes it easy to understand and implement [10], [11]. Expanding the scope of the BCF specification to include contract management methodology from IDM Part 2 or support of other process-related activities will make the specification more complex and potentially limit some of its current momentum in the industry at both implementer and practitioner level. The IFC specification was originally challenged by the same need to expand, so a layer-architecture was defined that provides the data schema with a modular structure to ease future development and allow for implementation to be selective and reusable [24].

The data schema structure has a resource layer at the bottom, a core layer in the middle, and an interoperability layer and a domain layer on top [7]. Fundamental structures and classes are defined in the core layer, and shared classes are defined in the interoperability layer. Domain-specific classes are defined in the domain layer, and resource definitions used in other layers are defined in the resource layer. The architecture is built on a “ladder principle” [24]. At any layer, a class may reference a class in the same or a lower layer, but may not reference a class from a higher layer. This allows for software implementation to be selective, because implementation of a class (in most cases) requires only implementation of the class and classes in lower layers.

If the BCF format is expanded, a similar architecture could be applied to achieve similar benefits. In the light of the findings in this paper, a proposal for a BCF data schema architecture was developed and is illustrated in Figure 2. There is a core part of BCF that is needed to support the requirements identified and the use cases illustrated. This includes definition of the topic, users involved, dates, commenting, simple relationships and, to support the requirements of IDM Part 2, hierarchical relationships. Together, these constitute the core layer. In the interoperability layer, linkage to documents, BIM and data snippets are defined because these are applicable to many activities. The domain layer from IFC is here called the activity layer because it represents definitions for specific process-related activities, such as contract, cost or risk management. For example, the activity schema for cost

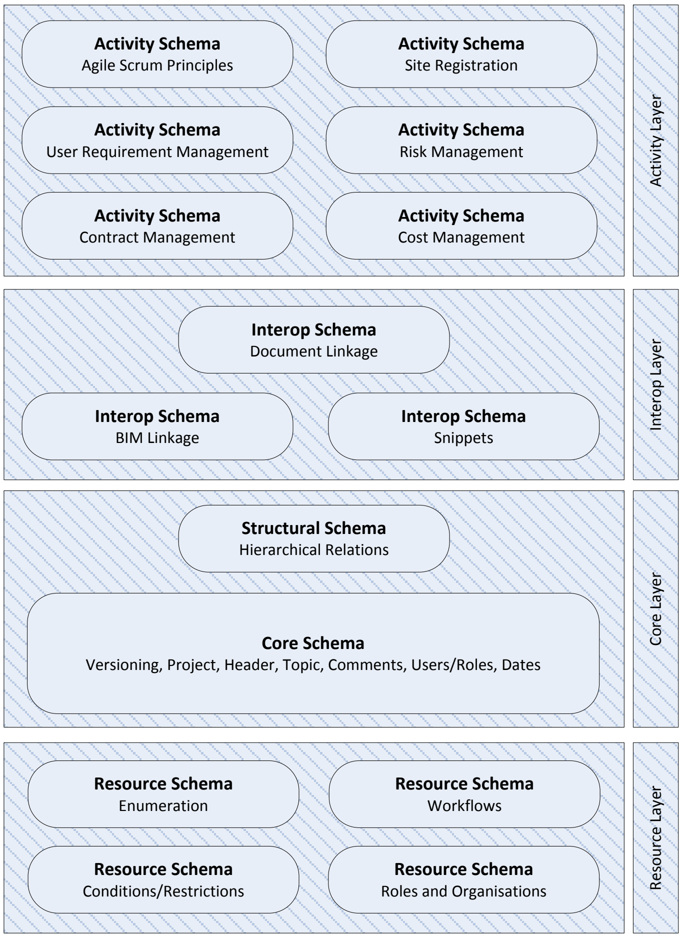


Figure 2: Proposal for an expanded BCF data schema architecture

management could include attributes for the cost of services or contracts, and for contract management the schema could include attributes for the send and receive log.

In the resource layer, expansions to incorporate several of the additional options of IDM Part 2 could be included because these can act as support for several activities. The resources could include options to define workflows, conditions, roles and enumerations for selected attributes. The six activity schemas are examples of activities that could be implemented, but actual industry needs should define the priorities for implementation. In the light of the findings in section 4, implementing missing elements from IDM Part 2 would in itself address most of the current needs of the industry.

At the same time, moderation in the range of activities supported should be considered to keep the specification simple. The existing functionality of BIM Snippets, which provides an option to exchange parts of a different data structure, could be used not only to exchange BIM data, but any relevant data. For example, a workflow defined in the BPMN format [25] could be attached as a *Snippet*, instead of requiring an extension of BCF to define complex workflows. In the light of the literature reviewed in this paper, there seems to be a difference between when an activity requires only one or more attributes to be fully supported by BCF and when it requires significant expansions to BCF to be supported. In the latter case, the use of snippets should be considered. Implementing workflows in BCF could therefore be done by defining a resource schema for simple transactional workflows in BCF and promoting an implementers' agreement to use BPMN to support more advanced workflows. BPMN shares significantly fewer similarities with BCF than IDM Part 2, which makes harmonisation less attractive.

8. Conclusions

Expanding the BCF specification will allow BCF to support the exchange of information for a broader range of process activities and add considerable value in an open and decentralised information system for the AEC industry. Using the IDM Part 2 specification as a starting point will support several key needs of the industry. The current BCF specification has limitations and the current implementation is error-prone. Along with an expansion of the specification, a certification solution similar to the official IFC certification should be considered. As with the IFC certification, a BCF certification could start by focusing on support for elements and attributes in the proposed core and interoperability layers. Practical testing of the proposed setup and BCF specification architecture will be required to determine the desired rate and direction of an expansion.

9. Acknowledgements

We would like to thank Léon van Berlo from TNO, Klaus Linhard and Georg Dangl from iabi, and Ruben Blair from Bakker & Spees for sharing their knowledge on BCF and IDM Part 2 and engaging in valuable discussion on the research topic.

10. References

[1] E. Pikas, L. Koskela, M. Thalfeldt, B. Dave, and J. Kurnitski, "Complexity in Designing Energy Efficient Buildings : Towards Understanding Decision Networks," in *Proceedings of IGLC23 – 23rd Annual Conference of the International Group for Lean Construction* (2015) pp. 213–222.

[2] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, 2nd Ed. (2011)

[3] L. Koskela, "An Exploration towards a Production Theory and its Application to Construction," *VTT Publications* (2000)

[4] J. M. Chachere, J. Kunz, and R. Levitt, "The Role of Reduced Latency in Integrated Concurrent Engineering," *CIFE Working Paper*, no. 116, April (2009)

[5] J. Sutherland, *The art of doing twice the work in half the time*. New York, US: Crown Business, 2014.

[6] L. Koskela, P. Huovila, J. Leinonen, "Design Management In Building Construction : From Theory To Practice," *J. Constr. Res.*, vol. 03, no. 01 (2002), 1–16

[7] BuildingSMART, "Industry Foundation Classes - Version 4 - Addendum 1," (2015). [Online]. Available: http://www.buildingsmart-tech.org/ifc/IFC4/Add1/html/. [Accessed: 19-Jul-2016].

[8] BuildingSMART, "BCF intro," (2016) [Online]. Available: http://www.buildingsmart-tech.org/specifications/bcf-releases/bcf-intro. [Accessed: 19-Jul-2016].

[9] BCF Implementer Support Group, "XML specification for BIM Collaboration Format" (2016) [Online]. Available: https://github.com/BuildingSMART/BCF-XML. [Accessed: 19-Jul-2016].

[10] K. Lindhard and R. Steinmann, "BIM-collaboration processes - from fuzziness to practical implementation," in *European Conferences On Product And Process Modeling In The Building Industry (ECPPM)* (2014), 27–32

[11] L. van Berlo and T. Krijnen, "Using the BIM Collaboration Format in a Server Based Workflow," *Procedia Environ. Sci.*, vol. 22 (2014), 325–332

[12] ISO 29481-2, *Building information models - Information delivery manual - Part 2: Interaction framework*, Geneva (2012)

[13] *U106, Digital Mangelinformation (in Danish)*. Herlev, Denmark (2014)

[14] M. H. Parsianfar, "Open formats in a communication system," Technical University of Denmark, Kgs. Lyngby (2016)

[15] S.-A. Kim, Y. Choe, M. Jang, and W. Seol, "Design process visualization system intergrating BIM data and performance-oriented design information," *Proc. 28th Int. Symp. Autom. Robot. Constr.* (2011), 728–733

[16] S. Bertelsen, "Construction as a complex system," *Proc. IGLC*, vol. 11 (2003), 143–168

[17] M. T. Shafiq, J. Matthews, and S. R. Lockley, "A study of BIM collaboration requirements and available features in existing model collaboration systems," *J. Inf. Technol. Constr.*, vol. 18 (2013), 148–161

[18] P. Coates, Y. Arayici, L. Koskela, M. Kagioglou, et al. "The limitations of BIM in the architectural process," *First Int. Conf. Sustain. Urban. (ICSU 2010)*, no. December (2009), 9

[19] M.T. Shafiq, J. Matthews and S. Lockley, "Requirements for model server enabled collaborating on building information models," *First UK Acad. Conf. on BIM, 5–7 Sept. 2012, Northumbria Univ. Newcastle upon Tyne, UK* (2012)

[20] S. G. Yeomans, N. M. Bouchlaghem and A. El-Hamalawi, "Provisions for proficient Construction Project Extranet Protocols to facilitate Collaborative Extranet Working," *Proc. 22nd CIB-W78 Conf. Inf. Technol. Constr. Dresden, Ger.* (2005), 155–162

[21] BuildingSMART, "BIM Collaboration Format v2.0 Technical Documentation," *GitHub* (2015). [Online]. Available: https://github.com/BuildingSMART/BCF-XML/tree/master/Documentation. [Accessed: 22-Jun-2016].

[22] J. G. Hoeber, D. M. Alsem, P. H. Willems, "The management of information over the life-cycle of a construction project using open-standard BIM," *Proc. of the 32nd CIB W78 Conference, Eindhoven, The Netherlands* (2015), 295–301

[23] L. A. H. M. van Berlo, J. Beetz, P. Bos, H. Hendriks, and R. C. J. van Tongeren, "Collaborative engineering with IFC : new insights and technology," in *European Conferences On Product And Process Modeling In The Building Industry (ECPPM)* (2012), 811–818.

[24] IAI, "IFC Object Model Guide," International Alliance of Interoperability (1999)

[25] OMG, "Business Process Model and Notation (BPMN) Version 2.0," Needham, US (2011)

This thesis focuses on solutions to improve digitalization and integration in the building design process. The research draws on findings from previous research on information management, design management and socio-technical science and focuses in particular on an improved foundation for efficient planning and decision making processes.

Based on a range of case studies, interviews, surveys and development experiments, a design management methodology is proposed. The methodology contains information models for the mission, function, product, and process (MFPP) for building projects to summarize the findings in this research in a combined contribution to further research and development. The methodology is a pragmatic approach to more extensive PLM systems used in the manufacturing industry and incorporates an agile design development process. The MFPP methodology can serve as contribution to how several design and information theories and methods can be integrated into a common approach for efficient building design management.

DTU Civil Engineering
Department of Civil Engineering
Technical University of Denmark

Brovej, Building 118
2800 Kongens Lyngby
Denmark
Tel. +45 4525 1700

www.byg.dtu.dk

ISBN: 978-87-7877-461-3
ISSN: 1601-2917