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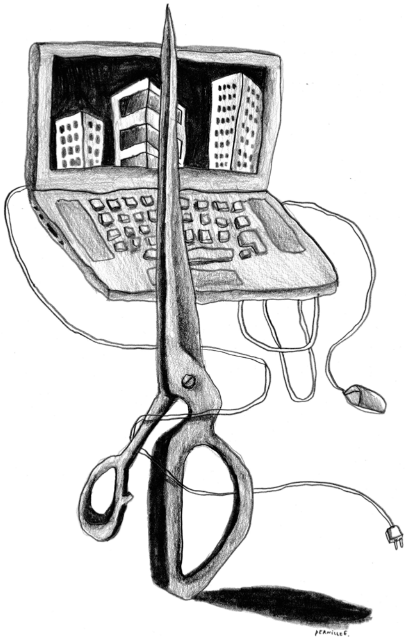

ECOLOGICAL BIM-BASED MODEL CHECKING

BY
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DISSERTATION SUBMITTED 2020

AALBORG UNIVERSITY
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ENGLISH SUMMARY

This project is motivated by the challenges experienced by the designers creating building designs. Designers often encounter challenges related to creating a building design that complies with a complex network of requirements from users, clients, and legislation. They compete in creating a design that meets these requirements but is challenged in ensuring that it complies with the requirements with the limited resources available. The high complexity and lack of resources make it difficult to ensure a sufficient quality of building design and consequently building designs lack quality and are subject to delays, which increases the cost of the finished building.

BIM-based Model Checking (BMC) can be used to automate a design assessment according to a set of rules to assist designers in creating better building designs. The design is formalized as a BIM-model that enables a mechanism to check if it complies with rules derived from the requirements — for example, rules for building codes, sustainability, or client requirements. Automating the design assessment can improve the speed, consistency, and precision, which could reduce design-rule non-compliance, potentially leading to better design quality using fewer resources.

Software developers and governmental agencies have created comprehensive BMC systems to improve the building assessment processes, mainly focused on subsets of building codes. However, the BMC systems have proven difficult to integrate into practice. While BMC systems encompass a potential to improve the design of buildings, it is indicated that there exist various socio-technical challenges for BMC systems to accommodate building design practices. Little effort has been made to study the use of BMC systems in practice, and research has mainly been focused on the technical aspects of BMC.

Design science research (DSR) methodology was used to investigate how to improve the practical use of BMC systems. DSR is a methodology that is primarily used in the domain of information systems research and contributes to guidelines for the design and evaluation of information systems research. The focus of using DSR is to develop an artifact (such as a

software prototype) that improves functional performance. The use of DSR entails a pragmatic approach to research by understanding and improving human practice. The understanding of human practice is built on the tradition of behavioral science, which focuses on explaining and predicting organizational and human phenomena. Improving human practice is built on the tradition of design science, which focuses on problem-solving to create innovations through the analysis, implementation, management, and use of information technology systems. DSR advocates that both behavioral and design sciences are integral to information systems research and builds on the tradition of pragmatics that the truth (justified theory) and utility (effective artifacts) of a system such as BMC should be evaluated according to the practical implications of its use.

Following the DSR methodology, the project investigates the use of BIM-based Model Checking (BMC) systems. The investigations were conducted through interviews, experiments, and observations that were used to inform the design and development of a BMC software prototype that was then evaluated with practitioners. The investigation identified that transparency, flexibility, and trust were important characteristics of a BMC system allowing proper use. The designers were required to understand the rationales of the decisions they made using BIM systems because they needed to make frequent changes, which demanded a continuous need to retool the BMC systems.

The designers would attempt to circumvent the information processes of the systems to ensure that the automation would match their environment. However, the failure to adapt the systems led to their restricted use or rejection. If a system were able to provide for changes to be manifested, it could accommodate the designer’s unique requirements for their businesses and projects. When the changes could be made, the automation from the system could provide the designers with results that matched their specific environment.

The challenges identified indicated that there was a need to approach the automation processes in BIM systems such as BMC differently. In much engineering research, the theory of rational choice is a dominant research perspective and works very well in many domains such as building statics. Theory of rational choice as: *to take a measured decision aimed at the* *realization of a particular goal, as in attempts to optimize an objective function* (Franssen and Bucciarelli 2004 p. 1).

However, when the rational choice theory is used in other domains that are subject to much uncertainty, such as the design process of buildings, such a perspective can be problematic. The design process of buildings is characterized as being emergent, dynamic, complex, chaotic, and subject to many uncertainties. It has been identified that people do not act rationally from a rational choice theory perspective but act on rationality from their context based on their goals and conditions. Such perspective opens up a plethora of potential variables related to assessing building designs according to rules.

Accommodating the potential variables related to making decisions on, e.g., the sustainability of a building would require a highly complex system that would be difficult and expensive to maintain. Moreover, the results of such a system would often not meet the requirements of the user's context of the project and the results that were intended to assist designers can therefore be rejected, misused or cause negative effects on the projects.

In this thesis, as an alternative, Ecological BMC is proposed, not built on rational choice theory but on ecological rationality to improve its practical usability. Ecological rationality brings forward the context of the rationality, formalized as statements used in BMC systems. What is rational in one context might not be in another, and therefore, an ecological rational approach makes use of heuristics because they can be ecologically rational to the degree that they are adapted to the context.

Heuristics are cognitive strategies to solve a problem by ignoring parts of the information, and do not try to optimize a solution. Instead, the focus is on finding a good enough heuristic for the context in which it is used. The ecological rational approach of heuristics is suitable for "large world" domains that are characterized as being very uncertain, containing many alternatives, and having limited data, such as many aspects of the building design process. Formalized heuristics can be used as rules and provide practical alternatives to the existing approaches of formalized rationalities in existing BMC systems.

In the development of an ecological BMC prototype, business process management (BPM), and process-aware information systems (PAIS) theories were applied. Both theories are related to the ecological rational perspective and aim to increase the flexibility of information systems primarily to ensure the adaptability of the systems to the practices where the systems are used. The first prototype made use of software components already known to the construction industry, the BIM-authoring system Autodesk Revit and the visual programming system Dynamo. The testing revealed that the flexibility was improved through better visualization of the information used in the BMC prototype, enabling the user to understand and adapt the system to the context of his project.

However, the software components did not properly allow for the flexibility needs of the practitioners to appropriately manage the information used in the prototype. A second prototype was made to improve the previously identified issues using the BPM software Bizagi as the checking mechanism and BIMserver as an IFC repository. This prototype allowed better management of the changing information related to the automated assessment. While the second prototype provided better maintainability.

The results from the study suggest that the use of BMC systems has the potential to improve building design practices but needs to be more flexible to enable the designer’s practices to incorporate changes into the system. The ability to incorporate changes into the system can potentially improve its use, making the results more relevant for both the designers’ organizations and the designers themselves. Thereby, moving away from the current inflexible handling of information in the BMC systems allows the automation of resource-demanding tasks such as assessing the building design faster, more precisely and consistently, resulting in fewer design flaws and better buildings using fewer resources.

DANISH SUMMARY

Dette projekt er motiveret af de udfordringer som designerne oplever med at skabe bygningsdesign. Designere støder ofte på udfordringer i forhold til at overholde de komplekse krav fra brugere, bygherre og lovgivningen. Designerne konkurrerer indbyrdes om at skabe designs der opfylder disse krav, men er udfordret af begrænsede ressourcer der er til rådighed. Den høje kompleksitet og mangel på ressourcer gør det vanskeligt at sikre en tilstrækkelig kvalitet i bygningsdesignet, og derfor mangler designet kvalitet og er forsinket, hvilket øger omkostningerne ved den færdige bygning.

BIM-baserede Model Tjek (BMC) kan bruges til at automatisere design evalueringer i henhold til et sæt regler for at hjælpe designere med at skabe bedre byggedesign. Designet er formaliseret som en BIM-model, der gør det muligt for en mekanisme at kontrollere, om den overholder regler udledt af kravene - for eksempel regler for bygningsreglementet, bæredygtighed eller krav fra bygherren. Automatisering af designevalueringen kan forbedre hastigheden, konsistensen og præcisionen, hvilket kan reducere uoverensstemmelserne imellem designet og reglerne, hvilket potentielt fører til bedre designkvalitet ved hjælp af færre ressourcer.

Softwareudviklere og statslige organer har skabt BMC-systemer til forbedring af byggeevalueringsprocesserne, primært fokuseret på bygningsreglementer. BMC-systemerne har imidlertid vist sig vanskeligt at integrere i praksis. Mens BMC-systemer har potentialet til at forbedre bygningernes design, findes der flere tekniske og sociokulturelle udfordringer der skal løses før at BMC-systemer kan integreres i praksis. I forskningen er der ikke gjort nogen indsats for at studere brugen af BMC-systemer i praksis, og har hovedsagelig været fokuseret på BMC's tekniske aspekter.

For at undersøge hvordan man kan forbedre den praktiske anvendelse af BMC-systemer er Design Science Reserach (DSR) metrologien blevet brugt. DSR er en metode, der primært anvendes inden for forskning af informationssystemer og bidrager til retningslinjer for design og evaluering

af informationssystemsforskning. DSR er blevet brugt til at udvikle et artefakt (f.eks. en software prototype) der forbedre en praksis. Brugen af DSR indebærer en pragmatisk tilgang til forskningen ved at prøve at forstå og forbedre menneskelig praksis. Forståelsen af menneskelig praksis er bygget på traditionen for adfærdsvidenskab, der fokuserer på at forklare og forudsige organisatoriske og menneskelige fænomener.

Selve forbedring af menneskelig praksis bygger på en designvidenskabelig tradition, der fokuserer på problemløsning via nyskabelser gennem analyse, implementering, styring og anvendelse af informationsteknologisystemer. DSR går ind for, at både adfærds- og designvidenskab er integreret i informationssystemforskning og er baseret på den pragmatiske forskningstradition der forudsætter at sandheden (anvendelse af relevante teorier) og anvendelighed (effektive artefakter) af et system som BMC skal evalueres i overensstemmelse med de praktiske konsekvenser af dets brug.

Efter DSR-metodens forskrifter bliver brugen af BMC-systemer undersøgt. Undersøgelserne blev gennemført igennem interviews, eksperimenter og observationer, der blev brugt til at informere design og udvikling af en BMC-prototyper, der blev evalueret af design praktikere. Undersøgelsen viste, at gennemsigtighed, fleksibilitet og tillid var vigtige karakteristika ved et BMC-system, der muliggjorde bedre praktisk anvendelse. Designerne blev gjort i stand til at forstå rationalerne af de beslutninger, de lavede ved hjælp af BMC-systemer.

Designerne havde også brug for at foretage hyppige ændringer, hvilket krævede et behov for at tilpasse BMC-systemerne. Designerne ville forsøge at omgå informationsprocesserne i BMC-systemerne for at sikre, at automatiseringen ville matche deres miljø. Manglende tilpasning af BMC-systemerne førte imidlertid til deres begrænsede anvendelse eller afvisning af systemet. Hvis et BMC-system var i stand til at facilitere ændringerne i systemet, kunne systemet rumme designers unikke krav til deres virksomheder og projekter. Når ændringerne kunne foretages, kunne automatiseringen fra BMC-systemet give designerne resultater, der matchede deres specifikke miljø.

Udfordringer viste, at der var behov for at håndtere automatiseringsprocesserne anderledes. Inden for det naturvidenskabelige område er teorien om rationalitet et dominerende perspektiv og fungerer godt inden for begrænsede og specifikke områder som bygningsstatistik. Men når det anvendes i andre domæner, der er udsat for stor usikkerhed, såsom mange andre aspekter i designprocessen af bygninger, kan et sådant perspektiv være problematisk. Designprocessen af bygninger er karakteriseret som dynamisk, kompleks, kaotisk og underlagt mange usikkerheder. At imødekomme de potentielt mange variabler i forbindelse med at tage beslutninger om fx bæredygtigheden ville kræve et meget komplekst system, som ville være vanskeligt og dyrt at vedligeholde. Desuden vil resultaterne af et sådant system ofte ikke opfylde kravene i projektets sammenhæng, og resultaterne, der skulle hjælpe designere, blev derfor afvist.

Som et alternativ foreslås økologisk BMC, der ikke er bygget på et traditionelt rationelt perspektiv, men på et økologisk rationelt perspektiv for at forbedre dets praktiske anvendelighed. Økologisk rationalitet fremmer konteksten af rationaliteten, formaliseret som udsagn anvendt i BMC-systemer. Hvad der er rationelt, er bestemt af det sammenhæng det forekommer i. Derfor anvender en økologisk rationel tilgang heuristikker, fordi de kan være økologisk rationelle i den grad, de er tilpasset til konteksten.

En heuristik er en kognitiv strategi brugt til at løse et problem ved at ignorere dele af informationerne og ved ikke forsøge at optimere en løsning. I stedet er fokus at finde en god nok heuristik for en bestemt kontekst. Den økologisk rationelle tilgang til heuristik er egnet til "store-verden" domæner, der er karakteriseret som meget usikre, indeholder mange alternativer og har begrænsede data. Lignende ”store-verden” karakteristika er dominerende i byggebranchen hvor heuristikker allerede bliver anvendt af bygningsprofessionelle. Et større fokus på at bruge heuristikkerne i oversættelsen af regler til BMC-systemer kan give et praktisk alternativ til eksisterende tilgange.

I udviklingen af en økologisk BMC-prototype blev processer for forretningsprocesstyring (BPM) og procesbevidste informationssystemer (PAIS) anvendt. Begge teorier er relateret til det økologiske rationelle perspektiv og sigter mod at øge informationssystemernes fleksibilitet primært for at sikre systemernes tilpasning til de metoder, hvor systemerne anvendes. Den første prototype benyttede softwarekomponenter, der allerede er kendt for byggebranchen, BIM-værktøjet Autodesk Revit og det visuelle programmeringssystem Dynamo. Evalueringen viste, at fleksibiliteten blev forbedret gennem bedre visualisering af de oplysninger, der blev brugt i BMC prototypen, hvilket gør det muligt for brugeren at forstå og tilpasse systemet til konteksten for sit projekt.

Softwarekomponenterne tillod imidlertid ikke nok fleksibilitet jf. brugernes behov til korrekt at håndtere de oplysninger, der blev brugt i prototypen. En anden prototype blev lavet for at forbedre de tidligere identificerede problemer ved brug af BPM-softwaren Bizagi som kontrolmekanismen og BIMserver som et IFC-lager informationslager. Prototypen muliggjorde bedre styring af de skiftende oplysninger i forbindelse med den automatiserede vurdering. Mens den anden prototype gav bedre vedligeholdelse.

Resultaterne fra undersøgelsen tyder på, at brugen af BMC-systemer har potentialet til at forbedre byggepraksis, men skal være mere fleksibel for at gøre det muligt for designerens praksis at indarbejde ændringer i systemet. Evnen til at indarbejde ændringer i systemet kan potentielt forbedre dens anvendelse, hvilket gør resultaterne mere relevante for både designernes organisationer og designerne selv. Derved kan bevægelsen væk fra den nuværende ufleksible håndtering af information i BMC-systemerne automatisere ressourcekrævende opgaver som at vurdere bygningens design hurtigere, mere præcist og konsekvent, hvilket resulterer i færre designfejl og bedre bygninger ved hjælp af færre ressourcer.

PREFACE

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Peter Nørkjær Gade
Aalborg University, 2020

THESIS OUTLINE

The thesis is based on papers that have been integrated into the main body of the thesis. The papers integrated into the thesis range from I-V and are presented below:

Paper I: *A Holistic Analysis of a BIM-mediated Building Design Process using Activity Theory.*
Published in *Journal of Construction Management and Economics*, November 2018.
Gade, Peter N; Gade, Anne N; Otrel-Cass, Kathrin; Svidt, Kjeld.

Paper II: *Analysis of DGNB-DK criteria for BIM-based Model Checking automatization*
Published as *DCE Technical Report No. 210*, August 2016.
Gade, Peter N; Jensen, Rasmus Lund; Svidt, Kjeld.

Paper III: *A business-based rule translation method used to translate sustainability rules.*
Submitted to the International Journal of Architectural Computing, February 2020.
Gade, Peter N; Jensen, Rasmus Lund; Svidt, Kjeld.

Paper IV: *Development and test of a flexible and transparent BIM-based Model Checking prototype.*
Accepted with revisions by the *Journal of Information Technology in Construction*, July 2019.
Gade, Peter N; Svidt, Kjeld.

Paper V: *BIM-Based Model Checking in a Business Process Management Environment.*
Presented and published in the proceedings of the *European Conference on Product & Process Modelling*, September 2018.
Gade, Peter N; Hansen, Ronni; Svidt, Kjeld.

CONTENTS

GLOSSARY

PAIS	Process-Aware Information Systems
BPM	Business Process Management
BIM	Building Information Modelling
BMC	BIM-based Model Checking
IFC	Industry Foundation Classes – An open data model for the construction industry
DSR	Design Science Research
AT	Activity Theory
HCI	Human Computer Interaction
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
BREEAM	Building Research Establishment Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design
BCA	Building and Construction Authority – in Singapore
DK-GBC	Green Building Council Denmark
Holistic	The relation to whole or complete systems rather than the dissection of parts
Bounded rationality	An idea that the rationality of decisions is limited by time and the cognitive abilities of the decision-maker
Ecological	Interactions between individual organisms and their environments

Ecological rationality	Is a practical rationality that is based on the notion that what is rational is based on its context and therefore cannot be normative.
Normative	Prescriptive statements that determinates norms or standards that are insensitive to the context
Heuristic	A practical approach to solving problems, e.g., rule-of-thumb, guesstimate, stereotyping, educated guesses or intuitive judgments
Satisficing	A heuristic focusing on searching through available solutions until an acceptable threshold is met
KPI	Key Performance Indicator
Revit	BIM-authoring software from Autocad
Dynamo	Visual programming software package used in the construction industry embedded in Revit
Point-cloud	A set of data points (x,y,z) created using 3D scanners that forms a cloud.
Lumion	Architectural rendering software
Vico Office	Price estimation software from Trimble
Ecotect	Sustainable building design software from Autocad discontinued in 2015
Bizagi Studio	BPM software used to automate processes
BIMserver	Open-source IFC-hosting software
Solibri	Solibri Model Checker (SMC) – Commercially available BMC software

1. INTRODUCTION

Designing buildings is a complex and comprehensive process that often leads to errors, making the buildings more expensive and causing them to perform less well. Performance requirements are continually rising to ensure that buildings become more sustainable, safer, and provide better services. Especially sustainability in buildings is becoming more popular ("A Second Look at Green Buildings: The Rise of Certifications around the World" 2011).

This demand is related to increased societal interest in the environment, a reduction in lifetime cost, and for reputational reasons (Nelson, Rakau, and Dörrenberg, 2010; Häkkinen, 2012), which manifest themselves in, e.g., legislative requirements (Azhar et al. 2008; Schlueter and Thesseling 2009). The industry has developed building assessment methods to support the development of sustainable buildings in order to standardize the evaluation of building performance with regard to sustainability and quality (Häkkinen 2012). These methods set multiple requirements for buildings to make them more sustainable.

While the increased requirements for sustainability enable designers to guide their design better to become more sustainable, they further increase the complexity of the design process. Ideally, the building design must be optimized regarding the sustainability assessment methods. However, such a process is subject to comprehensive consideration and embeds much complexity and uncertainty, which are difficult for designers to manage (Bragança, Mateus, and Koukkari, 2010).

According to Attia *et al*. (2017), inadequate design quality is responsible for the poor sustainable performance of buildings, and was identified as being related to inappropriate use of heuristics (mental strategies to solve problems) and a lack of properly integrated calculation-based design approaches. One of the typical mistakes is over-reliance on calculation-based results, without a critical view of their intrinsic uncertainty. Still, design flaws in building designs are responsible for more than 14 % of the mean cost of buildings (Lopez and Love 2012).

To improve the quality of the building designs, Building Information Modelling (BIM) is used to improve the exchange of information related to a building's life-cycle (Eastman et al. 2011) and has the potential to improve many aspects of the design process related to sustainability, including improved cross-disciplinary communication and reducing design task redundancy (Krygiel and Nies 2008).

The BIM-related concept of BIM-based Model Checking (BMC) makes use of the BIM models (digital representations of the design) created in the BIM process to automate the checking of the BIM model for conformity according to a set of specified rules (Hjelseth 2016). These rules are specified by the translation of, e.g., standards or manuals into computer executable statements. Using BMC systems can improve the designer's ability to identify inconsistencies between the design and the rules derived from the requirements in, e.g., sustainability assessment methods or building codes (Eastman et al. 2009).

BMC solutions can potentially improve several critical aspects of the design process by automating tasks related to assessing the design. Hence, the potential of using BMC solutions in design practices entails the computerization of the core aspects of the building design process as a complex and comprehensive undertaking. The basic premise of translating rules intended for human use into computerized rules necessitates that *"the computable model for code representation must possess enough elasticity and expressiveness to capture most of the provisions, similar to how a child grows from a simple stage to a more sophisticated stage without relearning everything from scratch: each stage from infancy to adulthood adds new skills by extending, refining, and building on the earlier representations and operations."* (Nawari, 2012, p. 291). Representing the rules in BMC solutions for execution to provide designers with feedback on their building design extends beyond the mechanism itself, to include also how it is maintained over time and can adapt to new situations of its use.

The early development of the checking elements in the concept known as BMC was initiated back in the mid-sixties by Fenves (1966). Fenves utilized a tabular decision logic to optimize the structural design of a building. Since then, the focus has been on the utilization of increasing computational capabilities to process information and the structured project and building design information located in BIM models. The research within the domain of BMC is primarily aimed towards the building code domain (Dimyadi and Amor 2013). In the domain of sustainability, some BMC research exists (Beach et al. 2015; Kasim 2015), but there are no commercially available BMC systems for sustainability. A few BMC systems exist that can conduct basic BIM model checking, such as Solibri Model Checker, which can assist designers with an assessment of geometrical collisions and information consistency in the BIM model. Other systems contain functionalities related to BMC, like Navisworks, which can detect inconsistencies between geometries.

Despite the potential of BMC to improve the quality of building designs, many BMC solutions are inhibited in their use in design practices (Dimyadi et al. 2016b; a; Dimyadi and Amor 2013; Hjelseth 2015a). The problems with the development and use of BMC solutions are based on various aspects of socio-technical challenges (Beach et al. 2015; Kasim 2015; Refvik et al. 2014), which are related to the human social and organizational factors of using technology (like BMC) (Baxter and Sommerville 2011).

Socio-technical challenges are related to a the collection of messy, complex problems related to the interaction between people and technology (Dwyer 2011). Much of the focus in the development of BMC has been on the technical aspect (Dimyadi and Amor 2013), yet the issues that inhibit its practical use have been identified as being of a “soft” socio-technical nature (Refvik et al. 2014).

Some of the challenges have been pinpointed as being related to representing and accessing the knowledge that is formalized as computer-readable rules, for example, multiple paths to compliance, or ambiguity in regulatory documents and implicit regulatory knowledge (Dimyadi et al. 2016b). However, very few studies are concerned with investigating these “soft” issues, which are reduced to being related to an isolated matter of implementation (Refvik et al. 2014) and currently there exist only limited empirical studies of BMC practices (Preidel et al. 2017). In the process of automating complex processes, failing to recognise and deal with the “soft” issues can lead to unintended consequences constraining the design.

This PhD project seeks to both investigate the “soft” issues and suggest how to improve the use of BIM-based Model Checking by focusing on the development of BMC prototypes that accommodate practically informed characteristics to enable better use. The research provides an in-depth investigation of how designers apply BIM-based solutions in the design process in order to better identify the characteristics of its environment that either enable or constrain the design process. The characteristics are used as a foundation for a further investigative inquiry on how designers are challenged in their manual work and how a successful BMC system has been implemented in practice. This insight has set the objectives for the development of a BMC prototype that aims to better support designers in both the translation and execution of rules specified in the sustainability assessment method.

2. RESEARCH DESIGN

This chapter presents how the research is designed in the thesis, including the background for the research question and methodology. The methodology section presents the logical procedures and thought processes that are applied for this thesis and provides an overall strategy of how the research questions were answered. This include a reasoning of the philosophy influencing the research regarding data collection and analysis. This reasoning is used to demonstrate the understanding of philosophical issues regarding the chosen stance. The choice of methodology regarding answering the research question is presented including how such stance sets limitations of the study and how it impacts how the sub-questions are asked.

2.1 THE RESEARCH QUESTION

BMC solutions have proven difficult to integrate into design practices (Dimyadi et al. 2016b; Hjelseth 2015a), and the reasons for this difficulty are multiple, including a range of socio-technical challenges. Still, most of the existing research is focused on either the technical aspects of BMC (e.g., using semantic technology for automating rule translation) or attempting to develop standards for rule formulation. Little emphasis has been given to investigating BMC solutions integrated into the design practices.

Nevertheless, scholars have indicated that the sources of the challenges of integrating BMC into the practices stem from socio-technical issues. According to Dr. Evelyn Teo at the University of Singapore, who has been involved in the ePlan-Check project, *“the technology is mature and available, it is the soft human aspects of organization, culture, and adoption of the technology that are the real challenges.”* (Refvik et al. 2014 p. 58). This quotation indicates that, technically, BMC systems are mature and can conduct model checks as intended.

However, it seems that practitioners often either reject or misuse the systems (Dimyadi and Amor 2013; Refvik et al. 2014) and these “soft” challenges are reduced to an issue of adoption. Because of that, the technology does not seem mature, and designers reject or misuse BMC systems because they contain characteristics that are problematic for them.

The contradictions between the current BMC solutions and practice has led to only a limited integration into design practices or even to downright rejection. For BMC solutions to be used in design practices to a greater extent, thereby increasing the effectiveness of the design processes, it is considered critical to investigate these contradictions. However, studies concerning these contradictions are currently few, and there is a limited exploration of them.

There are accounts of researchers interacting with practitioners to investigate general trends with BMC use (Hjelseth 2015a; Refvik et al. 2014). However, these accounts are based on limited numbers of interviewees and only included general questions about the use of BMC, like *"what is the most positive effect of using the model checking software?"* (Hjelseth 2015a). Also, other existing studies were based on students from BIM lectures using questionnaires (Preidel et al. 2017).

When BMC is put into practice, it becomes subject to multiple and unique contexts that restrict the degree to which users can improve their practices. Design practices are affected by the well-documented characteristics of the construction industry, including the complex, comprehensive, and chaotic uniqueness of building projects (Bertelsen 2003; Demian and Fruchter 2006; Larsson et al. 2014).

The complexity of these practices has furthermore increased due to the increasing sustainability requirements of buildings, necessitating further support for designers. This creates an elusive environment that can make it difficult for developers of BMC to foresee which characteristics might restrict its use. These characteristics are a product of how people, organizations, and the information technology itself intermingle and often produce unintended results that are elusive and difficult to identify (Brown and Duguid 1994).

Recently, there has been a focus on the need for more practice-based and holistic studies that are based on interdisciplinary approaches of research. Understanding the environments of how building designers work with sustainability assessment methods, and investigating how to improve them with BMC systems, entails new perspectives. Currently, the dominant perspective of BIM research is an engineering view, to produce technological solutions with a normative orientation (Koch et al. 2019; Miettinen and Paavola 2014). It has previously been suggested that the normative orientation of BIM systems (like BMC systems) needs to be complemented with an interdisciplinary approach to investigate the nature of the practices that BMC systems are envisioned to improve, in order to suggest new approaches of both rule translation and execution needed for successful BMC system use in design practice. Such an approach can help to identify problems and bottlenecks with the development of BMC systems, which can potentially enable better integration into practice. Therefore, the main research question is:

How can BMC systems better support designers in complex building design practices working with sustainability assessment methods?

The research question requires several methodological considerations. The question is deliberately approaching the domain of BMC from a socio-technical approach that not only brings forward technological functionality, "*How can BMC systems better support designers",* but also considers the societal aspects of the use of technology "*in complex building design practices working with sustainability assessment methods".* The sub-research questions are presented later, because they are derived from the methodology presented in the next section. 2.2 Methodology, in general, presents how philosophical reasoning influenced the answering of the research question.

2.2 METHODOLOGY

The methodology of this thesis addresses three essential dimensions to allow a critical evaluation of how the research questions were answered. These three dimensions are the research philosophy, the reasoning of the research and data collection (Sutrisna 2009). Discussing the research philosophy of the thesis assists in positioning the research's ontology and epistemology regarding answering how reality is perceived and how it will influence the research overall. Discussing epistemology assists in positioning the claims of what is assumed to exist based on a theoretical perspective. Discussing ontology helps position the assumptions of the reality / truth of the research derived from the research problem.

In this thesis, the methodology is influenced by the nature of the research question. As stated earlier, the research question brings forward the two aspects of both the technological functionality of BMC, "*How can BMC systems better support designers"* in a deterministic sense, and the society that it is intermingled with "*in complex building, design practices working with sustainability assessment methods".* Therefore, it challenges a deterministic approach of how technology is perceived and emphasizes a broader and interdisciplinary approach.

McLaren and Buijs (2011) argues that in much information systems research there has been an emphasis on how valid and reliable an instrument is, rather than how practically useful it is. Such a view is also known as a functionalist view, where systems are evaluated for isolated aspects, and it is believed to have a naive deterministic and positive impact on the "societies" the technology is introduced into (Hovorka 2009). Dealing with socio-technical challenges leads to dealing with a broader and often interdisciplinary issue that takes into consideration human, organizational and technological aspects.

Baxter and Sommerville (2011) argue that the socio-technical approach is very relevant in an age where large and complex systems are enforced on various practices. Such enforcement often fails to consider the unintended and problematic consequences the systems have for the societies they are trying to better. Instead, the failures of such systems are not always due to the technology itself, but rather to the failure to recognize the societal aspects (people and organizations) of where the technology is used (Mutch 2013).

A socio-technical approach to viewing technology and society has implications for how knowledge is achieved and puts forward a more pragmatic perspective. Emphasizing a pragmatist view of information systems research highlights the practical utility of systems. The practical utility of an information system is focused on producing results that are readily corroborated by emphasizing user testing and theoretically grounded research instruments.

There exist many research frameworks that can assist in answering socio-technical research questions, as posed in this thesis. In this thesis, the research methodology Design Science Research (DSR) is applied because it takes into account the socio-technical aspects of conducting research (Carlsson 2007; Carlsson et al. 2011). Here, design science research can be used to develop practical knowledge and theory to study specific information systems problems.

According to DSR, such knowledge must be considered as abstract and not understood as a specific recipe for designing and implementing individual information systems. Instead, it allows the researcher to transform the knowledge to fit specific problems, situations and contexts (Carlsson et al. 2011). Such knowledge can contribute to developing knowledge that can support practitioners in understanding which mechanism leads (or does not lead) to the desired outcomes.

2.2.1 DESIGN SCIENCE RESEARCH

In order to answer the research question, the Design Science Research (DSR) methodology was used. DSR has been developed as a methodology for the information systems research domain. It accommodates the relationship between practitioners in organizations using technology like BMC that are subject to *wicked* problems (defined later) related to the socio-technical challenges (Introne et al. 2013). Moreover, DSR can assist in creating information systems that more purposefully improve the practices of the individuals in organizations (Hevner et al. 2004).

DSR can be considered a pragmatist research methodology that focuses on the development of a purposeful IT artifact to address practical organizational problems. DSR is pragmatic in the sense that truth and utility are the same and that the research should be evaluated based on the practical implications (Aboulafia 1991). Artifacts are defined as constructs (vocabulary and symbols), models (abstractions and representations), methods (algorithms and practices) and instantiations (implemented and prototype systems), (Hevner et al. 2004). The development of an artifact (e.g., a prototype or proof-of-concept) demonstrates the feasibility of the process and the product that moreover provides proof that, for example, processes can be automated (proof by construction) (Hevner et al. 2004).

The knowledge output is achieved through the development and application of the designed artifact that seeks to solve business needs. The artifact provides vocabulary and symbols to define problems and solutions that exist in the co-existence between people, organizations and artifacts (such as BMC systems). The representation of the artifact and its use in a business environment reveal the problems occurring in the practice. These problems are revealed through the nature of DSR´s iterative search as a generative/test cycle (see Figure 1). Artifacts are developed to be tested to discover potential solutions to a problem that exists in the business environment. It is through this cycle that the abductive reasoning of DSR comes into play - abductive reasoning in the sense that it aims to give a possible precondition from a specific consequence.

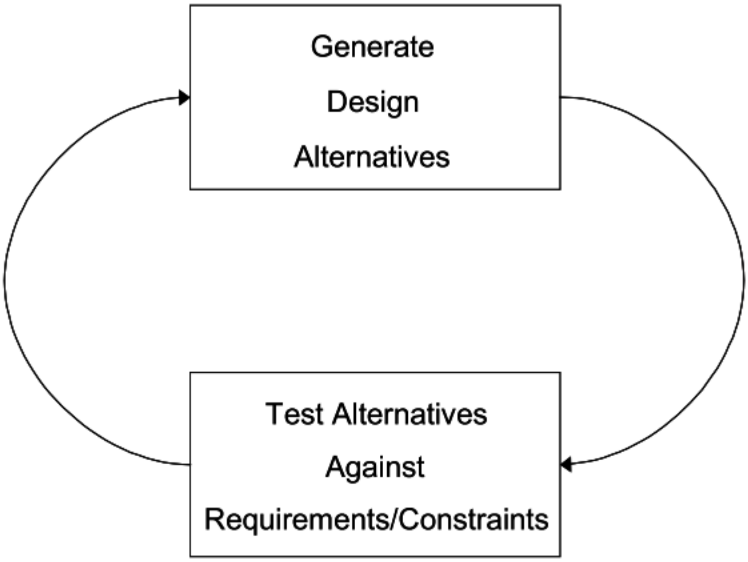

Figure 1: The generative/test cycle (Hevner et al. 2004).

According to Pries-Heje et al. (2011), abductive reasoning provides valuable insights because it constitutes one of many possible explanations and it is useful in understanding a phenomenon. From that, it creates a foundation for solving a problem. Abductive reasoning makes use of both inductive and deductive reasoning - inductive because it implies the use of theory to accommodate requirements that are then tested. The results from the tests allow for deductive arguments to be put forward and the tests are then continued until the results are satisfactory (Pries-Heje et al. 2011). Gregor (2009) argues that deductive reasoning alone is not sufficient for design because there does not only exist one potential solution for a problem but several. The abductive process of the generative/test cycle is created by continuously testing the artifacts against the environment without accommodating all potential requirements, but instead identifying and constructing an artifact that "works". The findings showing why the artifact works can be used in later research to be generalized into application on a grander scale.

DSR seeks to combine the two information systems disciplines of behavioral science and design science in order to achieve better practical utilization (Hevner et al. 2004). Behavioral science seeks to develop theories that explain human or organizational behavior. Design science aims to extend human and organizational capabilities by the creation of new artifacts like information systems through the *"analysis of the use and performance of designed artifacts to understand, explain and to improve the behavior of the social systems that the artifacts become a part of"* (Gregor and Hevner 2011).

The use of DSR entails a focus on understanding a problem domain before the development and application of the artifact and is based on the philosophical traditions of pragmatism, stating that truth (justified theory) and utility (practically useful) are inseparable (Hevner et al. 2004). It is the goal of behavioral science to find the truth that informs the utility. It is the goal of design science to find the utility through the development of an information systems artifact, because it may have an undiscovered truth.

The understanding of the problem domain is built on the behavioral science discipline, which has its roots in the natural sciences and aims to explain or predict organizational and human behavior. The contribution of behavioral science is to aid in the development and justification of theories that can be used to explain and predict a phenomenon related to the research question. These theories are impacted by the design decisions used to create the artifact and its functional capabilities.

The design science discipline has its roots in engineering and science domains and aims at problem-solving through the creation of innovative ideas, practices, and technical capabilities, which are used to address the research question's needs through the building and evaluation of the information systems artifact. The relationship between behavioral science and design science is illustrated in Figure 2.

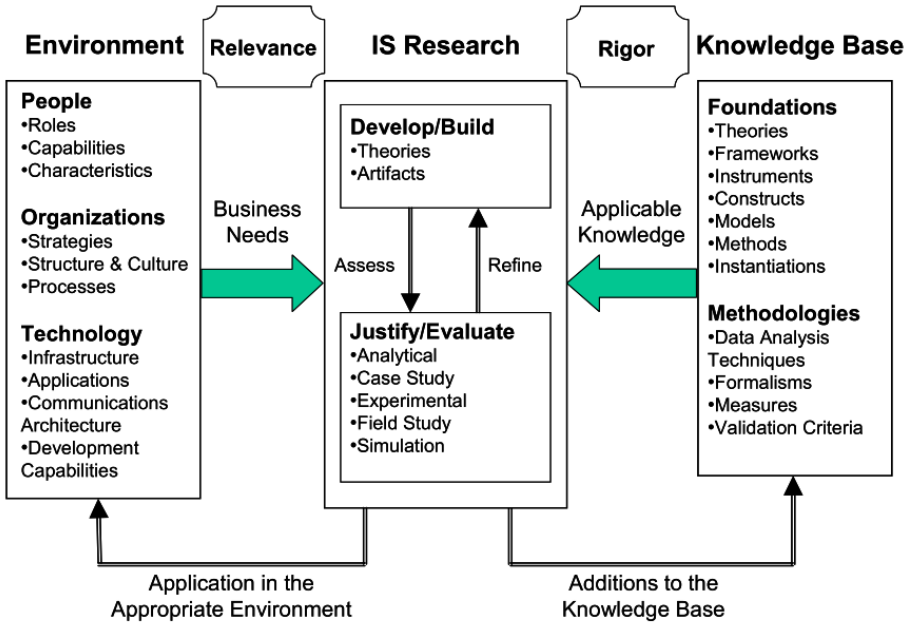

Figure 2: Information Systems Research Framework (Hevner et al. 2004).

In DSR and information systems research, the environment defines the problem to be researched. The environment consists of people, organizations, and existing (or planned) technology, which define the business needs and constitute the relevance of the research. The knowledge base consists of foundations (e.g., theories, frameworks, and instruments) and methodologies (e.g., data analysis techniques, formalisms, and measurements).

The knowledge base gives the research rigor using existing foundations and methodologies. Behavioral science contributes to methodologies rooted in data collections and empirical analysis techniques. Design science contributes to the computational and mathematical methods used to evaluate the effectiveness of artifacts (Hevner et al. 2004). When both sciences are applied to the business needs, they add a knowledge base that establishes the foundation of the research and is based on an oscillating process of assessing and refining the research, building theories, and information systems research that is justified/ evaluated through various forms of studies. This is a process that ultimately seeks to contribute to the existing knowledge base and application of the research back to the environment.

The advantage of using DSR in research is based on its contribution to solving *wicked* problems in information research (Hevner et al. 2004). *Wicked* problems are considered a reaction to the idea that the idealized system would function in the real world (Rittel and Webber 1973a). *Wicked* problems are characterized by being formed by unstable changing requirements and constraints in ill-defined environmental contexts where complex interactions occur between the sub-components and their solutions. These interactions are highly dependent on human cognitive abilities and human social abilities to create effective solutions.

The research question of this thesis: *How can BMC systems better support designers in complex building design practices working with sustainability assessment methods?* It can be considered subject to *wicked* problems according to the characteristics mentioned above. The challenges related to the use of BMC systems previously stated are profoundly affected by the "soft" socio-technical challenges as a result of the complex interactions of sub-components (e.g., BIM systems, design, people, and organizations). The use of BMC is characterized as being dependent on the collaboration between organizations and the people in building design projects which are constituted in design practices and ill-defined.

Using DSR to answer the research question of the thesis emphasizes ensuring the relevance of the business and its employees working with building design and sustainability assessment. The "truth" is following the pragmatist maxim of utility. The maxim referrers to how the practitioners experience utility and judge the practical effects. To ensure scientific rigor in DSR, it entails an emphasis on incorporating foundations and methodologies for the knowledge base. Using DSR can assist in generating knowledge through emphasizing insights into the problem domain and creating artifacts to help create better BMC solutions.

DSR provides a framework for conducting information systems research that considers two activities of improving and understanding information systems (Kuechler and Petter 2012). The first activity entails the creation of new knowledge through the design of artifacts, and the second activity, the analysis of the artifacts' performance. The use of DSR assists in a better understanding of how BMC systems both improve and constrain the design practices investigated by considering the environments using behavioral science theories. This understanding can be used to suggest novel approaches to improve the development and use of BMC systems so that designers of buildings can more efficiently create better buildings.

Using DSR, the following aim is to create an information systems artifact, in this case, a BMC system. The informed creation of the BMC system is used to produce additions to the existing knowledge base on how to improve the development of BMC systems by considering its application in design practices.

2.2.2 APPLICATION OF DESIGN SCIENCE RESEARCH

In order to apply DSR to the project, Peffers *et al.* (2007) provide a set of practical guidelines. These guidelines provide objectives, processes, and outputs following the DSR theories (Peffers et al. 2007). It assists in providing a structure for researchers to present research with a commonly understood framework and not just justifying research on an ad-hoc basis (Peffers et al. 2007). Six steps are conducted to achieve the objectives of DSR: problem identification and motivation, the definition of objectives for a solution, design, and development, demonstration, evaluation and communication, as illustrated in Figure 3.

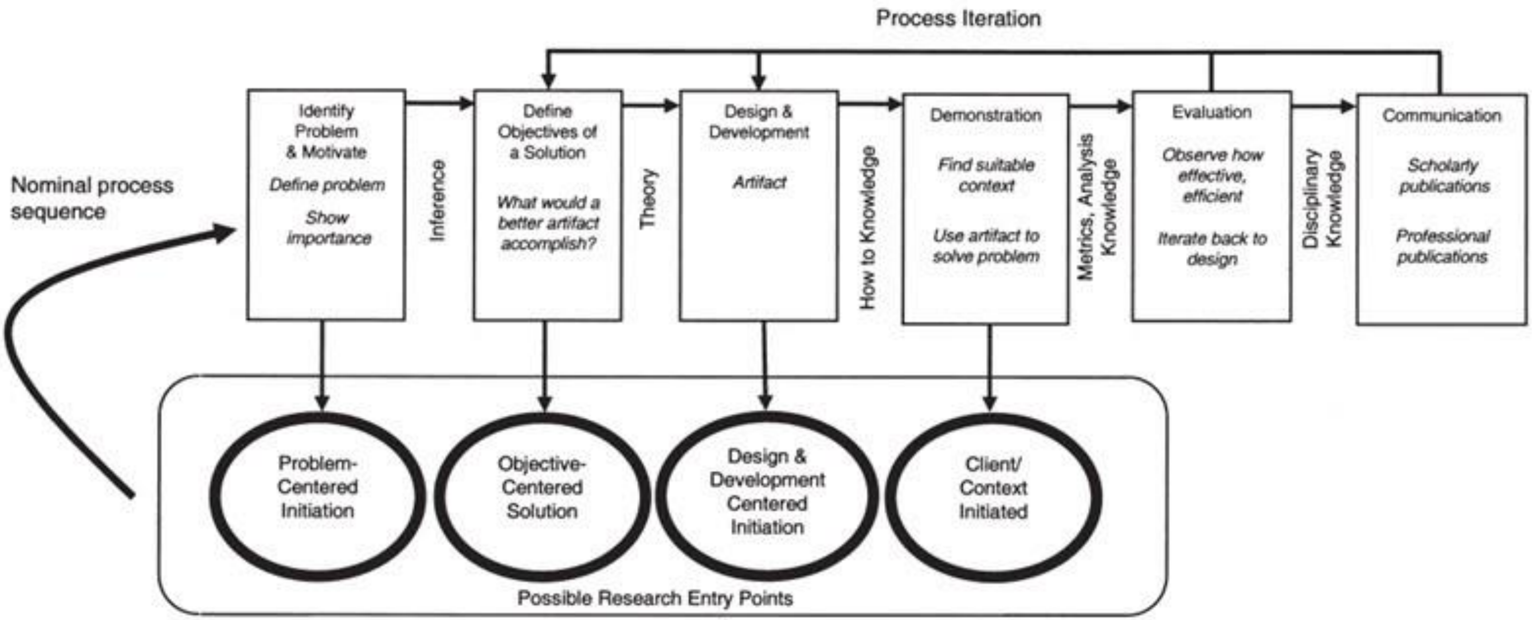

Figure 3: The DSR process model (Peffers et al. 2007)

Using the DSR methodology, research can be initiated from different entry points along with the objectives, either from a problem, objective, design, or client-focused initiation. In this thesis, the research entry point is from the problem-centered initiation because the problem related to the research question is vaguely defined in current research and is considered of great importance to the output of the thesis. A problem-centered initiation includes all the steps and places emphasis on the problem that is to be solved, identifying the motivation for its solution. This initiation follows the research of the nominal process sequence, as illustrated in Figure 3. Each step entails that a set of objectives are created to guide the research, along with the steps to answer the research questions.

2.2.3 SUB-RESEARCH QUESTIONS

In order to answer the research question, five sub-questions have been formulated in line with the DSR methodology. The sub-questions are focused on following the nominal process sequence explained above and finished off by being communicated in scholarly publications brought together in this thesis.

2.2.3.1 SUB-RESEARCH QUESTION 1

The first question is focused on the identification of problems. Currently, the issues regarding the use of BIM and related BMC systems in practice are based on socio-technical aspects that are situated in collaborative design environments. Therefore, the first sub-question is: *What are the consequences of using BIM-tools to mediate the building design process in a collaborative design environment?*

2.2.3.2 SUB-RESEARCH QUESTION 2

The second sub-question aims to investigate the nature of existing rulesets such as the sustainability assessment method for the purpose of automation and therefore aims to answer: *What is the sustainability assessment criteria best suited for automation?* The results of answering this question are used for identifying the objectives of the research in what criteria to automate and exploration of their formalized nature.

2.2.3.3 SUB-RESEARCH QUESTION 3

The third sub-question is a more holistic study incorporating multiple DSR methodology sequences (see Figure 3). It continues to explore the problems that the practitioners are subject to, the objectives to solve, the design of a translation method and evaluation of it through an example. Therefore, the third sub-question is: *How can the translation of natural language to executable computer language be improved for practices?*

2.2.3.4 SUB-RESEARCH QUESTION 4

The fourth sub-question is also a holistic study covering the DSR methodological sequences of problem identification, the definition of objectives, design of a BMC prototype, and evaluation of it. However, this study emphasizes the evaluation part of the prototype, and therefore, the fourth sub-questions are: *How are the socio-technical challenges of flexibility and transparency are experienced by practitioners using BMC systems?*

2.2.3.5 SUB-RESEARCH QUESTION 5

The fifth and last sub-question is also a holistic question exploring a novel approach of utilizing business process management systems to conduct the checking. The use of business process management is based on previous articles problem identification and is therefore focused on reevaluating the definition of the objectives and the design aspect. The evaluation of the prototype is limited and reduced to a real experiment using the prototype to evaluate a sub-criterion from DGNB. Therefore, the final sub-question is: *How is it possible to improve the flexibility of BMC in a Business Process Management environment?*

These sub-questions are presented below in Table 1 with information about which methods are used and which papers they are answered.

Table 1: Sub-research questions used to answer the main research question, the methods used to answer the question and the papers they are answered in, and what DSR activities the sub-questions follow (Dark grey indicates the main focus, light grey indicates a secondary focus).

Sub-questions	**Methods**	**Answered in**	**Identify prob.**	**Define obj.**	**Design**	**Dem.**	**Eval.**
What are the consequences of using BIM-tools to mediate the building design process in a collaborative design environment?	Case study, Observations, Document analysis, Affinity diagramming.	Paper I: A Holistic Analysis of a BIM-mediated Building Design Process using Activity Theory.					
What sustainability assessment criteria are best suited for automation?	Rule classification	Paper II: Analysis of DGNB-DK criteria for BIM-based Model Checking automatization					
How can the translation of natural language to computer executable language for BMC be improved for building design practices?	Activity checklist, Semi-structured interviews, Affinity diagramming, Rule classification	Paper III: A business-based rule translation method used to translate sustainability rules					
How are the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) are experienced by practitioners using BMC systems?	Prototype development, Scenario testing, Activity checklist, Semi-structured interviews, Observations.	Paper IV: Development and test of a flexible and transparent BIM-based Model Checking prototype					
How is it possible to improve the flexibility of BMC in a Business Process Management environment?	Prototype development, Test case	Paper V: BIM-Based Model Checking in a Business Process Management Environment					

2.3 PRACTICE AS ACTIVITY

This thesis builds on a critical focus of how BMC systems are used in practice and how BMC systems can improve future practice and emphasizes the concept of information systems and practice. In order to obtain rigor according to the DSR methodology, a knowledge base of foundations and methodologies is used, as illustrated in Figure 2. Activity Theory is used to complement DSR to provide a theoretical framework to describe and analyze the design practices using BMC systems. Activity Theory can assist in investigating the socio-technical relationship between practitioners and their use (or lack use) of BMC systems (Kaptelinin and Nardi 2012).

There exist many approaches for examining the use of information systems in practice, but post-cognitivist theories have become increasingly prominent in many research domains. The post-cognitivist approaches are founded on the resistance to the cognitive perspective of seeing information systems as mere cognitive simulations with little regard to the context in which they are being used (Barton 2006). An example of a cognitivist view of a calculator only focuses on how it can transfer the cognitive processes of calculating, e.g., arithmetic, from the brain into an application.

Instead, the post-cognitivist view holds that human action is dependent on the human sense of context in the given moment, and is often discussed as the difference between Heidegger's (1962) notions of present-at-hand and ready-to-hand. Heidegger's notion of present-at-hand entails that objects (like an information system) consist of facts that are present and observable. However, this view is not interested in understanding its usefulness or history. This is similar to the cognitivist view of "just" looking at the thing that is to be automated, dislocated from its use.

Only when an information system fails, we are confronted with the existence of the contextual parts (parts that affect its use) of the activity that causes the failure (Orlikowski 1992). When the calculation application is rejected by users who want something calculated, the contextual causes of the failure reverse themselves. However, the more that an information system is seamlessly integrated into an activity, the more it will be taken for granted and the less it will be reflected upon, ultimately constraining human action (Orlikowski 1992).

Heidegger (1962) argues that humans strive to achieve “something” in the world through the use of systems (like information systems) without “active thought,” an activity he calls ready-to-hand. When people pick up a calculator and start adding or subtracting, they do not actively think about the use of the calculator. If one looks at information systems as present-at-hand, one might make the mistake of neglecting critical aspects of the functioning of the system.

Heidegger (1962) reasons that we can only see objects (like information systems) if we are willing to place an emphasis on the context of where objects (information systems) are used, in order to lay a proper foundation for scientific investigations. Therefore, as Heidegger argues, practice is beneficial as the primary object of investigation. Practices embed knowledge about the use of systems by practitioners that is highly individualized and tacit (Dias 2006).

In order to frame the concept of practice for this research, Activity Theory can assist. Activity Theory is a post-cognitivist view of human activity that emphasizes the context of an object in order to understand how it is used in practice. Activity Theory is built on the Russian psychological tradition of the 1920s and 1930s, mainly represented by Lev Vygotsky and Sergei Rubinstein, which gave rise to the socio-cultural aspects of psychology. The socio-cultural aspect was an attempt to overcome the divide between the human mind, culture, and society. In Activity Theory, the human mind is considered a product of culture and society.

Activity Theory is used to assist in both evaluating and designing information systems, which entails the use of information systems in practice and that people’s use of technology (as a part of the culture) shapes who people are and become (Kaptelinin and Nardi 2012). Technology is then not considered as a neutral entity that one picks up according to the demands of a task. In Activity Theory, objects are everything “objectively” in the world. The human strives to transform these objects, which constitutes the core of human activities. For example, a human who strives to build a roof aims to transform logs, tiles, and nails into the shelter. The context of this activity is then the history of the activity, the systems, and signs and socio-cultural entities (like cultural norms, rules, and regulations) that form the activity (Engeström 2000).

Activity Theory provides theories for describing human activities with tools employing the concept of *tool mediation*, concerning the human use of tools, both material (computer) and symbolic (languages, numeric systems, algebraic notations), to transform *objects* (Kaptelinin and Nardi 2012). Such view entails that people do not interact with the tool (e.g., a computer) but the object (i.e., world) through the computer. *Objects* are everything objective represented in the world, from design, learning to actual *objects* like a building.

The motives for transforming the *objects* are embedded in the *objects* (i.e., for a doctor, the object of his work is embedded in his patient, where the motives of healing him are derived). This transformation is known as the concept of *"object orientation"* (Kaptelinin et al. 1999), where actions and operations are directed towards the transformation of the object. Actions happen with active consideration (i.e., driving a car with a stick the first time), and operations are actions done without consideration (driving with a stick after five years) (Kaptelinin et al. 1999).

The implication of applying Activity Theory to research is that it can provide a clarifying and descriptive tool related to complex social practices (Nardi 1996). It brings forward intentionality, history, mediation and collaboration related to the use of information systems. It emphasizes that human activity is not dislocated from the surroundings but is instead intertwined in a social matrix of people and artifacts (e.g., information systems), where every person plays a part. Activity Theory uses the notion of mediation, where the human experience is shaped by the artifacts that we use.

In this thesis, the focal point of interest is the practice, because the nature of the question entails "*How can BMC systems better support designers in complex building design practices working with sustainability assessment methods?"*. As indicated earlier, BMC systems are challenged due to their lack of practical usability. Therefore, the emphasis is on exploring and investigating the practices as a key to providing for better development and use of BMC systems. Using practices as a focal point for the research entails that they are investigated to discover either aspects that might hinder the proper use of BMC systems or changes required to these practices. Therefore, it is a post-cognitivist theoretical framework, where Activity Theory is used as a foundation related to the behavioral science aspect of DSR to assist with the description and analysis of the practices investigated to support the justification of further theories used to develop and evaluate the artifacts produced in the thesis. The placing of Activity Theory in DSR as a foundation can be found in the Information Systems Research Framework of DSR in the previously presented Figure 2.

2.4 LIMITATIONS OF THE STUDY

The focus of this Ph.D. project has been on investigating and improving issues related to the practical adoption of BMC systems, thereby emphasizing qualitative methodologies suitable for examining practices. Research in this domain is limited, and this study is, therefore, more exploratory. This is aligned with the DSR methodology, where a mix of mainly qualitative research methodologies like case studies and interviews can assist in obtaining insights to clarify problems previously identified (Hevner et al. 2004).

Such qualitative studies used in DSR can provide in-depth insights into the practices; such studies are typically conducted with a limited number of inquiries. This can give voice to the practices explored, but qualitative studies cannot go beyond that. In order to make the findings generalizable, the findings of this thesis must be verified further than is possible with qualitative inquiries.

Hevner (2004) argues that the dangers of using DSR are an overemphasis on technology that creates IS solutions that are well-created but useless in practice. On the other hand, there is also a danger that an overemphasis on the behavioral science aspect could lead to overemphasis also on contextual theories and a failure to identify appropriate technologies, which could lead to outdated or ineffective IS artifacts. Because of these dangers, it is essential to balance the dichotomies between overemphasis on either the developed IS artifacts or the behavioral science by means of completing full DSR research cycles. A full DSR research cycle implies both developing an IS artifact for specific problems using relevant behavioral science theories and analyzing the artifact's performance.

The problems that DSR typically deals with are, as stated earlier, “wicked problems”. Problems that have unstable requirements and constraints require complex interactions, and often they need change. Wicked problems have a critical dependence on human cognitive and social abilities (Rittel and Webber 1973a). Working with wicked problems entails that every problem is essentially unique due to its situated context.

While there can be many similarities among problems and their context, there are always differences. These differences can be of overriding importance and therefore a direct or one-to-one transference of knowledge can be problematic (Rittel and Webber 1973a). However, the dealings with wicked problems give insights into problems and bottlenecks experienced in practices that can inform further studies in developing and implementing BMC systems.

The exploratory nature of this study means that it provides insights into the nature of the problem in order to better understand the implications of using BMC systems in design practices to assist in creating novel and improved systems. The nature of wicked problems also entails that there are potentially many ways of explaining as well as solving such problems, because there are many potential perspectives from which the wicked problem can be framed and therefore also solved.

3. A HOLISTIC ANALYSIS OF A BIM-MEDIATED BUILDING DESIGN PROCESS USING ACTIVITY THEORY (PAPER I)

In DSR, the focus is on contributing to the applicability of information systems such as BMC so as to better address the problems faced by users (Peffers et al. 2007). The applicability of information systems entails an effort to identify and understand the problems and to justify the value of a specific solution. In this thesis, the aim is to identify the problems of why systems like BMC are challenged in supporting designers. While there exist various commercial and non-commercial systems, they have a limited impact on the design process (Hjelseth 2015a).

3.1 THE NEED FOR EMPIRICAL INVESTIGATION OF SOCIO-TECHNICAL CHALLENGES

Several attempts to develop intricate systems to automate processes related to design assessment with BMC systems have failed, and there are few empirical investigations into why these systems fail. Currently, there do not exist any qualitative investigations of why practitioners have rejected BMC systems, and only vague and abstract notions of "soft challenges" of a socio-technical nature (Refvik et al. 2014).

Typically, such challenges are reduced to those that arise from poorly written regulatory documents, ambiguity or the "problematic" tacit knowledge of the construction industry (Dimyadi et al. 2016b; Fiatech Regulatory Streamlining Committee 2012; Ghannad et al. 2019; Park et al. 2016; Solihin 2016; Song et al. 2018). However, efforts to explore these soft challenges in depth are few and limited.

In order to investigate the soft challenges of BMC that are related to the socio-technical challenges that hinder proper use and integration of BMC in design practices, activity has been chosen as the entity for a holistic study, which is conducted using the theoretical framework of Activity Theory, which brings forward aspects considered essential for investigating practices, such as intentionality, social aspects, and a focus on how BIM systems mediate such practice (i.e., activity). The framework also emphasizes the notion of contradictions that arise between the sub-elements of the activity (e.g., artifacts, subjects, objects) or between activities that can assist in revealing potential socio-technical challenges. Specifically, it is the decisions that are analyzed to highlight how BIM systems either provide or do not provide the necessary feedback for designers to enable them to make the best or optimal decisions.

3.2 MAKING THE BEST DESIGN DECISIONS USING BMC

Making the optimal decision requires that it is possible to prove that no better solution exists, and there is a strategy to find that solution (Gigerenzer 2007). Often systems like BIM and BMC systems are used to identify such solutions by providing the designer with feedback. BIM and BMC systems both provide the user with feedback on the BIM-based design's performance.

While there is a difference between the general concepts of BIM and BMC, they are interrelated. BMC systems make use of BIM model information where the checking is formalized into rules. Other systems that make use of BIM information to perform analysis for the designers are foundationally like BMC systems.

Ideally, BIM and BMC systems can provide designers with feedback to enable them to optimize their design decisions. The design process (especially regarding the design process supported with BIM) is often viewed as the constrained optimization of an objective function that is intended either to minimize constraints (minimizing cost) or to maximize utility (m^2 of office space) (Flager et al. 2009a; Watson 2011).

However, a design that processes this objective function is often considered a moving target because the objective function is continually changing (Chachere and Haymaker 2008). Clients change their minds, new products emerge, and legislation tightens, as often experienced in the construction industry (Bertelsen 2003; Boyd and Bentley 2012; Cicmil and Marshall 2005).

Depending on the context of the optimization using BMC systems (i.e., to optimize the assessment of building codes) and the context of where the systems are intended to be used (e.g., the design project), this manifests a contradiction. The contradiction arises because the objective function of the assessment is not stable and changes throughout the design process, but is often hard-coded in the BMC tools. Optimization that exceeds the constraints makes it computationally unfeasible, as Simon (1957) argues.

As noted by Halpern, Mitchell and Geoghegan (2017 p. 119), *"even a problem as apparently simple as determining the most optimal route for a salesperson who needs to visit fifty cities would be impossible if one were to try to calculate all possible solutions. There are 49! (= 6.1 x 10^{62}) possible solutions to this problem"*. To solve a problem like this would require a trillion computers that could calculate a trillion solutions per second, with a total computation time of 15 billion years (Halpern et al. 2017).

3.3 INVESTIGATING SOCIO-TECHNICAL CONSEQUENCES FOR BIM-MEDIATED DESIGN

Investigating the socio-technical challenges that BIM and BMC systems are subject to, the decisions that affect the building design are holistically investigated using Activity Theory in the next article. The results of the article will be used to provide the characteristics of the design process in order to identify and understand what characteristics need to be accommodated to create a BMC solution that can better support designers in making their decisions in sophisticated building design practices working with sustainability assessment methods.

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A holistic analysis of a BIM-mediated building design process using activity theory

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ABSTRACT

Building Information Modelling (BIM) is said to hold potential for increasing efficiency of the design processes in the building industry. However, designers struggle at times to apply the different BIM-tools. In order to understand this disjoint, it is necessary to understand first the existing practices of different specialists in the building design process in order to improve future development and implementation of BIM. The aim of this article is to investigate the consequences of using BIM-tools in a collaborative building design setting consisting of different specialists. A case study was carried out to trace when BIM-tools were used (or not) in an inter-organizational design process of a naval rescue station in Denmark. The design process was holistically examined through the lens of Activity Theory which is an analytical framework. Five key findings were identified: the mediating role of 3D visuals, real-world coupling with point cloud, rule-breaking to ensure design completion, inability to integrate BIM-analysis into the design and the use of heuristics to form and choose among design solutions.

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Introduction

Creating a building design that involves the integration of Building Information Modelling (BIM)-tools is a complex process since it requires input from multiple specialists. To better understand how BIM-tools are used in the building design processes, we conducted an in-depth investigation to identify the consequences of such an activity.

It is quite common that substantial amount of errors are made during the design stage of a building project, which increases the overall building projects cost (see, for example, Lopez and Love, 2012, Peansupap and Ly, 2015, Shamsudeen and Biodun, 2016). Lopez and Love (2012) found that the cost of the direct and indirect design errors was on average 6.85% and 7.6%, respectively. Another study done by Flager and Haymaker (2007) found that building designs were only iterated 2.8 times on average because of inefficient processes that could decrease the designer's opportunity to optimize the design. The building design process can be described as a process of exploration where the designers search for, identify, choose, assemble and specify a design within a *space of possible solutions* (Logan and Smithers 1993, Gero 1998). However, humans, like the designer, have limited cognitive abilities to process large and complex networks of consequences that one solution may have compared to another (Miller 1956, Kleinmuntz 1985, Simon 1991). Without the support of tools to present and externalize the design intent and consequences, designers will need to rely on their internal mental abilities to assemble the solutions into a design. Dorst (1996) and Simon (1957) pointed out that this may lead to difficulties to handle the complexity of *space* resorting to using heuristics techniques, like *satisficing*, where people tend to select the first and apparent option (Simon 1957) in difficult decision-making situations. However, it has been reported that satisficing often leads to poor performance solutions (Kleinmuntz 1985).

BIM is considered one of the solutions to improve the process of design (Krygiel and Nies 2008, Eastman *et al*. 2011, Demian and Walters 2014). It is argued that using BIM-tools to mediate the design can support the exploration of *the space of possible solutions* and lessen the need for satisficing by allowing for faster, more accurate and consistent evaluation of the design performance (Krygiel and Nies 2008, Eastman

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et al. 2011, Bryde *et al.* 2013). The creation of BIM-models enables the possibilities to coordinate the design and to use BIM analysis tools to predict the consequences of the solutions. Surveys indicate that the use of BIM-tools is becoming the standard approach for designers to mediate the creation of building design in multiple nations (Bernstein *et al.* 2014, Malleson and Watson 2016, Waterhouse and Philp 2016). In one account, United Kingdom companies are close to having reached Level 2 BIM, which indicates that BIM-models are used in a federated model to better exchange information in projects (Waterhouse and Philp 2016).

The use of BIM-tools is considered a complex topic which demands new understandings of what building design actually is (Oxman 2006). Organizations and BIM-tool developers are still figuring out how best to use it and further develop it to be integrated into the design practices (Malleson and Watson 2016). Dilemmas occur because of the introduction of new technology in old practices. The benefits of the technology are first properly achieved when both the practice and the technology are in the balance, limiting the dilemmas of its use. Notions of the interplay between BIM and the practices are, therefore, of high importance in the attempt to understand how such balance is achieved.

In a recent article by Miettinen and Paavola (2014), it is argued that research often neglects the unique characteristics of how users adopt the use of BIM and that research that concentrates on a predominantly normative approach tends to portray such activities as too optimistic. The normative approach is defined as a way to optimize the efficiency and economy of technological systems by experimenting with the best parameters for operating a system (Miettinen and Paavola 2014). This critique is extended in other research such as Harty and Whyte (2009), Neff *et al.* (2010) and Kokkonen and Alin (2016) who also call for qualitative research to complement the normative studies of BIM practices. Other studies have already contributed to improving the understanding of how BIM is used in practice, each focusing on individual aspects of using BIM, for example; representation (Bouchlaghem *et al.* 2005, Whyte *et al.* 2016), collaboration (Kerosuo *et al.* 2013, Kokkonen and Alin 2016, Poirier *et al.* 2016), interaction (Oxman 2006) and decision-making (Schade *et al.* 2011). However, there are only a few studies that attempt to provide an in-depth and holistic analysis of how BIM is used in the design process.

In this article, we seek to contribute with a holistic account of how BIM is used in a design project. The research question is: what are the consequences of using BIM-tools to mediate the building design process in a collaborative design environment? We hypothesize that the use of BIM-tools for feedback in the design process may improve the building process overall (through new opportunities for a more efficient design process that aids the designers in design exploration that reduces the need for satisficing and to make more informed choices). To address the research question, we have investigated a single case study of an intensive building design workshop, organized to apply BIM-tools. The empirical material from observations was analyzed using Activity Theory as a framework assisting in achieving a holistic perspective (Kaptelinin and Nardi 2012). One of the benefits of using Activity Theory for a holistic analysis is its top-down approach of analyzing how activities play out between people, intentions and technology (Kaptelinin *et al.* 1999).

BIM-tool use in practice and ways of analyzing it

It has been established that the use of BIM-tools in practice is sensitive to the complex forms of social and individual activities (Kerosuo *et al.* 2015, Vass and Gustavsson 2017). People's usage of tools is shaped by cultural norms, values and regulations when doing work, which can result in rejection or the inefficient use of these tools (Nardi 1996). The role that digital tools play in supporting designers in the design process was theorised by Oxman (2006) who suggested that these tools allow designers to interact with their design. Oxman focused on the individual interaction with design activities such as generation and evaluation through design tools. However, such activities can be difficult to track in design projects due to the distributed way of working in the construction industry. An attempt to better track the designers' interactions with their design was proposed by Whyte *et al.* (2016). The authors suggested that the connections between different design representations (e.g. BIM-models, paper drawings and physical mock-up models) should be tracked across time and disciplines to reconstruct practices and observing their effects on the design. The authors used Actor-Network Theory and Latour's (1986) notions of how designers' visual representations develop their understanding of design as their theoretical framework. Tracking people's evolving interactions through representations of their design products (e.g. 3D model, drawings) allowed identifying how representations were used across locations and time. In a study by Neff *et al.* (2010), data from a case study were used to analyze how people utilized digital models, based on the idea of boundary objects (Star and Griesemer 1989), to foreground the evolution of design in relation to communication and collaboration between different specialists. Concentrating on boundary objects means that the design product becomes a central object that exists at the boundary between different specialists, iterates between them and is changed by their different inputs. In this study, we were interested in using the analytical framework of Activity Theory that is explained next.

Using activity theory to study the application of BIM-tools in building design

Activity Theory has widely been applied in a broad range of domains including learning, organizational and Human-Computer Interaction studies. However, only a few studies have been conducted that were using it to analyze the use of BIM-tools (Mäki and Kerosuo 2014, Kerosuo *et al*. 2015). Activity Theory can assist when a holistic analysis approach is desired since it places emphasis on identifying human intentionality and its impact on the interactions that involve the use of technology. In Activity Theory tools such as BIM are examined by looking at the motivations of the people using it, unlike in Actor-Network Theory (Whyte *et al*. 2016) where networks of people and technology are considered being symmetrical. Activity Theory is argued to provide a more holistic analysis since it draws attention to the difficulties with information systems implementation, focusing on the complex social practices of people who are interacting to create a design (Miettinen and Paavola 2014).

Activity Theory is a sociocultural theoretical framework used to conduct qualitative analyses for understanding cultural and institutionalized practices. Activity Theory, as a method of analysis, pays attention to the interactions that unfold when people use particular tools in the pursuit of a specific goal (Miettinen *et al*. 2012). The theory assumes that studies of people's activities cannot be reduced to assessing individual or internal processes only and allows for the close examination of the interactions between human subjects and the world around them (Engeström 2005). Activity Theory takes note of the instruments that mediate the pursuit of goals and in doing so it foregrounds the transformations that occur as a result of this engagement (Nardi 1996). Such transformations may be desired, planned or not, and allow a researcher, upon closer inspection, to take note of intentionality, history, mediation, collaboration and development (Nardi 1996).

Activities are seen as high-level abstractions and are the unit of analysis in Activity Theory (Kaptelinin and Nardi 2012). In an activity, human subjects are motivated to transform their *motives* of achieving a goal (e.g. the design of a building) by taking *actions* that are operationalized (e.g. making a design decision). A simple example would be the motivation for designing a house (an activity). This motive results in specific actions such as the creation of a building design, which is operationalized by sketching on paper. *Actions* are described as all the steps taken in pursuit of a particular object (e.g. search for, identify, choose, assemble and specify a design), including the unconscious steps (e.g. when walls are drawn they define and limit the size of a room). Since actions move in the direction of pursuing a particular object, they are defined as object-oriented (Engeström 2000). Operations, in contrast, describe the routine processes that allow for the adjustment of an action. The object of an activity is embedded within the motivations of individuals and related communities (Engeström 2010). Activity Theory also allows for the analysis of the social aspects that shape activities (Engeström 1987) including rules (the cultural and organizational rules affecting the activity), community (various communities affecting the activity) and division of labour (the division of activities among subjects in the system).

The instrument or tool plays a central role in a subject's ability to realize a goal, thereby transforming the object into an outcome of the activity. Béguin and Rabardel (2000) argued that the instrument used in an activity is a composite entity based on both the subject (user's cultural history of using the instrument) and the object (what is to be transformed). The composite entity consists of an artefact structure (material or symbolic) and a psychological structure, which is used to organize an activity. For example, BIM-tools are used based on their functional capabilities (artefact structure) and how the subject chooses to organize the activity to transform an object. This composite nature of the instrument mediates the subject–object relationship in activities (Béguin and Rabardel 2000).

The success of the transformation of the object of a design activity may be hindered by what is described in Activity Theory as contradictions, which is explained next.

Contradictions and how they are manifested

In Activity Theory, situations that cause problems or the breakdown of activities are described as contradictions. Engeström (2001) explained that contradictions are historically accumulated tensions that can exist within and across activities. When contradictions occur they typically enforce a response, for example, a reflection, on how to continue pursuing the goal of the original activity. Engeström (2001) argued that the key to Activity Theory is understanding contradictions since they reveal how activities transform (Engeström 2000, 2010).

In order to identify contradictions, it is necessary to understand that contradictions manifest themselves as dilemmas (Bonneau 2013). Dilemmas are defined as expressions of incompatible evaluations, for example, ethical choices that have to be made to identify the benefit for either the client or the user, or the dilemma of choosing a window based on aesthetics, sustainability or price. Dilemmas are often multifaceted and subject to the components of the activity and can happen at the individual level or amongst groups of people. When people work together they often try to overcome the tensions that were created by dilemmas (Deken and Lauche 2014). This cooperation is achieved by aligning, integrating or even innovating their work practices. However, simple transfers of practices are often impossible since they happen through accidental or deliberate improvisation (Orlikowski and Yates 1995). Identifying the contradictions within an activity provides fruitful points of entry to understand the kinds of issues people experience and the nature of negotiations or measures they take to alleviate them.

Methodology

In this study, a case study was analyzed using Activity Theory to investigate how BIM mediates design practices holistically. Case studies are most suitable for research that concern complex phenomena in real-life contexts (Baxter and Jack 2008) that are hard to study out of context (Runeson and Höst 2009) and where researchers have less control over the events (Yin 2009). Applied correctly, case studies can assist the systematic study of expert knowledge and practices (Flyvbjerg 2016) if they base their conclusions on multiple sources of evidence (qualitative and/or quantitative), that was collected consistently, and add the resulting new insights based on established theory (or the lack of) (Runeson and Höst 2009). Using a case study, methodology and an Activity Theory framework for analysis allowed a systematic and organized focus on gaining a contextualized understanding of expert practices.

The case – design of a naval rescue station

We followed a design project that was tendered by the Danish Defence Estates and Infrastructure Organisation for a new naval rescue station and associated quay in Northern Denmark. The Danish Defence Estate organized the design process as workshops with help from hired workshop facilitators. The setup of the workshop was experimental and deviated from traditionally organized projects. Traditional projects do not require that diverse expert teams work together at the same time and in the same space. This method of project design has been critiqued to cause a fragmentation of knowledge transfer (Lindner and Wald 2011, Fulford and Standing 2014). Therefore, the project design in this study adopted a workshop format that was facilitated as a collaborative environment similar to the big room (AIA 2007) to support concurrent engineering (Kamara *et al.* 2007). A team of specialists was hired to participate in a collaborative environment and to give the specialists support in their decision-making was BIM-tools used to improve the representation and analysis of the design. Emphasis was placed on creating a collaborative environment to optimize opportunities for participants to contribute their insights supported by the BIM-tools. Incentives were created to diminish the traditional boundaries of service to motivate the participants to create the best building to reduce the risk for potential legal, political and management issues such as responsibility and ownership of information (e.g. the specialists was hired from a single consultancy firm).

The goal of these workshops was to develop a design from an initial design specification and turn it into a preliminary project. The workshop facilitators created a scorecard based on the clients' and users' needs that were formulated before the workshops in the initial design specification. Seven indicators were used; cost, design aesthetics, constructability, sustainability, building code requirements, time (to construct) and design quality. Sustainability was based on the Danish sustainability assessment method DGNB (GBCD 2014).

A decision was made by the facilitators to focus on three performance indicators to be evaluated through three commercially and widely used BIM-tools in the Danish construction industry: aesthetics, cost and sustainability. Lumion (2017) was intended to be used for assessing design aesthetics, Vico Office (Vico Software 2017) was intended to be used for assessing the cost of the building, and Ecotect/Green Building Studio (Autodesk 2017a) was intended to be used for assessing sustainability. Autodesk Revit 2014 (Autodesk 2017b) was used to generate the BIM-models, where Revit BIM templates that included building objects like windows, doors and walls were prepared. Moreover, a method for classifying the BIM objects used to design the BIM-models that intended to improve the use of,

Table 1. The intended use of BIM-tools and other related tools in the workshop.

Tools used in the workshop	Tool category	Indented output
Autodesk Revit	BIM Authoring tools	2D documentation of the design and a BIM-model to be used by visualization and analysis tools.
Point clouds	Reality capture tools	To be used as a reference of the buildings existing environment and interior.
Lumion	Visualization tools	Visualizations for the project participants to inform the project KPI's.
Vico Office	Cost analysis	A cost analysis to inform the project KPI's.
Ecotect (Green Building Studio)	Sustainability analysis	A sustainability analysis to inform the project KPI's.

Table 2. Overview of participants in the workshop.

Workshop participants	Organization
Client	Danish Defence Estate
Client	Danish Defence Estate
Client	Danish Defence Estate
Facilitator 1	BIM advisory company
Facilitator 2	BIM advisory company
User 1	Rescue Station Personnel
User 2	Rescue Station Personnel
Client Advisor	Design consultancy company
Architect	Design consultancy company
Cost-specialist	Design consultancy company
Structural engineer	Design consultancy company
Sustainability-specialist	Design consultancy company
BIM-modeller 1	BIM-modelling institution
BIM-modeller 2	BIM-modelling institution
BIM-modeller 3	BIM-modelling institution
BIM-modeller 4	BIM-modelling institution
BIM-modeller 5	BIM-modelling institution

e.g. Vico Office was prepared. The classification of objects was intended to help the designers ensure that the correct quantities from the BIM-models were used to represent the right quantities in Vico Office, increasing the validity of the cost estimation. Point clouds were made of the existing conditions before the workshop took place. The scans included the existing building, its inventory, and its site and were loaded into the BIM-authoring tool. An overview of the used BIM-tools can be found in Table 1. The use of the BIM-tools was aimed to inform the KPIs to enable the workshop participants to make better design decisions and to improve communication by enabling faster expressing of solutions in the BIM-model and faster assessment of the performance impact of the solutions.

The workshops were initiated with a start-up meeting introducing the setup of the workshop presenting the KPIs. Afterwards, the participants gathered to initiate the design meetings and started formulating and negotiating potential solutions. When something was ready to be manifested, such as a solution related to the layout of the building, the BIM-modellers interpreted and expressed the participants' solutions. When the BIM-modellers had manifested the solutions in the BIM-model, the participants gathered to discuss the solutions further. The participants would move between the meeting table away from the BIM-modellers and back to the BIM-modellers' projector screens throughout the workshops. The intended outcome from the clients was that the workshop would result in a design that was evaluated with the KPIs informed by the BIM-analysis tools and documented sufficiently for the building authority to assess the design for building permit. The workshops were conducted over 3 months with four workshop-sessions, including three 1-day workshops and one 2-day workshop. All of the workshops were observed.

Workshop participants

The designers participating in the workshop were hired through a consultancy company. The design consultancy company sent five design specialists to accommodate the needed services as well as to participate in the workshops. They were a client advisor, an architect, a cost-specialist, a structural engineer and a sustainability-specialist. To assist the specialists, BIM-modellers were invited from a BIM-modelling institution to share the advantages of using BIM. This way of organizing the setup was done to ensure that the users of the BIM-tools possessed the necessary level of BIM education and were familiar with the capabilities of the BIM-tools. The BIM-modellers manipulated and assessed the BIM-models according to the instructions of the specialists. Besides the clients, facilitators, specialists and BIM-modellers, the users of the building participated. Table 2 shows an overview of the participants. The participants all joined in the workshop and received the initial design specifications before the first meeting.

Data collection and processing

Systematic participant observation was the primary source of data collection. This included taking field notes, photos, and making video recordings. Moreover, products from the workshop including BIM-model files and 2D drawings were collected. All participants had provided their informed consent for this kind of data to be collected from them. 30.5 h of video recording was captured, downloaded and analyzed. To ensure a systematic analysis of video recorded material the event-logging software

Behavioural Observation Research Interactive Software (BORIS) was used for video coding (Friard and Gamba 2016).

The data were coded with a main focus on the mediating role of various BIM-tools. The coding was conducted according to Activity Theory by identifying dilemmas and resulting actions, and/or changes to the object of design. We used Bonneau's (2013) earlier stated definition of dilemmas as a basis for identifying contradictions. Actions that resulted in design solutions were analyzed to identify what degree they were informed by information produced by the BIM-tools or not. For example, by observing the information produced by the BIM-tools and if they were used actively in making decisions. We analyzed the actions to examine how they led to particular solutions as parts of the object of design. In this way, we identified also any changes to solutions as they manifested in the object of design.

Findings

Through the analysis of the observations, using Activity Theory, a pattern of three main themes were identified and categorized in our findings:

1. 3D visualizations to facilitate the pursuance of design solutions
2. Transformations of the building design through rule breaking
3. Difficulties in conducting performance analysis and evaluation

These themes refer to the different aspects of BIM use in context that surfaced during the analysis of the observed events. We analyzed data stemming from video recordings, field notes, photos, drawings and BIM-models, totalling 1504 separately identified events.

Theme 1: 3D visualizations to facilitate the pursuance of design solutions

The first theme has to do with the transformation of people's ideas into a computer-generated visualization. When the workshop participants congregated next to the computer screens showing 3D models, the joint viewing of these models created at times dilemmas. The reason for this was that the 3D visualizations redefined individual specialists' understandings of the design. In one observation, the users realized that the lookout room was placed too low for the users of the building to get a proper overview of the harbour. This disagreement created the need to solve the dilemmas by finding an agreed upon solution (i.e. action). In the above example, expanding the building vertically to position the lookout room higher was one of these solutions. However, actions to accommodate such needs would at times lead to new dilemmas that needed to be negotiated and required further manipulation of the model.

Key revelations from these observations were that the issues we identified here had to do with managing internalized (mental) ways of problem-solving building design and the resulting disagreements that were manifested in the externalizations through the BIM models. It meant that the resolution of these dilemmas required some degree of social coordination. In another example, the BIM-modellers were creating a layout of the rooms of the building when the architect asked for a design solution to address that there would be different kinds of users of the building who have different needs.

> Architect: "We have visitors that arrive through the staircase to see the lookout room (to the harbour). We need a presentable entrance for the visitors, so they do not interfere with the personnel (rescuers)". (Observation 2, 02:28:00)

This dilemma was pointed out by the architect due to her experience with users of buildings. It meant that the team had to pursue finding design solutions that would satisfy the design constraints, requirements and goals. These moments were important markers throughout the design phases. We found that the 3D visualizations made with the BIM-authoring tool manifested the dilemmas to occur between the participants. Our observations indicated that the clients, users and specialists could explore the design in more detail by asking the BIM-modellers to focus on certain aspects of the 3D visualization as seen in Figure 1. The ability to zoom into specific details of the design model gave new insights into previously unknown or hidden design features, enabling the team to identify those and negotiate actions to address them. Another observation showed that the shifts between perspectives of the building between, e.g. 2D plans and 3D plans mediated the design process and assisted in the spontaneous identification of new dilemmas.

> The architect is arguing about the placement of the control room, pointing at a projected 2D plan view: "We are a bit unsure if it is ok located down here (control room), when the boats are out here (in the harbour) and if you get the view needed on the ground floor. Is it possible to look at it in 3D?"
>
> The BIM-modeller quickly shifted to a 3D representation of the building.
>
> Architect: "Space-wise is it acceptable. But it is just an industrial hall; it is not a pretty building". (01:55 Observation 4)

Figure 1. Picture from the video observation depicting users, clients, specialist designers, facilitators and BIM-modeller designing a building using BIM.

The use of the BIM-authoring tools allowed quick manifestation and dissemination of each participant's design intent. In an observation, the client voiced the need to reuse tiles from the existing building. In order to accommodate this need, the BIM-modellers were able to integrate the reused tiles from the existing building into the new design. This allowed the participants to scrutinize the consequences of integrating the tiles in the new design, which allowed the participants to re-negotiate and solve the dilemma.

In one example, the client wanted to reuse tiles from the old building this was observed to be quickly integrated into the BIM-model and allowed the other participants to scrutinize the consequences of, e.g., aesthetics allowing the participants to re-negotiate and solve the dilemma.

In addition to the use of 3D models of the design, point clouds representing the existing conditions were also used. The point clouds were integrated into the BIM-authoring tools allowing the designers to identify dilemmas during the development of the BIM-models (see Figure 2). The point clouds representing the equipment (e.g. the rescue boat) were used to ensure that there would be enough space in the boat hall. A dilemma arose when the modellers used the point clouds to identify constraints to the shape of the building. The restrictions of the shape would spark new dilemmas for the design team to counter.

Following the coding of the video material and the analysis of the episodes, it was noted that overall, most of the registered dilemmas occurred amongst the participants when they were discussing the 3D visual representation of the BIM-model. 71% (1065 events) of the dilemmas registered were connected to discussions about 3D visualization, 29% (439 events) without. The 3D visualization produced with the help of BIM-authoring tools represented externalized design insights that required at times re-negotiating earlier design decisions and the transformation of mental models into design model manifestations.

Theme 2: Transformations of the building design through rule breaking

On several occasions, it was observed that the BIM-modellers would deviate from previously specified rules regarding the use of BIM. Rules related to the correct use of, e.g., BIM-object and classification. Rule-breaking was observed when participants tried to accommodate the project's timeframe and other constraints. The observations showed that at times the BIM-modellers would improvise and bypass pre-defined rules (e.g. rules of BIM-object classification) of BIM-modelling, to represent real-world objects (which are critical for using BIM-Analysis tools). Such improvisation ensured progress in the creation of the visual model but created problems for the use in analysis tools.

The participants' collective motivation to create a highly developed design in a short amount of time, satisfying the clients was prioritized over the rules for

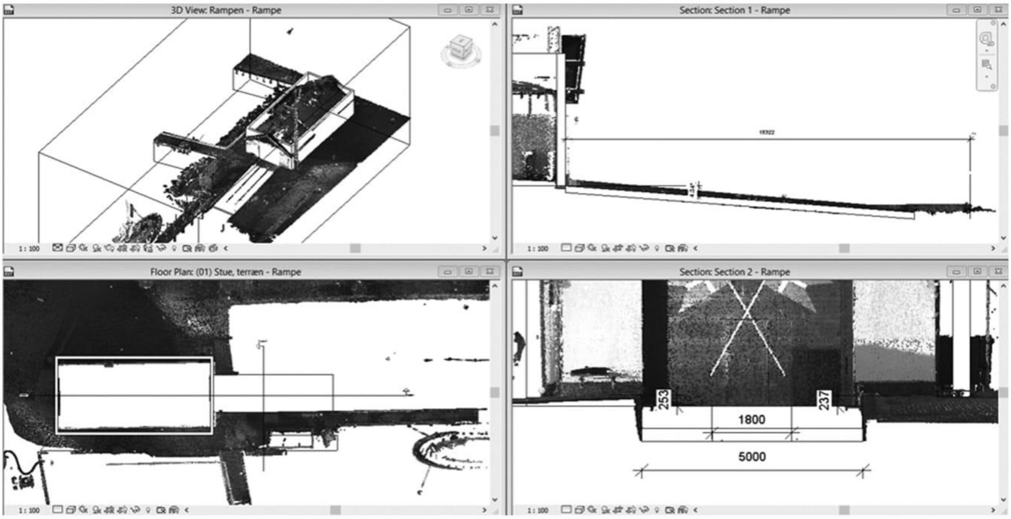

Figure 2. Pictures from the BIM-authoring tool showing how an early BIM-model was used with the point cloud scanning to ensure that distances in the BIM-model matched the distances measured with the point cloud scanning.

correct use of BIM-tools and resulted in creative and sometimes problematic problem-solving. An example of this was when the BIM-modeller followed the architect's instructions for modelling the space layout instead of using the correct (according to the predefined BIM-modelling rules) BIM-objects to represent real-world objects (e.g. use a roof in Revit to represent a roof in real-life). On another occasion, a BIM-modeller used a slanted floor BIM-object to model an existing ramp for the boat to satisfy a specialist designer's need to connect between the ramp and the new building. The BIM-model was developed to meet the immediate needs of the specialist designers but not to be used in BIM-analysis tools. The BIM-modellers responsible for using the BIM-analytical tools had to re-interpret and re-classify the BIM-model for BIM-analysis, which delayed the process and made the results arrive too late to be included in the decision-making. The BIM-modelling rules were created with the intention to allow for correct and quick estimation of the price of the building design. However, the BIM-model went through so much re-work that the price estimation made with Vico Office was out of sync with the development of the design. When the BIM-modellers had corrected the BIM-model (e.g. by properly classifying the BIM-objects), it was obsolete because new decisions had been made in the meantime. It was curious to note that the improvisations and rule-breaking were beneficial for the process since it allowed the design to develop quickly. We frequently observed that the BIM-modellers improvised and adapted to the immediate needs of the participants of the workshop not letting, e.g., BIM-modelling rules slow down the design process.

An important finding in this theme was that we identified a hierarchy in achieving certain design goals. We identified in our observations a hierarchy of goals and that they determined how the design progressed. This meant that breaking certain rules was accepted since it was deemed important at that point in time.

Theme 3: Difficulties in conducting performance analysis and evaluation

Through the design process, the facilitators intended that the BIM-models created during the design activity should be used with the BIM-analysis tools to assess the BIM-model's performance according to the three performance indicators: cost, sustainability, and design aesthetics. These indicators should help focus the design according to the goals, constraints, and requirements of the initial design specification. However, this was only achieved with limited success. Figure 3 shows, for example, that only few performance indicators were identified. While cost was identified (see Figure 3, 'Pris'), the analysis was not generated through the BIM-models but was based on extracted quantities form the BIM-model matched with "experience" based prices by the cost-specialist

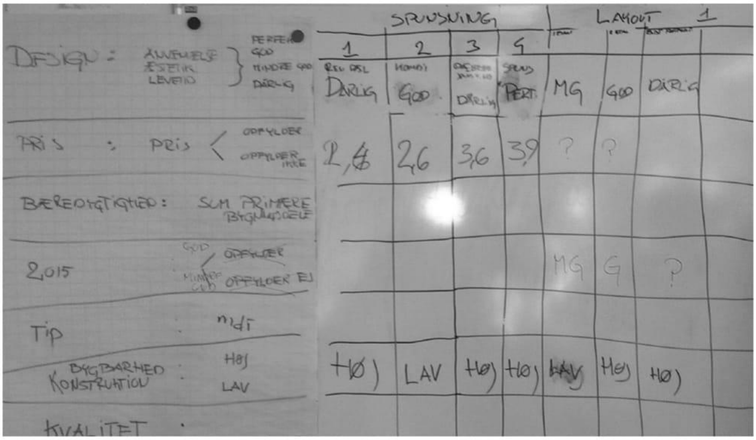

Figure 3. A picture of the near-empty scorecard giving an overview of each of the building solutions' performance. Mainly subjective estimations of the performance were made. From the top left solutions (1,2,3,4 quay solutions 5,6,7 building solutions): design aesthetics, cost, sustainability, energy consumption, time, buildability and quality (Buhl *et al.* 2014).

on paper. Only the design aesthetics indicator was analyzed, based on the visualizations using the BIM-authoring tool.

Besides the planned KPIs, other spontaneous indicators were assessed during the workshop. The BIM-modellers used the scheduling functionality in Revit to collect quantities to inform the participants about general quantities of building objects (e.g. wall, roof, floor and quay quantities) and areas. For example, schedules were created to enable a comparison of the areas in the BIM-model with requirements specified in the design brief.

> Client 1: "The area´s we specified in the building program did they ever get into the model so we could check that the building complies?"
>
> BIM-modeller finding the room schedule in Revit, specifying the areas of the building. BIM-modeller: "It is 447 (m^2)."
>
> Architect: "Is that right?"
>
> BIM-modeller: "Yes".
>
> Architect: "That is not what we calculated it should be 497 (m^2)" BIM-modeller: "Our results are the net area". Architect: "It is too much anyways, approx. 10% too much".
>
> Identifying that the area of the building exceeds the maximum (450 m^2 gross area) specified in the building program.

Lumion was intended to be used to improve the visualization of the BIM-models. However, this had limited success because these visualizations were created only on the last day and were observed to produce no dilemmas. None of the participants found any additional value in the information the visualization produced.

Ecotect was supposed to produce an analysis of the design of the BIM-models to evaluate sustainability. However, the participants did not use the results as an indicator of the design solution's performance in the scorecard shown in Figure 3. The client believed that during the days of the workshop and with the use of BIM, Ecotect would enable the sustainability specialist to produce comparative performance results and documentation of both the DGNB and the legislative requirements of energy consumption.

> Client 1: "I want the solutions printed out" (the results of the analysis)
>
> Sustainability-specialist: "These are the results calculated before we met today. This is the calculation of the energy consumption."
>
> Client 1: "Does this not come out from here" (pointing towards the BIM-model).
>
> Facilitator 1: "No, we can make scenario comparisons."
>
> Client 1: "We have to get the scenarios out, so we can compare each scenario. We already got some scenario calculations" (from Ecotect).
>
> Sustainability-specialist: "We cannot compare the results with mine."
>
> Observation 4 – 03:01:00.

The sustainability specialist argued that the output of the Ecotect analysis software was not applicable to the Danish standards of calculating environmental performance. The results from Ecotect were intended to

Table 3. The actual use of BIM-tools and other related tools in the workshop.

Tools used in the workshop	Tool category	Observed practice
Autodesk Revit	BIM Authoring tools	• Revit used to produce documentation of the design • BIM-models used by BIM-analysis tools
Point clouds	Reality capture tools	• Point clouds used in BIM-modelling process
Lumion	Visualization tools	• Lumion used to create enhanced visualizations of BIM-model but not used for decision making
Vico Office	Cost analysis	• Vico Office used to make cost analysis of solutions using the quantities from the BIM-model • Since results were delayed they could not impact on the decision-making process.
Ecotect (Green Building Studio)	Sustainability analysis	• BIM-models used in Ecotect to produce a sustainability analysis • Results not used for the decision-making process

be used as reference but did not carry much validity. Therefore, the results were not used as performance indicators of the building scenarios, and the results produced by Ecotect were rejected by the sustainability specialist due to a lack of transparency. The clients expressed dissatisfaction with the lack of performance results of the design, due to the extra cost associated with the BIM setup. The clients had envisioned that the results of the BIM-analysis tools would play a larger role in the assessment of solutions. The consequences of implementing BIM-tools resulted in a disjoint between expected benefits and what actually took place.

The BIM-modellers worked with Vico Office throughout the workshops, but the results were not ready in time to be included on the scoreboard as indicators of the solution's estimated cost. The BIM-modellers' improvisations in the creation of the models had created inconsistencies making it challenging to analyze the BIM-models. In the finishing minutes of the last day of the workshop, the cost-specialist expressed:

> Cost-specialist: "We have still not seen the results from Vico (Office)" Observation 5 – 05:19:00

Multiple events were observed using BIM-tools for subjective performance assessments. This meant that the solutions regarding, e.g., building components (such as windows, doors, roofs) were assessed and decided upon using *satisficing*, just like in traditional design projects. The widespread use of *satisficing* to form the design solutions was particularly evident during a conflict that was based on a series of design dilemmas. The actions based on satisficing was used to counter the dilemmas were only superficially addressed according to the facilitator who complained that the participants did not explore enough solutions.

Another observed example of the use of *satisficing* was when the sustainability specialist was constraining the space of possibilities when the participants were trying to find a solution for complying with legislation regarding energy consumption. Decisions had to be made on how many photovoltaic panels were to be placed on the roof to counter an excessively high energy consumption. The participants agreed on a viable solution in estimating the area of photovoltaic panels on the roof. However, it was identified afterwards that this solution was not allowed due to energy calculation rules. One of the target goals was to evaluate the building regarding aesthetics, sustainability and cost. However, the BIM-modellers were unable to provide the expected insights with the tools; therefore, the specialists resorted to alternative "tools" of evaluation using their subjective assessment of sustainability. An overview of the observed outputs from the use of BIM-tools is listed in Table 3.

Discussion

A majority of the dilemmas and subsequent negotiations on how to solve them took place in the vicinity of the display of the 3D visualization. This proximity was necessary for the specialists, clients and users to interact with the BIM-modellers and the 3D models in order to convey their ideas and responses. This also meant that when dilemmas manifested themselves in the BIM-models participants acted spontaneously on those. This kind of interaction is also what Gero (1998) described as the design process as a sequence of situated acts. The use of the BIM-models to create not only 3D visualization but also 2D plans and sections allowed the participants to reflect and merge both their individual and social understanding of the building and align it with their motivations of what the building should be. These reflections were communicated to the BIM-modellers who responded through adaptations to the BIM-model. During the design process, non-alignments between the participants' motives for their design goals and what was visualized enforced renegotiations and resulted in new solutions.

The advantage of using BIM-based compared to non-BIM-tools for creating the building design was observed to both be the ability to re-use the information for other purposes, e.g. for BIM-analysis tools like Lumion or Vico Office. Moreover, it gave the BIM-modellers the ability to rapidly extract quantities of the design.

On several occasions, the participants required quantities that were used for decision-making such as crude cost estimations based on information from the BIM-model. Though informed by quantities gathered from the BIM-models, the participants often resorted to *satisficing* strategies, drawing on previously tried and tested solutions they knew from previous design projects.

In a study by Neff *et al*. (2010), it was argued that the explicitness of the BIM-model reduced the possibility of interpretative flexibility, which could constrain the creation of knowledge between specialists. They argued that the lack of information on paper drawings is an interpretive benefit because it allows each specialist to defer the rest of the information a specialization (e.g. structural engineering). Designers need a possibility for vague communication to keep some negotiations open and that BIM-tools lacking this possibility and this may ultimately lead to the poorer cross-disciplinary creation of knowledge. Our findings did not indicate that the explicitness of the BIM generated design model constrained the cross-disciplinary creation of knowledge. We found that the detailed and explicit representation of the design was coupled with the occurrences of dilemmas that the participants tried to address and this assisted them in developing the design. The explicitness of the design intents through the BIM-model created cross-boundary knowledge (e.g. space layout) Thereby, the results of the interviews are more related to the approach to organizing the use of BIM, rather than the technology itself.

A similar critique was put forward by Scheer (2014) who wrote that BIM-tools were limited in expressing the shape of the design because of an excessive focus on performance rather than design aesthetics. In our project, the architect interacted with the BIM modellers throughout the design process, jointly shaping the building design. Some of those interactions were managed and solved through the 3D models while other issues were solved using pen and paper to explain ideas that were then transformed digitally. This form of explicitness was observed to be a key benefit throughout the design process contrary to Scheer's (2014) arguments.

We observed that the participants aligned and compromised their work practices with the task at hand. When people want to work together successfully, they need to combine their dispersed objects of design (i.e. the different understandings and motivations of the design) into a shared object of design (Puonti, 2004). Bypassing some of the BIM-tool functionality was due to the architect resorting to practices she was familiar with. Puonti (2004) explained that when dispersed objects fuse together, they form new work practices and transform design. Since the participants had to address several dilemmas, they had to solve problems to secure the development of their design (Engeström 1991). It means that the development of the design product, the resulting work practices and the integration of BIM-tools were a result of socially created dilemmas.

This observation also echoes findings by Deken and Lauche's (2014) on collaborative innovation, who argued that objects (i.e. the design) emerge simultaneously with the formation of work practices. Because of the existence of dilemmas, new practices emerged that were at times improvisations to meet the demands of changing design.

The facilitators created rules how the BIM-tools were supposed to be used, but this was at times circumvented during the workshops. Davies & Harty's (2014) investigation on the implementation of BIM-tools at a building site revealed that efforts to extensively plan the use of BIM-tools were unsuccessful since it was highly affected by the emergent and dynamic conditions of the project. Both Ecotect and Vico Office were difficult to apply alongside the development of the BIM-model and to perform the analysis of the BIM-model certain information and consistency were needed. Our findings indicate a dilemma between the emergent nature of the design process and the need to comply with BIM-modelling rules. Non-compliance with the BIM-modelling rules leads to challenges in use, e.g. BIM-analysis tools to inform about design performance.

These findings are similar to Davies and Harty's (2013) investigation of how BIM-tools were used on site. Rules specifying the use of BIM-tools were prepared, but emergent needs during the process were prioritized. The emergent and changing needs are a fundamental trait of the processes in the construction industry and for the use of BIM-tools to be relevant they need to adapt to such changes better as experienced in both Davies and Harty's (2014) investigation and this. The setup, in this case, meant that the team had a limited timeframe in which they had to produce the building design. It determined the speed at which decisions had to be made including those to do with rule breaking to speed up the process.

Not being able to provide better insights, the specialists used satisficing in the decision-making process that led to a limited exploration of the space of possible solutions, leading to design flaws, e.g. like the event with the photovoltaic panels. These flaws add to Dorst's (1996) observation that designers still

Table 4. Overview of findings.

	Findings	Consequence for the design	Role
Theme 1	The 3D visualizations prompted participants to identify concerns or ideas which they pursued to solve.	Initiated discussions to improve the design of the building.	Assisting in mediating immediate visualization of emerging ideas.
	Point clouds were used with the BIM-model and enabled a 3D visualization of the design in the existing context.	Ensured alignment of the design with the building site and the inventory.	Acted as underlays in the BIM-authoring tool to further assist in identifying the potential dilemmas with the design and the site and inventory.
Theme 2	BIM mediated design resulted in developmental transformations of the building design process.	It ensured that the design progressed but at times it led to rule breaking.	The BIM authoring tool was used in a 'quick and dirty' approach to support design discussions immediately.
Theme 3	Discrepancy between the Ecotect processing of the results and the rules of estimating energy consumption in Denmark	The results were not used in the decision making.	The BIM-analytical tool was expected to support design decisions.
	Solutions were based on experience-based knowledge rather than insights based on results from BIM-analysis tools.	The optimization quality of suggested solutions was the same as projects without BIM.	BIM was used to analyze design aesthetics, but the results of Vico Office and Ecotect was not used in the decision making.

succumb to satisficing, and, in our case, they did so even when mediated by BIM-tools. Moreover, this reaffirms Kleinmuntz's (1985) observation that satisficing can cause inaccuracies and flaws, like the one observed with the solution related to photovoltaic panels that did not provide valid results that would work within a Danish context.

In this case study, we applied Activity Theory as our analytical lens because it allowed us to examine the object of an activity and any actions taken by people towards realizing its transformation (Engeström 2000). The use of Activity Theory allowed us to track motives, dilemmas and actions that led to changes in the object in design, thereby showcasing the holistic entities that constitute the activity of design, including individual, social and instrumental dynamics mediated by BIM-tools. The findings of our case-study are presented in Table 4 to indicate how the different functionalities of the BIM-tools either enabled or constrained aspects of the planned use.

The 3D visualizations allowed the individual participants to manifest their intentions, and this created at times dilemmas that the participants had to solve. Point clouds assisted in this process by providing a detailed representation of the building site and the inventory that would affect the design. This also shows how people's activities were driven by their motives. By transforming objects in their environments they were able to achieve their motives (Kaptelinin *et al.* 1999). We observed that during the development of the object (the building design), the people involved in the process faced many dilemmas. However, their desire to pursue the motive of their activity resulted in improvisations and at times rule breaking. Taking various actions in response, shaped the object of design, and the actions were either supported or constrained by using BIM-tools. Because of such improvisations, it was difficult to use BIM-analysis tools to inform the decision-making, which instead mainly relied upon satisficing.

Conclusion

The aim of this article was to show, analyze and discuss an investigation into the consequences of using BIM-tools in a collaborative building design setting consisting of different specialists. We presented a case study of an inter-organizational design process of a naval rescue station project in Denmark. The activities were observed and the data were analyzed using Activity Theory framework to explore the complex social practices when people with different expertise come together. Utilizing this framework allowed for the identification of dilemmas during the development of the design using BIM-tools. Dilemmas were identified as all the instances where an activity had to be interrupted and where the team had to negotiate their understandings in order to pursue their shared goal to finish the building design by coming up with new solutions. This approach helped us to examine the mediating role of the different tools they used in the design process activity and study how BIM-tools shaped the production of the object (the building design), and how it evolved at particular points in time. Utilizing Activity Theory for the analysis allowed us also not to be limited to an examination of technical capabilities but identify how different expertise and nested understandings shaped what people saw – or not – that BIM-tools afforded to the design process.

We found that BIM-tools played a central role in the development of this design since they created visualizations that drew different team members together to communicate issues they detected and how to overcome them. These responses were typically situated improvisations that were implemented at the moment to ensure the continued progress of the transformation of design. The BIM-modellers' primary motivation was to ensure the progression of the design development and not to optimize the use of BIM-tools and this meant that the improvisations caused inconsistencies in the BIM-models. These inconsistencies created difficulties in applying the BIM-analysis tools as intended to evaluate the performance of the suggested solutions and did not provide for an exploration of the space of possible solutions. However, the project concluded with a finished design even though it did not fully implement the available suite of BIM-tools as intended. Additionally, the building was built and was recently awarded a prize for its design (Skagen Byfond 2017).

Our study was limited to focusing on one experimental case, where only a few selected BIM-tools were applied within a limited timeframe. This Danish case study presented a situation where BIM-tools were used in a cooperative setting. However, it must be noted that this scenario does not represent necessarily a traditional where teams do not necessarily work together at the same time at the same physical location. The significance is that the case represents a uniquely orchestrated situation to examine the possibilities of collaborating with the help of some BIM-tools. Future research in this field may benefit from exploring our findings in different constellations and perhaps also in different cultural/country settings to expand the understanding of how BIM-tools may be applied in practice.

We suggest that future research should investigate how BIM-tools can be further developed and applied in building design practices to assist the designers in going beyond satisficing and extend the bounded rationale we humans are limited to. In this specific workshop setup, the participants used BIM-tools typically used in the Danish building industry, though potentially more flexible and rapid BIM-tools existed at that time.

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4. ANALYSIS OF DGNB-DK CRITERIA FOR BIM-BASED MODEL CHECKING AUTOMATIZATION (PAPER II)

In order to explore the socio-technical relationship between the design participants and the BIM systems, the holistic framework of Activity Theory was used for describing and analyzing human-supported activities. Activity Theory assisted in framing the activities of design participants creating a design mediated through the BIM systems. Here, Activity Theory provided a framework for describing the context, situation and practice of the activity, emphasizing aspects of intentionality, history, mediation, collaboration and development (Kaptelinin and Nardi 2012).

4.1 USING ACTIVITY THEORY TO IDENTIFY SOCIO-TECHNICAL CHALLENGES IN A BUILDING DESIGN CASE MEDIATED WITH BIM

For Paper I, "A Holistic Analysis of a BIM-mediated Building Design Process using Activity Theory", Activity Theory assisted in forming a holistic investigation of how design participants used BIM systems to create a building design by giving answers to the first sub-research question *"What are the consequences of using BIM-tools to mediate the building design process in a collaborative design environment?".*

The aim of answering this sub-question was to investigate and bring forward the socio-technical aspects of how a society like the design participants used technology and to better conceptualize aspects that either supported or constrained the use of BIM systems. A case was observed to study the practice of building design mediated by BIM. From this observation, 30.5 hours of video recordings, field notes, photos, drawings and BIM models were captured.

The data gathered was framed according to the Activity Theory framework, including identifying the entities of the Activity Theory system of objects, subjects, artifacts, rules, communities and division of labor. Afterwards, the data was coded into events that identified contradictions that were related to the mediating artifact of BIM tools. In total, 1504 contradictions were identified. For example, the primary type of contradiction identified was dilemmas (expressions of incompatible evaluations) such as when two design participants expressed differences between the building program's area requirements and the area in the BIM model.

The contradictions identified were categorized into themes, consequences for the design, and roles. Finally, the results were compared with related research. The timeline and output of how the research was conducted can be viewed in Figure 4.

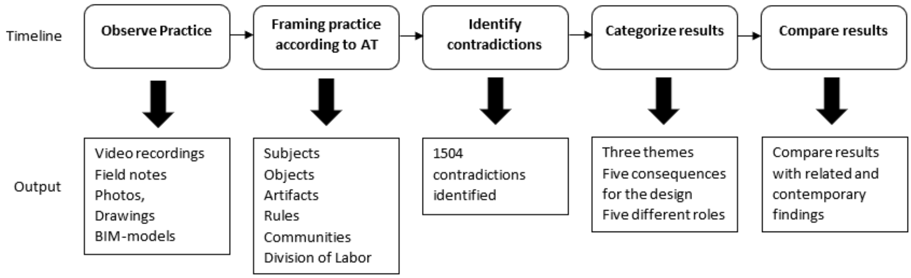

Figure 4: The timeline of research activities and their output of Paper I.

4.2 A FAILURE MAKE INFORMED DECISIONS BASED ON BIM-SYSTEMS FEEDBACK

The results from Paper I indicated that the use of heuristics was a pivotal approach to make design decisions. The designers did not make use of the automated analysis provided but instead used the BIM models' 3D representation of the design to visualize the choices made in the design process. Though the designers got feedback from both Vico Office and Ecotect, they did not apply the information to the decisions that they made.

The findings of the case study indicated that the design process was highly emergent and required much flexibility from the designers and the systems they used. To deal with such an environment, the designers applied experience-based heuristics to suggest decisions using the 3D model as a foundation. These suggestions would be communicated to other designers, which would then often result in contradictions. These contradictions would then manifest themselves in decisions modeled into the BIM model.

Systems like Vico, Ecotect and, for example, BMC systems are all built on idealized models and processes concerning how the world they automate functions and what feedback is needed. Such systems allow for a user input but are often highly constrained. The findings in the article indicated that more flexibility might be needed in order to accommodate the situated and emergent nature of the design process. Similar findings have been reported by Cross (2001), who argued that a successful design process is characterized by the designer's ability to be flexible, which requires opportunistic (but not ill-behaved) behavior. This is similar to the behavior observed in the case presented in Paper I, where a clear hierarchy of needs trumped specific modeling rules. Here, the systems did not provide the necessary flexibility to work in a design process that did not follow these modeling rules.

4.3 THE BOUNDED RATIONALITY OF THE BUILDING DESIGN PROCESS

The findings of Paper I could indicate that the BIM modelers showed opportunistic behavior by neglecting important BIM modeling rules. While such behavior could be perceived as irrational, it was rational in the context, ensuring that the design progressed within the short timeframe and still reached a satisfactory level of quality (e.g., won an architectural prize). The design project participants' behavior provided a design that had undergone scrutiny with not only explicit performance indicators like cost, but also implicit performance indicators of aesthetics, buildability and political aspects. Moreover, it could be seen as the best approach following Simon's (1957) idea of bounded rationality, where it is acknowledged that people are subject to mental constraints that limit both their cognitive abilities and resources.

Following the Bounded Rationality perspective, sound decisions are made by balancing the cognitive cost of making decisions and the quality of the outcome, i.e., the satisficing heuristic. The BIM modelers decided to emphasize BIM model progression based on feedback from the consultants, who employed experience-based heuristics not based on the BIM systems feedback. While the BIM systems were able to produce consistent and precise results, there is an inherent danger that the idealized processes embedded in the BIM systems overemphasized aspects that are not relevant for the participants' context, which can be a source of error in the system's feedback.

The BIM model design was only affected by the feedback from experienced designers, who used their experience to steer the design during the process. This experience can be viewed as heuristics (mental strategies) that specialists and experts use to make decisions in uncertain environments (Guindon 1990; Stingl and Geraldi 2017). While the use of heuristics is viewed as a sound strategy to deal with the uncertainty of situations to make decisions, heuristics is also criticized and often ignored (Gigerenzer and Goldstein 1996), not only in general but also in the building design domain (Dorst 1996; Flanagan and Norman 1993; Maqsood et al. 2004; Sujan et al. 2019).

The main criticism of the use of heuristics is that it is often perceived as a lazy approach that is highly prone to errors and typically seen as a shortcut, which induces biased assumptions in the decisions made. Sujan et al. (2019 p. 222) state: *“Cognitive biases are systematic discrepancies between the ‘optimal’ answer in a judgmental task and the decision-maker's actual answer”.* Such a statement illustrates the ambition to reach an optimal answer and is not an isolated aim in much building design research (Attia et al. 2013; Nguyen et al. 2014; Rittel and Webber 1973b). Sujan et al. (2019) follow a perspective that is prevalent in decision research, where bias is defined as a systematic deviation of rational choice.

Following a rational choice perspective entails that all relevant information must be evaluated before deciding on the search for the optimal solution. However, in uncertain situations like the building design domain (Bertelsen 2003; Cross 2001; Wood et al. 2013), an optimal solution does not exist and can therefore not be assumed (Brighton and Gigerenzer 2015). The consequence of such an approach to decision making is that we would never see any buildings being built because considering all relevant information and the complex networks of relationships that such process constitutes would make it impossible.

In many cases, a “bias” is needed in order to make a decision without considering all relevant information and relationships and still make an effective decision (Brighton and Gigerenzer 2015; Gigerenzer and Todd 1999; Samson 2016). In many cases, a "biased" decisions can even lead to better decisions (DeMiguel et al. 2007). As Lucas (2000) argues, the bias is necessary in order for us to simplify complex multi-dimensional issues, making us able to make decisions in an uncertain environment. One perspective of the BIM modeler's behavior could be that they employed a bias in order to simplify the design process so as to progress the design.

4.4 BOUNDED RATIONALITY AND BIM-SYSTEMS

In many cases, there are substantiated benefits of ignoring information in relation to making successful decisions in uncertain domains of activity (Brighton and Gigerenzer 2015; DeMiguel et al. 2007; Samson 2016) such as the building design process. It was identified in Paper I that the uncertainty of the building design process arose from the initial lack of understanding of the design, which was iteratively improved through the use of the 3D BIM model representation, which allowed the participants to identify contradictions between the manifested decisions in the BIM model. One example was user identification of rooms that were too small, which led to moving the walls. Such dynamics are sources of uncertainty because the end result is an activity involving exchange of ideas, requirements and constraints. Such dynamics and uncertainty must ideally be accommodated by the BIM systems that are intended to mediate such process.

The contemporary approach to dealing with the uncertainty in BIM systems has mainly been focused on creating complex systems, with the aim of comprehending as many scenarios as possible (Attia et al. 2013; Nguyen et al. 2014; Wang et al. 2005). Specifically, in research, there exist many proof-of-concept BMC systems aimed towards finding optimal solutions (Jiang and Leicht 2015; Macit İlal and Günaydın 2017; Zhang et al. 2013). For example, Macit Ilal and Günaydin (2017 p. 56) describe an optimal solution as one that one that does not allow ambiguities and contradictions but is comprehensive.

While the ambition of finding an optimal solution is laudable, in practice it entails great complexity because many rules contain deliberate ambiguities that are very complicated to accommodate when used for BMC systems. Such systems strive for "the optimal" and require that all relevant parameters are identified and comprehend all potential BIM model scenarios. As a result of this, it can be viewed as the ambition to create an “optimal solution” (e.g., the most optimal sustainable or buildable design), which entails a complex system.

The ambition to identify the “optimal solution” is also known as the rational choice perspective, which emphasizes that people will be fully able to trust, understand and apply such systems in their practice. While it is not possible to represent all potential scenarios, users can accept that their scenario will not be represented in the BMC systems information processes and conform to their project to accommodate the BMC systems-imposed constraints. Alternatively, either the developers must continually attempt to accommodate the scenarios that arise for the users of BMC systems and attempt to integrate them into the systems information processing, or the users must have access to change the information processes.

The “optimal solution” approach also requires that users fully understand all the advantages and limitations of the system (e.g., Ecotect) when it is used in their practice and that they will adapt their BIM models to Ecotect. Here, the misuse of Ecotect manifests a contradiction between how such systems are developed and how people are supposed to act. Systems like Ecotect are developed to function in a rational environment where people use all accessible information, including the likelihood of future events, to optimize their decision making (Boudon 1998). However, as previously indicated in Paper I (Gade et al. 2018) and other literature (Cross 2001; Lawson 2005; Logan and Smithers 1993), designers are not rational and do not follow the most rational path because it does not exist in the entirety of the many unique building design processes.

However, it is essential to acknowledge that the pursuit of rationality in some contexts can be more “rational”, while in others it is not. Gigerenzer and Gaissmaier (2011) argue that one has to distinguish between “small and big worlds”. The model of rational choice works in “small worlds” consisting of a few alternatives and with high certainty (e.g., building statics). When applied in “large worlds” containing many alternatives and low certainty, such an approach becomes problematic. In “large worlds”, the optimal choice does not exist and cannot be assumed due to the many uncertainties and alternatives. For designers to consider all the potential alternatives and accommodate the uncertainties is not a practical solution in “large world” domains (Simon 1957).

Therefore, the development of a practical BMC system entails a balancing of what can be constituted as “small world” aspects of rules, being more normatively defined (e.g., score formulas) and what is “large world” (e.g., buildability), being less normatively defined. A potential solution is not necessary to solve complex problems in environments with many uncertainties and many alternatives with complex BMC systems. Instead, rather than pursuing the “ideal of rationality” in the “large world” of building design, BMC systems using a heuristics approach can assist.

4.5 HEURISTICS CAN OUTPERFORM COMPLEX MODELS OF OPTIMIZATION.

The findings of Paper I indicated socio-technical challenges between how BMC systems formalize the information processes in the systems and in practice, which led to rejection of the system´s feedback. Using these insights, an alternative is suggested in order to improve the development and use of BIM / BMC systems. The alternative is based on Bounded Rationality (Simon 1957) and takes an Ecological Rational approach (Gigerenzer and Goldstein 1996) to how information processes are manifested in the BMC system following the use of heuristics.

A key entity in Ecological Rationality, adhering to the constraints of bounded rationality, is the use of heuristics. Heuristics are reasoning processes used by both humans and animals to make quick and efficient decisions (Nisbett and Lee 1985). In the words of Gigerenzer (2008 p. 20), *“Heuristics are frugal”* because they ignore information and do not attempt to optimize, but instead try to find a satisfied solution. Deliberately ignoring information in environments that are too uncertain for an “optimized” decision to be made can potentially provide better results (DeMiguel et al. 2007).

Historically, the use of heuristics has been perceived as simplistic and lazy (Samson 2016). However, lately, the use of heuristics has been found to outperform the use of complex models of optimization (DeMiguel et al. 2007; Gigerenzer and Gaissmaier 2011). An example of how heuristics can outperform the complex models can be exemplified by the model presented by Nobel laureate Markowitz of economic asset allocation (Markowitz 1952). Markowitz developed and used a mean-variance model that was based on the assumption of a rational choice using historical data to maximize the return and minimize the risk of asset allocation.

However, for Markowitz's private retirement asset allocation, he did not use the model but instead used a simple heuristic that specifies that the allocation of money must be equal to the amount of funds (1/N). While such an approach might seem silly, a study showed that among 12 different policies using complex models of optimization (often Bayesian), the 1/N heuristic outperformed all of the complex models based on the optimal choice (DeMiguel et al. 2007).

This example demonstrates the issue of uncertainty known as the *Turkey Illusion* (Taleb 2010), which is an overestimation of historical data. The mean-variance model used for asset allocation failed compared to the simple heuristic because it was built upon the notion that history can provide an answer to the future. This rationality did not work due to the uncertainty of the context (how people behave regarding economics) and was consequently overfitted with historical data.

The simple heuristic performed better because it did not overfit the past data, as it did not use any. The advantage of the heuristic was the predictive uncertainty of the economy. *"The larger the uncertainty and the number of assets and the smaller the learning sample, the greater the advantage"* (Gigerenzer 2008 p. 23). While rational choice theories are sound approaches to calculate, for example, structurally sound buildings, i.e., "in small worlds", they have limited use in contexts of great uncertainty "in large worlds".

4.6 HEURISTICS AND BMC SYSTEMS

Previous research has indicated that heuristics are indeed used by building designers when making design choices (Buckley et al. 2018; Daly et al. 2010; Sprinkle 2018; Stingl and Geraldi 2017). However, this perspective has not yet been used in BMC research, to the author´s knowledge. In expert-systems research, it has previously been noted that, in developing rule-based systems applied for difficult problems, the use of heuristics can be beneficial (Ajith 2005). Heuristics can aid in finding / translating a set of rules that are satisfactory for a specific problem. Moreover, heuristics can make decisions more manageable for the users of the systems by being less complex and thereby easier for them to comprehend.

The findings of paper I (Gade et al. 2018) indicated that the users either attempted to adapt the BIM systems to fit their context, rejected using the system at all, or neglected the feedback the system provided. Similarly, BMC systems have been misused, rejected and only a few systems are in use (Beach et al. 2015; Hjelseth 2015a; Khemlani 2015, 2018; Refvik et al. 2014). By recognizing the cognitive limitations and the contextual conditions of the design process, it is possible to create BMC systems that can give satisfactory assessment feedback to enable users to make better decisions in their design practice. To develop BMC systems that better support designers in complex building design practices working with sustainability assessment methods, an ecological rational approach could be beneficial.

Ecological rationality is the notion that human rationality is the result of an adaptive fit between the human mind and the environment (Gigerenzer and Goldstein 1996). An example of such relationship was observed in the Paper I (Gade et al. 2018), when designers turned to the satisficing heuristic; by allowing them to formalize their ecological rationality through heuristics in BMC systems. Their use of the systems and the feedback from these systems should yield better opportunities to improve their decision making.

A system that makes use of heuristics can deal better with conditions of uncertainty and limited time, knowledge, or computation – in essence, conditions that characterize the design of buildings. The context of building design is considered a highly complex undertaking (Dubois and Gadde 2002; Winch 1989; Wood et al. 2013), is subject to much uncertainty, and can be classified as being in a “large world” context. These are inherent characteristics that explain why the construction industry is lagging behind other industries in digital development (Gandhi et al. 2016; *Rapport: Byggeriets digitale udvikling* 2018; Seismonaut 2018; Watson 2011).

Besides what was identified in Paper I, according to Dubois and Gadde (2002), the uncertainty is due to unfamiliarity with the local resources and environment, as well as the lack of uniformity of materials, work and teams with regard to place and time, i.e., the uniqueness of the project and unpredictability of the environment. The complex and uncertain context of the design process makes it difficult to create systems to inform this context.

The ecological rationality approach is different from the traditional approach to developing BMC systems. Currently, BMC systems remain complex and are limited in the extent to which they allow users to scrutinize the systems processes and adapt them. They are built based on the rational choice theory, according to which it is possible to specify a set of general rules (which are often complicated to adapt) that should be used in any given context. Using an ecological rationality approach to BMC will allow designers to create or adapt the formalized rules to fit their context of use, potentially allowing the BMC systems to provide better feedback, according to evidence from other domains (Gigerenzer and Todd, 1999; Abraham, 2005; Reijers and Liman, 2005).

4.7 RULE ANALYSIS FOR BMC-SYSTEM AUTOMATION

The next article focuses on identifying suitable rules from a sustainability assessment method to be used in the BMC prototype. In Denmark, a second-generation sustainability assessment method named Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB-DK) is the de facto standard for sustainability assessment. It is complex, comprehensive and requires many considerations by designers in the design process, which makes it difficult and resource-demanding for many designers to accommodate (Ding 2007; Häkkinen and Belloni 2011). For that reason, suitable criteria from DGNB-DK will be identified for use in the BMC prototype. The article provides a general analysis of the criteria so as to identify the best criteria to use for the prototype. Therefore, the next article strives to answer the second sub-research question, *what sustainability assessment criteria are best suited for automation?*

Analysis of DGNB-DK criteria for BIM-based Model Checking automatization

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by

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Abstract

This report includes the results of an analysis of the automation potential of the Danish edition of building sustainability assessment method Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) for office buildings version 2014 1.1. The analysis investigate the criteria related to DGNB-DK and if they would be suited for automation through the technological concept BIM-based Model Checking (BMC).

Contents

Introduction

Automating rule assessment of building designs requires translation of rules made for human use to rules understandable for computers. This technical report contains an analysis of Danish edition of the building sustainability assessment method Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) for office buildings version 2014 1.1.[1].

The analysis of DGNB-DK will help to determine what aspects of DGNB-DK is most important to automate first.

Method

Two recent classification methods for BMC rules by Solihin & Eastman [2] and Hjelseth [3] were deemed inconsistent to classify rules with in relation to this context. Much interpretation was required, and it was difficult to ensure consistent results of rule classification every time. Rule classification is a complex task. Large works by the Business Rule Group [4] reveal many abstract faces to rule classification. Aspects that is not covered in current literature dealing with rule classification in relation to BMC [2,3].

In this report, the rules of DGNB-DK are analyzed on a simple but important premise. Rules can either be classified as the following:

1. **Explicit formulated rules**
   Evaluation of rule ECO1.1 [1]

Evalueringspoint		
Gruppe	Tjeklistepoint (TLP)	LCC (DKK/m^2)
A	100	≤ 21.000
B	90	≤ 23.000
C	80	≤ 25.000

2. **Be implicit formulated in prose**
   Evaluation of rule SOC1.7-1.1 [1]

BESKRIVELSE	TLP
Adgangsveje og parkeringspladser er delvist overskuelige og med åbent indkig.	1

   Translated text: "Partial overview of access roads and parking lots and open with a look inside."

It is, however, acknowledged that rules described in manuals like DGNB-DK are described in prose to set the scene for the human reader. Therefore, the analysis focuses on the evaluation tables, which constitute how the criteria are evaluated. All of the criteria contain prose outside the tables where nuances to the rules are formulated, these are not considered in this analysis. This analysis focus on the evaluation tables found at the end of the description of the criteria in the DGNB-DK manual.

Analysis

The results of the analysis are portrayed in Table 1.

Table 1: Classification of sub-criteria in DGNB-DK

Nr.	Criteria	Indications	Explicite formulated rules	Implicite formulated rules	Score Weight	Nr. of explicite sub-criteria	Nr. of implicit sub-criteria	Total nr. of sub-criteria	Explicit %	Explicit weighted value	Implicit %	Implicit weighted value
ENV1.1	**Livscyklusvurdering (LCA) - Miljøpåvirkninger**				7,9	5	0	5	100%	7,9	0	0
	1.	Global opvarming (GWP)	x									
	2.	Ozonnedbrydning (ODP)	x									
	3.	Fotokemisk ozondannelse (POCP)	x									
	4.	Forsuring (AP)	x									
	5.	Næringssaltbelastning (EP)	x									
ENV1.2	**Miljøricisi relateret til byggevarer**		x		3,4	1	0	1	100%	3,4	0	0
ENV1.3	**Miljøvenlig indvinding af materialer**				1,1	3	0	3	100%	1,1	0	0
	1.	Anvendelse af træ og træmateriale	x									
	1.1	forskallingstræ	x									
	2.	Anvendelse af natursten	x									
ENV2.1	**Livscyklusvurdering (LCA) - Primærenergi**				5,6	3	0	3	100%	5,6	0	0
	1.	Forbrug af ikke-vedvarende primærenergi (PEnr)	x									
	2.	Samlet forbrug af primærenergi (Petot)	x									
	3.	Andel af vedvarende primærenergi	x									
ENV2.2	**Drikkevandsforbrug og spildevandsudledning**		x		2,3	1	0	1	100%	2,3	0	0
ENV2.3	**Effektiv arealanvendelse**				2,3	2	2	4	50%	1,15	0,5	1,15
	1.1	Anvendelse af "genbrugsarealer" vs. anvendelse af ubebyggede arealer		x								
	1.2	Bebyggelsestætheden	x									
	2	Miljømæssige forbedringer af arealet										
	2.1	Oprensning af forurenet jord.		x								

	2.2	Positiv indflydelse på grundens biofaktor	X									
ECO1.1	**Bygningsrelaterede levetidsomkostninger**		X		11,2	1	0	1	100%	11,2	0	0
ECO2.1	**Fleksibilitet og omstillingsevne**				7,5	4	0	4	100%	7,5	0	0
	1.	Arealudnyttelse	X									
	2.	Rumhøjde	X									
	3.	Bygningsdybde	X									
	4.	Vertikale adgangsveje	X									
	5.	Fleksible planløsninger		X								
	6.	Konstruktion		X								
	7.1	Tekniske installationer - indeklima		X								
	7.2	Tekniske installationer - køling		X								
	7.3	Tekniske installationer - varme		X								
	7.3	Tekniske installationer - afløb		X								
ECO2.2	**Robusthed**				3,7	3	3	6	50%	1,85	0,5	1,85
	1.1	Levetid facade	X									
	1.2	Levetid tag	X									
	1.3	Levetid gulve, vinduer og døre	X									
	2.1	Byggeteknisk udførelse		X								
	2.2	Robuste løsninger		X								
	2.3	Tidsfrister for den aktuelle byggesag jfr. Bygge rating skala		X								
SOC1.1	**Termisk komfort**				4,3	7	1	8	88%	3,7625	0,125	0,5375
	1.	Operativ temperatur/vinterperiode	X									
	2.	Træk/vinterperiode		X								
	3.	Asymmetrisk strålingstemperatur og gulvtemperatur/vinterperiode	X									
	4.	Relativ luftfugtighed/vinterperiode	X									
	5.	Operativ temperatur/sommerperiode	X									
	6.	Træk/sommerperiode	X									

	7.	Asymmetrisk strålingstemperatur og gulvtemperatur/sommerperiode	X									
	8.	Relativ luftfugtighed/sommerperiode	X									
SOC1.2	**Indendørs luftkvalitet**				2,4	2	0	2	100%	2,4	0	0
	1.	Flygtige organiske forbindelser (VOC)	X									
	2.	Ventilationsrate	X									
SOC1.3	**Akustisk komfort**											
Er ikke med i Etage egendommel	1.	Enkeltkontorer og kontorer < 40 m^2										
	2.	Åbne kontorlandskaber > 40 m^2										
	3.	Auditorier og konferencerum										
	5.	Kantiner >50 m^2										
	2.	Ventilationsrate										
SOC1.4	**Visuel komfort**				2,6	3	4	7	43%	1,114286	0,57142857	1,485714286
	1.	Dagslys i bygningen	X									
	2.	Dagslys på permanente arbejdspladser	X									
	3.	Udsyn		X								
	4.	Ingen blænding ved dagslys		X								
	5.	Ingen blænding ved kunstig lys		X								
	6.	Lysfordeling fra elektrisk belysning		X								
	7.	Farvegengivelse	X									
SOC1.5	**Brugernes muligheder for styring af indeklimaet**				1,6	0	7	7	0%	0	1	1,6
	1.	Ventilation		X								
	2.	Solafskærmning (udvendig eller ml. ruder)		X								
	3.	Blændingsbeskyttelse		X								
	4.	Temperaturer i fyringssæson		X								
	5.	Temperaturer i sommerperioden		X								

	6.	Styring af elektrisk belysning		X								
	7.	Betjeningsvenlighed		X								
SOC1.6	**Kvalitet af udendørs friarelaer**				0,9	4	10	14	29%	0,257143	0,71428571	0,642857143
	1.1	Aktivering af tagflader	X									
	1.2	Tagbeplantningens type	X									
	1.3	Facadeintegrerede udearealer		X								
	1.4	Bygningsintegrerede udearealer		X								
	1.5	Særlige arealer i stueetagen		X								
	1.6	Beplantning på facader	X									
	1.7	Orientering af bygningsrelaterede friarealer, tag- og facadearealer i forhold til verdenshjørner	X									
	2.1	Integrering af nødvendige tekniske opbygninger		X								
	2.2	Designkoncept for udendørs anlæg		X								
	2.3	Beplantningstype på terræn, tag og facade		X								
	2.4	Driftsaftale eller plejeplan for beplantningen		X								
	2.5	Social anvendelse af udearealer		X								
	2.6	Koncept for forbedringer af mikroklimaet		X								
	2.8	Kendetegn ved udearealernes indretningselementer		X								
SOC1.7	**Tryghed og sikkerhed**				0,9	2	7	9	22%	0,2	0,77777778	0,7
	1.1	Overskuelige veje og parkeringspladser		X								
	1.2	Oplysning af veje og parkering	X									
	1.4	Veje til cykelparkeringapladser	X									
	1.5	Tekniske sikkerhedsanordninger		X								
	1.6	Sikkerhed uden for almindeligge arbejds og åbningstider		X								
	2.1	Evakueringsplaner		X								
	2.3	Forebyggelse af risikoen for		X								

		brandgas										
	2.4	Flugtveje uden forhindringer		x								
	2.5	Betjeningsanvisninger for ventilationsanlæg		x								
SOC2.1	**Tilgængelighed**				1,7	0	7	7	0%	0	1	1,7
	1.	Parkering, afsætning og adgangsveje		x								
	2.1	Adgangsveje i bygning (generelt)		x								
	2.2	Adgangsveje i bygning (døre)		x								
	2.3	Adgangsveje i bygning (trapper)		x								
	2.4	Adgangsveje i bygning (elevatorer)		x								
	3.	Toilet og baderum		x								
	4.	Reception og serviceareal		x								
SOC2.2	**Offentlig Adgang**				1,7	0	5	5	0%	0	1	1,7
Ikke i Etageegendomme	1.	Principiel adgang til bygningen		x								
	2.	Åbning af udeanlæg for omverdenen		x								
	3.	Åbning af faciliteter i bygningen for omverdenen		x								
	4.	Mulighed for udleje af lokaler til udenforstående		x								
	5.	Variation i anvendelse af offentligt tilgængelige arealer		x								
SOC2.3	**Forhold for cyklister**				0,9	3	2	5	60%	0,54	0,4	0,36
	1.1	Cykelparkeringspladsernes antal og indretningsprincip	x									
	1.2.1	Cykelparkeringspladsernes placering		x								
	1.2.2	Cykelparkeringspladsernes afstand i forhold til hovedindgangen/indgangene	x									
	1.3	Cykelparkeringspladsernes indretningsniveau		x								
	2.1	Tilbud til cyklister	x									
SOC3.1	**Arkitektonisk kvalitet**				2,6	0	9	9	0%	0	1	2,6
	1.1	Gennemførelse af en arkitektkonkurrence		x								
	1.2	Konkurrenceproces		x								

	1.3	Implementering af det vindende projekt		x								
	1.4	Udpegning af designteamet		x								
	2.1	Gennemførelse af en totalentreprisekonkurrence		x								
	2.2	Vægtning af arkitektonisk kvalitet		x								
	2.3	Mulighed for variation i løsningsforslag		x								
	3.	Jurybedømmelse		x								
	4.	Forudgående variantundersøgelse		x								
SOC3.2	**Bygningsintegreret kunst**				0,9	2	2	4	50%	0,45	0,5	0,45
	1.	Finansielle midler til bygningsintegreret kunst	x									
	2.	involvering af kunstnere og kunsteksperter	x									
	3,	Offentliggørelse		x								
	4.	Alternativ dokumentation		x								
SOC3.3	**Plandisponering**				0,9	0	11	11	0%	0	1	0,9
	1.1	Bygningstypens mulighed for differentieret anvendelse		x								
	1.2.1	Fællesfaciliteter og opholdsarealer inde i bygningen		x								
	1.2.2	Multifunktionsrum		x								
	1.2.3	Ekstra tilbud for brugerne		x								
	1.2.4	Børnepasning og/eller skifte- og ammerum		x								
	2.2.1	forudsætninger for at adgangsveje kan bruges til andre anvendelser		x								
	2.2.2	opholdskvalitet i adgangsvejene		x								
	2.4.1	Visuelle relationer til omgivelserne		x								
	2.4.2	Udsigt		x								
	2.5	Indendørs orientering		x								
	2.6	Integreret udformningsdesign/møblerbarhed		x								
TEC1.1	**Brandsikring**				4,1	0	3	3	0%	0	1	4,1

	1.	Basisindikator		x								
	2.	Passiv brandsikring af bygninger, herunder flugtveje		x								
	3.	Aktiv brandsikring		x								
TEC1.2	**Lydforhold**				4,1	5	0	5	100%	4,1	0	0
	1.1	Luftlydisolation vægge	x									
	1.2	Luftlydisolation etagedæk	x									
	2.	Trinlydisolering	x									
	3.	Lydisolering med udefrakommende støj	x									
	4.	Støj fra tekniske installationer	x									
TEC1.3	**Klimaskærmens kvalitet**				4,1	5	1	6	83%	3,416667	0,16666667	0,683333333
	1.	Isoleringskrav for bygningsdele	x									
	2.	Linjetab	x									
	3.	Dimensionerende transmissionstab for klimaskærmen	x									
	4.	Fugtsikring		x								
	5.	Lufttæthed, infiltration q_{50}	x									
	6.	Vinduernes energimærke	x									
TEC1.4	**De tekniske systemers tilpasningsevne**				2	5	6	11	45%	0,909091	0,54545455	1,090909091
	1.1	Råhusets udformning og fleksibilitet	x									
	2.1	Alle komponenters tilgængelighed i teknikcentralen med henblik på modernisering og en senere udskiftning		x								
	2.2	Planlægning		x								
	2.3	Tilgængelighed i vertikale skakter		x								
	2.4.1	Skakter til VVS, el- og itforsyning	x									
	2.4.2	Ventilationsskakte	x									
	2.4.3	Elevatorskakte		x								
	3.1	Varmesystem og varmefordeling	x									
	3.2	Kølesystem og kølefordeling	x									

	4.1	Systemintegration - tilstand og mulighed for udbygning		X								
	4.2	Integration af funktioner i et overordnet system		X								
TEC1.5	**Bygningens vedligehold og rengøringsvenlighed**				4,1	1	7	8	13%	0,5125	0,875	3,5875
	1.	Bærende konstruktioner		X								
	2.	Ikke bærende konstruktioner - ude (glas)		X								
	3.1	Gulvbelægning		X								
	3.2	Smudsopsamlingszone		X								
	3.3	Rengøringsvenlig indretning - Radiator	X									
	3.3	Placering af trappeværn		X								
	3.3	Er toiletter indrettet så de er rengøringsvenlige		X								
	3.3	Er søjlerne placering med tilstrækkelig afstand til øvringe bygningsdele		X								
TEC1.6	**Egnethed med henblik på nedtagning og genanvendelse**				4,1	0	4	4	0%	0	1	4,1
	1.	Arbejdsindsats ved nedtagning af bygningsdelen		X								
	2.	Koncept for nedtagning og genanvendelse		X								
	3.	Vurdering af materialernes ressourceudnyttelse		X								
PRO1.1	**Kvalitet i forberedelsen af projektet**				1,4	0	3	3	0%	0	1	1,4
	1.	Indledende rådgivning		X								
	2.	Bæredygtighedsmål for projektet		X								
	3.	Brugerens indflydelse på energiforbruget		X								
PRO1.2	**Integreret design proces**				1,4	0	4	4	0%	0	1	1,4
	1.	Interdisciplinært design team		X								
	2.	Brugerindflydelse		X								
	3.	Borgerdeltagelse		X								
	4.	Bæredygtighedsplan		X								

PRO1.3		**Vurdering og optimering af kompleksitet i planlægningen**			1,4	0	12	12	0%	0	1	1,4
	1.	Energikoncept		x								
	2.	Vandkoncept		x								
	3.	Optimering af dagslys/kunstigt lys		x								
	4.	Affaldskoncept		x								
	5.	Målings- og overvågningskoncept		x								
	6.	Koncept til understøtning af bygningens fleksibilitet i forhold til ombygning, nedrivning og genanvendelse		x								
	7.	Koncept til sikring af bygningens rengørings- og vedligeholdelsesvenlighed		x								
	8.	Vurdering af alternative løsninger ved hjælp af livscyklusvurderinger, LCA		x								
	9.	Vurdering af alternative løsninger baseret på levetidsomkostninger, LCC		x								
	10.1	Kvalitetssikring i udførelsen af brandsikringskonceptet - planlægning		x								
	10.2	Kvalitetssikring i udførelsen af brandsikringskonceptet - ibrugtagning		x								
	11.	Koncept for klimasikring		x								
PRO1.4		**Bæredygtighedsaspekter i forbindelse med udbudsmateriale og ordretildeling**			1,9	0	2	2	0%	0	1	1,9
	1.	Integration af bæredygtighedsaspekter i udvælgelseskriterierne		x								
	2.	Integration af bæredygtighedsaspekter i tildelingskriterierne		x								
PRO1.5		**Vejledning om vedligehold og brug af bygningen**			1	0	3	3	0%	0	1	1
	1.	Vejledning om vedligehold, inspektion og drift		x								
	2.	Opdatering af tegningsmateriale, skemaer, beregninger og anden dokumentation, som bygget		x								
	3.	Udfærdigelse af		x								

		brugerhåndbogen										
PRO2.1	**Byggeplads/Byggeproces**				1	0	6	6	0%	0	1	1
	1.	Minimering og sortering af affald på byggepladsen		x								
	2.	Lavt støj- og vibrationsniveau på byggepladsen		x								
	3.	Byggeplads med lavt støvniveau		x								
	4.	Miljøbeskyttelse på byggepladsen (miljøbeskyttelse af byggegrund)		x								
	5.	Energiforbrug på byggepladsen		x								
	6.	Naboinformation		x								
PRO2.2	**Dokumentation af kvalitet i udførelsen**				1,4	0	4	4	0%	0	1	1,4
	1.	Dokumentation af de anvendte materialer og hjælpestoffer		x								
	2.1	Måling af lufttætheden og termografisk undersøgelse		x								
	2.2	Måling af lydisolering/støjbeskyttelse		x								
	2.3	Fugtindhold i byggematerialer		x								
PRO2.3	**Commissioning**			x	1,4	0	1	1	0%	0	1	1,4
SITE1.1	**Mikroområde**				0	7	4	11	64%	0	0,36363636	0
	1.	Jordskælv		x								
	2.	Uvejr		x								
	3.	Oversvømmelse	x									
	4.1	Udeluft - partikler	x									
	4.2	Udeluft - Ozon	x									
	4.3	Udeluft - Kvælstofoxid	x									
	5.	Udendørs støjniveau	x									
	6	Jordbundsforhold		x								
	7.	Elektromagnetiske felter	x									
	8.	Radon	x									
	9.	Laviner		x								
SITE1.2	**Områdets og kvarterets image og tilstand**				0	0	2	2	0%	0	1	0
	1.	Ekspertudtalelse		x								

	2.	Bygningens indflydelse		X								
SITE1.3	**Trafikforbindelser**				0	1	4	5	20%	0	0,8	0
	1.	Placeringen af det nærmeste stoppested for et offentligt transportmiddel	X									
	2.	Områdets dækning af cykelstier		X								
	3.	Vejnettes kvalitet		X								
	5.	Transportkoncept, trafikkoncept		X								
	6.	Parkeringskoncept		X								
SITE1.4	**Adgang til faciliteter i nærområdet**				0	3	0	3	100%	0	0	0
	1.	Påkrævet/meget relevant	X									
	2.	Ønskeligt/også relevant	X									
	3.	Parker	X									

Results

The results of the analysis showed that of 39 criteria, there were identified 214 sub-criteria. The criteria without sub-criteria counts as having one sub-criteria. 34 % could be categorized to contain explicitly formulated rules. 66 % of the sub-criteria were categorized to contain rules formulated implicitly, Figure 1. The analysis show that 60 % of the DGNB-DK score is based on explicitly formulated rules and 40 % of the score is by implicitly formulated rules, Figure 2.

- Most of the sub-criteria in DGNB-DK contain implicitly formulated rules.
- The explicitly formulated rules weigh the most according to the score of DGNB.DK.

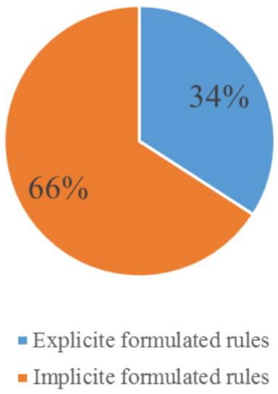

Figure 1: Classification of formulated rules in DGNB-DK criteria.

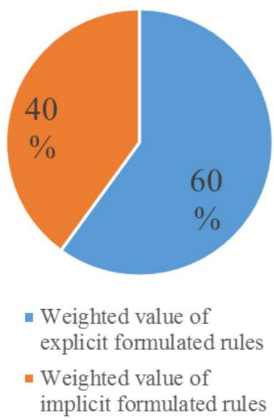

Figure 2: DGNB-DK score weight relative to formulation of rules

Conclusions

This results from the analysis show that DGNB-DK is by large implicit formulated. However, the weight of the score represented by 60 % in the criteria are explicit formulated rules. From this analysis, it is indicated that DGNB-DK is a qualified subject for further research to automate the rules. Automating DGNB-DK's rules will allow the designers for assessing the most important criteria related to the DGNB-DK assessment of buildings.

References

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5. A BUSINESS-BASED RULE TRANSLATION METHOD USED TO TRANSLATE SUSTAINABILITY RULES (PAPER III)

The previous paper investigated the rules of DGNB-DK in relation to how they were formulated. This was done to further understand the problems of using rules for BIM-based rule checking. Previous literature has identified issues related to implicitly formulated rules, and therefore it was of the importance of identifying to what degree rules were either explicit or implicate formulated.

5.1 RULES FROM DGNB-DK ARE IMPLICITLY FORMULATED

The results of paper II indicated that of 39 criteria containing 214 sub-criteria, 66 % were categorized as being implicitly formulated, and 34 % as explicitly formulated. While most of the criteria are considered implicitly formulated, the weighted value of the score is lower than the explicit. The weighted value of the explicitly formulated criteria is 60 %, while for the implicitly formulated criteria it is 40 %. The results indicate that while most of the criteria are implicit, they do not affect the overall score as much as the explicitly formulated criteria.

The implicitly formulated criteria require a higher degree of expert knowledge to apply some discretion. As in the example given in the article, for the sub-criterion SOC1.7-1.1 it is possible to obtain 1 TLP (a score in DNGB-DK) point if a “partial overview of access roads and parking lots from the outside”. The formulation of the rule is somewhat vague and requires the expert to constitute what a “partial overview” is, for example. Criteria such as SOC1.7-1.1 require developers to interpret such terms, with the risk of either overcomplicating or misinterpreting the criteria. The majority of implicit formulated rules were identified under the categories of social quality (SOC), technical quality (TEC) and process quality (PRO).

5.2 MANAGING IMPLICITLY FORMULATED RULES

Research regarding qualitative and quantitative, explicit, and implicit dichotomies in the domain of BMC systems is limited (Dimyadi and Amor 2013; Ismail et al. 2017). However, some researchers have attempted to address this subject (Nawari, 2012; Hjelseth, 2015). Nawari (2012b) briefly theoretically discussed potential challenges related to translating rules in the construction industry that are subject to the nature of the human language. He pointed out the challenges of ambiguity and vagueness in how rules are expressed. For example, words used to express rules will possess an open-ended number of senses, which is not a defect, but is essential for people to express a variety of things.

Citing Charles Sanders Pierce, *"It is easy to speak with precision upon a general theme. Only, one must commonly surrender all ambition to be certain. It is equally easy to be certain. One has only to be sufficiently vague. It is not so difficult to be pretty precise and fairly certain at once about a very narrow subject"*. As Nawari (2012b) states, it is futile to make any attempt to develop a precisely defined ontology of everything, but he suggests creating resources of informal classifications like a thesaurus, and formal theories about narrowly delimited subjects. The question then raised is how such resources can be bridged into formally defined logic and programming language and contain enough elasticity and expressiveness (Nawari, 2012).

While such insights are proposed, in the contemporary methods of rule translation proposed by Hjelseth (2015a) the goal of translation is to avoid the "knowledge soup" consisting of vagueness, uncertainty, randomness, and ignorance. A general premise here is that the translation rules for BMC will be problematic as, if *"the text itself is very unstructured and unclear it may lead to instability in development of the rules."* (Hjelseth and Nisbet 2010 p. 10). Though acknowledging the complexities in the way that this knowledge soup affects the practical use of BMC systems, the solution to this problem is peculiar. As stated by Nawari (2012b), ambiguity and vagueness are not defects but necessary for people to express a variety of things. However, Hjelseth's methods (2015a) strive to remove the vagueness and ambiguity based on the view that ambiguity and vagueness are problematic. Not acknowledging the limitations of formalized logic removes essential aspects of the knowledge tacitly embedded in the rule.

Sowa (2004 p. 16) states: *“Although most syntactic patterns can be programmed as grammar rules, the enormous flexibility and novel collocations of ordinary language depend on semantic patterns, background knowledge, extralinguistic context, and even the speaker's and listener's familiarity with each other's interests, preferences, and habits.”* This quotation highlights that the soup is highly contextual, yet Hjelseth’s (2015a) approach is an attempt to create normative rules that are insensitive to Sowa’s situated perspective of knowledge, because the argument is put forward that *“terms (language) within AEC-industry are a limited domain”*, which allows for a shared understanding of the translation, i.e., allowing a normative translation (Hjelseth 2015a).

Deciding upon which aspects of the construction industry can be constituted as a limited domain is debatable. Demaid and Quintas (2006) argue that to create systems that make use of formal knowledge in the construction industry, it requires situated knowledge to be managed in not only national but also business contexts. In projects, Weiss and Bucuvalas (1980) argue that people operate from the knowledge that they have gathered haphazardly over time. This knowledge is used to deal with the intended, unintended, rational, and irrational effects when dealing with issues in the design project (Demaid and Quintas 2006). When systems developers fail to acknowledge the nature of knowledge, *“…there is not only huge scope for misunderstanding but … there is a high risk of misinformation, misinterpretation and misplaced ‘faith’…”* (Demaid and Quintas 2006 p. 609).

5.3 EXISTING ATTEMPTS TO TRANSLATE IMPLICITLY FORMULATED RULES

Hjelseth (2015a) attempted to mitigate the vagueness of the rules by creating a method named Test Indication Objectives (TIO). Hjelseth (2015a) states *“Transformable rules are characterized by an indirect relation between the qualitative objectives (goals/intentions) in the regulation and discrete quantitative metric in the rules applicable for implementation into BIM-based model checking software.”* While using TIO for translating rules into quantitative and explicit formal statements that can be used in BMC systems, they might fall short of the challenges pointed out earlier by Charles Sanders Pierce and Demaid and Quintas (2006). While the translation contains precision, removing vagueness, uncertainty, randomness, and ignorance, one must surrender all ambition to be certain. As a result of this, it is possible to provide precise results from a BMC system. However, what do these results mean, and what premises are they built upon? Moreover, will such translation not just serve as an illusion of certainty and be misinforming and provide misplaced faith?

While it is possible to make normative translations of rules, the translations might fall short due to the complexities related to the knowledge soup. Contexts are essential for how knowledge as rule logic is represented. Formalizations of knowledge have their limits. Kant (1800) states that concepts can never be defined entirely because they are based on experience and only exist as declarations.

A person declares one's thoughts or accounts about what the person understands by a concept, even in what could be constituted as "limited domains" (similar to the aforementioned "small worlds"), which Hjelseth (2015a) proposes that the construction industry is. Other seemingly "limited domains" have accepted such a premise. Representing knowledge formally requires enormous attention to detail that often makes it impractical, for example, to keep two independently designed databases containing knowledge consistent. Because of this, when banks merge, they either keep both databases running or close the accounts in one of the databases and recreate them in the other (Sowa 2004).

5.4 NO EMPERICAL INVESTITATIONS EXPLORE TRANSLATION ASPECTS OF RULES RELATED TO BMC

There are currently no empirical investigations that seek to explore how BMC systems could deal better with the challenges of formalizing knowledge in explicit rule statements from both quantitative and qualitative sources. Insights into how practitioners use rules in the design of buildings could help to give voice to socio-technical characteristics that are important for how rules are used in practice, which might have consequences in terms of why some translations fail or succeed. Such empirical inquiry could help inform new methods of translation rules for BMC systems to help make them better to use in practice and thereby allow for better integration.

Paper III aims to examine practices both supported and unsupported by BMC systems to identify characteristics that could inform better ways of defining translation rules for BMC systems using both implicit and explicit rules. The results of the inquiry are used to develop a new method for translating rules, which is also exemplified to show its usefulness. The article follows the steps of Peffers *et al*.'s (2007) design science research methodology, presented earlier and illustrated in Figure 3.

These steps build on the results from the previous articles but continue to explore the phases of "problem identification", "define objectives of a solution" and "design and demonstrate. Semi-structured interviews from Danish and Singaporean companies related to sustainability and BMC were inquired. These interviews were conducted using the Activity Theory checklist emphasizes the activity in how people act in their practices. Activity Theory has a focus on object-orientedness, internalization/externalization, tool mediation, development and social aspects (Kaptelinin et al. 1999).

It has historically been difficult to pin contextual factors of practices that cause socio-technical issues and to alleviate this difficulty the Activity Theory checklist was developed (Kaptelinin et al. 1999). The semi-structured interviews and the checklist was used to assist in answering the sub-research question *"how can the translation of natural language to computer executable language for BMC be improved for building design practices?".* Note that the sub-research question is not explicitly stated in the next article, but instead an aim is stated that is used to answer the question.

Business-based Rule Translation Method for BIM-based Model Checking

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ABSTRACT

Increasing requirements make the building design process more complex, and designers need systems that provide better assistance. A crucial aspect of creating a design is assessing it according to a set of rules. Model-checking based on building information modeling (BIM) has the potential to assist the designer' s building assessment. However, it is challenging to apply BIM-based model checking (BMC) systems in practice due to socio-cultural challenges that result in practitioners rejecting or misusing the systems. In this study, we investigated practitioners' experiences with their work supported and unsupported by BMC systems. The challenges were related to the translation of rules used in the assessment because they become more explicit and thereby reduce the designer's interpretative flexibility. The insight from the experiences was used to create a method of translation to improve the use of BMC systems. The method emphasizes translation of rules from business and project context using

business rule theory. To exemplify its applicability, the method was used to translate a sustainability criterion.

INTRODUCTION

Building designers are challenged by the complexity of building designs due to factors such as increasing functional and legislative requirements. Many of these requirements come from the increasing emphasis on sustainability. According to Attia et al. [1] and Darko & Chan [2] the designers are challenged by ineffective processes. Many of these challenges arise from the inability of the designers to fully comprehend the complexity, uncertainties and efficiently carry out the assessment (e.g. of the sustainability requirements) to ensure that the design is improved according to the requirements [2]. These requirements are typically formalized as rules specified in, e.g., building codes or sustainability assessment methods and used to improve the designs.

The BIM-based Model Checking (BMC) systems are used to automate the assessment of rules using BIM models. The checking is conducted by translating natural language rules into explicit computer-executable code, which is used by a checking mechanism to assess information from a BIM-model that returns the checking results. The BMC systems are said to improve the speed, consistency, and precision of the assessment building designs [3–5]. However, BMC has yet to become an integrated part of the design practice [6–8]. The BMC approach has been proven to work in controlled environments, but it works to a lesser degree in real-life practices [6,9,10]. Few commercial BMC systems exist, and only a few companies have integrated them using the system's basic functionalities, such as geometrical collision checking or information validation [8]. More significant BMC initiatives, such as the Singaporean CORENETs ePlanCheck project, have encountered significant challenges in the attempt to integrate a BMC system into practice [6,9,10].

As previously highlighted, one of the main challenges is related to how BMC systems are applied in the design practice. As the translation of rules is a foundation for the successful use of BMC, we aim to explore how to provide with an alternative to conduct rule translation that can improve practical use. Currently, a normative approach to translation is dominant, and no emphasis has been made to the empirically-based exploration of how the translation could be improved. Based on the findings, a method of translation is proposed and used to translate a rule to exemplify its usefulness.

EXISTING METHODS FOR TRANSLATING RULES

In a study by Ismail, Ali, and Iahad [11] identified 23 methods for rule translation to translate various regulations ranging from building code topics (accessibility, fire safety, and occupant circulation) to sustainability. Among the 23 methods are Hjelseth & Nisbet´s [12] method named Requirement, Applicability, Selection, and Exception (RASE), used to translate rules with a focus on improving usability for domain experts in the construction industry. Similar efforts of improving practical use of BMC systems were made by Dimyadi [13] that emphasized the use of Compliant Design Procedure formalized with Business Process Model Notation to guide the compliance audit process. Other methods of translation include the use of semantic web language and resource description framework graphs [14,15], natural language processing [16] or conceptual graphs to represent knowledge in rule translation [17]. Other rule-based languages include LegalRuleML and RuleML that are based on eXtensible Markup Language (XML) but are not directly related to the building environment, yet they contain a wide range of resources and tools [5]. Ghannad et al. [18] made use of LegalRuleML and visual programming to reduce the complexity and increase the ease of translating rule for BIM-based Model Checking. Lastly, Song et al. [19] proposed using Natural Language Processing and Deep Learning to enable semantic analysis process in order to support rule interpretation.

Ismail et al. [11] conducted a literature review of existing methods and concluded that these methods were sufficient enough to translate rules for BMC systems. Because of the lack of use in practice was reduced to a matter of implementation [11].

Seeing the translation method as an external and deterministic force on practices has been argued by Orlikowski [20] as incomplete because it is also subject to the social and strategic actions of the practices. Taking into consideration the practice can allow for a deeper and more dialectical understanding of the methods and the practices that makes use of them. As existing research related to BMC systems have identified issues related to the ”soft challenges” of using BMC in practice [3,9], practices are explored to provide further insights to relevant characteristics that need to be accommodated in order to improve the translation of rules.

The existing methods have not emphasized practitioner inquiry as a foundation of the methodology development, but instead, they are built on predominantly a “normative” perspective of understanding rules. An example of the “normative” approach can be found in the Hjelseth & Nisbet [12] RASE methodology that emphasizes using rules as “normative texts,” which can be considered universally valid. The “normative” perspective of understanding rules is typically based on a top-down, or rule enactor perspective that entails a deterministic view that separates the translation of rules and their use. Such perspective can be problematic because it neglects the practices contexts and cause the practitioners to either misuse or reject the BMC systems that make use of the translations.

METHODOLOGY

To better understand the design practitioner's environment, two building design environments were explored using semi-structured interviews by opposing the normative perception in developing a more practitioner-friendly methodology for translating rules. The first environment explored was based in Singapore, where companies are supported by a BMC system. Singapore was chosen because of their efforts to the development and implementation of BMC. The second environment explored was in traditional practices in Denmark that are unsupported by BMC systems and are challenged by the complexity of rules from sustainability assessment methods. Denmark was chosen because of its sustainability efforts in the construction industry. The insights gained from the interviews were used to propose a new method for translating rules used in BMC systems. The method was then used for translating a sub-criterion from a sustainability assessment method to exemplify usefulness.

Background of the traditional sustainability assessment practice in Denmark

The DGNB-DK is a building sustainability assessment method used in the Danish construction industry that vastly increases the design complexity and contains multiple rules [21]. The DGNB was initially German, but it was adapted to a Danish context and launched it in the spring of 2012. The DGNB-DK covers six areas of quality: environmental, economic, social, technical, process and location. The exact number of criteria vary, depending on the specific scheme (i.e., office buildings or low-rise housing). The "office buildings" scheme of the DGNB-DK has 39 criteria with 214 sub-criteria. Each criterion is weighted differently from the overall score achievable for a building [21]. The authors identified more than 2000 rules using the definitions of rules from Hay & Healy [22]. Currently, the DGNB-DK assessment process is mainly supported by spreadsheet templates.

Background of the BMC-supported practice in Singapore

Many building design companies in Singapore have successfully integrated a BMC system that automates the assessment of a building design's buildability. The Building and Construction Authority (BCA) in Singapore specifies the measurement of buildability of newly constructed buildings using the metric Buildable Design Score for the building (Bscore). The buildability score is based on quantities from the building design combined with a labor-saving index (LSI). The LSI is a parameter that determines the labor intensiveness of building objects, such as walls and floors [23]. Singapore's Institute of Architects in collaboration with the BCA has developed a BMC solution named the electronic Buildability Design Appraisal Score (eBDAS) BIM system, which automates the assessment of the Bscore using BIM-models. The eBDAS (not BIM) started as an expert system in 2004 that was able to electronically understand building designs from 2D computer-aided design (CAD) data submitted by architects and engineers [24]. Later, eBDAS was developed to support BIM. Thereafter, it was named eBDAS BIM. The eBDAS BIM method can use quantities from the BIM model that can be transferred through either a plug-in (currently only supported by Revit) or through Industry Foundation Classes (IFC) 2x3 export files. The LSI information for the objects can either manually be typed into the BIM model from the authoring system or in the eBDAS BIM system.

Semi-structured Interviews using the Activity Theory Checklist

Semi-structured interviews were used to describe the practice experienced in a natural setting. The semi-structured interviews were carried out according to the theories from Barriball & White [25] and conducted with both individuals and groups. This method assists the interviewer in exploring the perception and opinions of the respondents within complex topics by exploring attitudes, values, beliefs, and motives while supporting comparability between the respondents [25], thus allowing for subjective ideas. Semi-structured interviews allow for "probing" when answers are vague, which can be defined as asking follow-up questions in responses not fully understood by the interviewer or to obtain more in-depth information [26]. The interviews were primarily undertaken face-to-face and were one to two hours in length.

The interviews were used for a qualitative inquiry to understanding the practices. The interviews were conducted according to the Activity Theory Checklist [27]. The Activity Theory Checklist is a method for investigating user interaction with technology or the lack thereof [28]. The method provides a framework for understanding human relations with technology built on psychological and sociological theories [27]. The Activity Theory Checklist provides a set of “skeleton” questions that interviewers can apply to investigate the interviewee’s interaction with technology. The questions are modified to suit the interviewer’s topic of research and seek to ensure that the interviewees are questioned according to the aspects that define their practice to explore the challenges with the technology. Kaptelinin et al. [27] argued that by having a predetermined set of questions built on this method, the objectivity of the interviews would increase. Without this approach, it would result in a more random approach to interviewing, which can lead to missing critical aspects in the understanding of the use of technology [28].

Developing solutions based on technology is not only a matter of input-output between a person and a machine, but it requires a rich depiction of the user's situation [28]. The theoretical framework of Activity Theory (AT) provides theories for describing human activities, which was built on Soviet psychological research traditions [28]. The Activity Theory Checklist uses the AT concept of tool mediation (Kaptelinin, Nardi, and Macaulay, 1999; Quek and Shah, 2004). Tool mediation concerns the human use of tools, both material (computer) and immaterial (routines) to transform objects. Objects represent everything objectively represented in the world, from the object of teaching children mathematics to the creation of a building. The use of the checklist assists the interviewers in exploring the critical aspects that include the use of technology, and in this case, how complex rules and BMC systems mediate the design process.

Interviewee selection

The interviewees were chosen from two design environments, as previously stated. The first environment represented nine designers from four companies working with a building design that is subject to accommodate complex rulesets, like the DGNB-DK set in Denmark. The interviews were conducted to focus on the role of systems in their work and how they mediate the creation of the design. The interviewees were selected to represent a traditional design environment and included representatives from both architectural and engineering businesses working with DGNB-DK. The second design environment represented four designers and two rule enactors and four BMC/BIM-systems developers from six companies in Singapore. Table 1 gives an overview of the interviewees, their role, company type, and size.

Table 1: Background of the 19 interviewees.

	Role	Company type and size according to the European Commission (2003)
Denmark (n=9)	Design practitioner and DGNB Consultant – MSc	Large engineering company
	Design practitioner and DGNB Consultant – MSc	Medium sized architectural company
	Design practitioner and DGNB Consultant – MSc	Medium sized architectural company
	Design practitioner and DGNB Consultant – BSc	Medium sized engineering company
	Design practitioner and DGNB Consultant – Construction Architect	Large architectural company
	Design practitioner and DGNB Auditor – Construction Architect	Large architectural company
	Design practitioner and DGNB Auditor – MSc, PhD	Medium sized engineering company
	Design practitioner – Construction Architect	Medium sized engineering company
	Design practitioner – Construction Architect	Medium sized engineering company
Singapore (n=10)	BIM manager	Large consultancy company
	BIM manager	Small BIM consultancy company
	Design and BMC practitioner	Large consultancy company
	Design and BMC practitioner	Large consultancy company
	BMC developer	Small developer company
	BMC developer	Small developer company
	Rule enactors	Large public institution
	Rule enactors	Large public institution
	BIM developer	Large BIM developing company
	BIM developer	Large BIM developing company

The results were transcribed and analyzed through categorizing and organizing the results with affinity diagramming. Affinity diagramming is a method that can be applied for organizing qualitative data in complicated domains [30].

RESULTS AND DISCUSSION

Results from the traditional Danish sustainability assessment practice

The interviewees expressed various characteristics related to the use of rules in the traditional design practice, which both identified how they accommodated the rules in creating the building design and why they often rejected systems that potentially could automate their work.

An essential aspect for the interviewees was the need to ensure certainty in processing the design information according to the rules. Using systems to automate their work moved tasks away from themselves and thus made their work more efficient. However, this entailed a need from the interviewees to ensure certainty as to how the system would automate their work. To obtain the certainty, the interviewees expressed that they required transparency of the systems they used.

The transparency would allow the designers to scrutinize the automation, which has two advantages. First, it would assist in establishing certainty. Second, it would assist in understanding the consequences of their design choices according to the system. The interviewees argued that it could be challenging to predict the consequences of their design choices if they lacked transparency. Therefore, improving the transparency could potentially also improve the designer´s ability to predict the consequences of their design according to the automation. An issue expressed by the interviewees was that systems often lacked transparency because the automation (i.e. the information processing) was hidden in unformalized rules embedded in the hard code. The interviewees argued that the majority of the systems that could potentially automate some of their tasks were rejected because the systems lacked transparency, and they were unable to establish enough certainty and trust. A concrete example was given regarding calculating the Life-Cycle Cost (LCC). The interviewees had attempted to scrutinize various systems for automating the calculation of LCC, but none of them provided adequate transparency, and all systems were rejected. Therefore, they relied on custom-made spreadsheets to make the calculations.

The interviewees also voiced that system rejection also was related to a lack of adaptability. While transparency would allow the interviewees to understand how the systems processed the information, the adaptability would allow the interviewees to change the processes. Some systems only allowed for minor adaptions, which required the interviewees to manually conduct comprehensive post-editing of the results and resulted in minimizing the benefits of the automation. It was important for the interviewees for the system to allow them to be able to adapt the information processing according to their contexts, both about the business and the project. The interviewees explained that they often experienced the need to spend a great deal of time, altering the results of the calculations. For example, at the company for the interviewees, they used a solar performance system to assess the solar performance of rooms. Using this system required the users to make manual calculations of the results of the system to make them usable for their national context. This would only be possible because the system was sufficiently transparent and allowed the users to identify what adaptions of the results were required to be made.

The interviewees explained that the systems first needed to be adaptable to national contexts (i.e., national standards) and then business contexts. The business contexts affect the level of the information processing quality, which is done according to the strategy and values for the business. Also, the project context often required that the systems be adapted due to unique characteristics. For example, systems can be challenging for the understanding of a design manifested in a BIM-model. Here, rooms can overlap due to the possibility of rooms being embedded in other rooms (a service kitchen-room can be embedded in a break room), which can pose a challenge for a system to recognize the calculation of air circulation, for example. Here either the design or the system must be adapted to the purpose of automating the task. This requires that the designers steer the system to take such characteristics into account to produce relevant results. The interviewees argued that the transparency of the rules was essential for establishing certainty and trust through the ability to scrutinize the automation. Interviewees argued that a lack of transparency, and thereby the ability to obtain trust, often resulted in a rejection of systems.

Results from the BMC-supported assessment practice

The interviewees in Singapore expressed overall satisfaction with the eBDAS BIM system. The BMC system developers could provide the designers with an effective BMC system that assisted the designers in assessing the Bscore of their building designs and helped the rule enactors to receive more consistent evaluations of the Bscore. Moreover, the use of eBDAS BIM fit into the businesses use of BIM according to both BIM-managers and developers.

The interviewees in Singapore expressed that the automation of the Bscore assessment vastly increased the speed of the designer's buildability assessment process. An interviewee expressed that they reduced the workload of one person from two weeks to half an hour and increased the consistency and precision of the assessment. The main issue encountered in using eBDAS BIM was ensuring the consistency between the correct object types (e.g., that roofs are modeled with roof objects and not floor objects) and LSI values (e.g., that brick walls are assigned the brick wall LSI value). The calculation itself was conducted in seconds.

The use of the eBDAS BIM system transformed the division of labor related to the assessment process. Previously, there had been a more significant separation between the designers and the Bscore assessors. They have since merged. It is now the designer creating the BIM-models that are responsible for ensuring consistent object types and LSI values in the model. Previously, this was located beside the actual creation of the design. The use of eBDAS BIM now requires that the designers are aware of the consequences of their design decisions related to the eBDAS BIM. This is because the information in the BIM-model is directly used in the automation of assessing the Bscore. This dispersion of the division of labor required that the BIM-modelers can foresee how their design choices affect the results from eBDAS BIM. However, this contradicts with the interviewees explaining that the eBDAS BIM system is both largely black-boxed (when the information processes are hidden) and hard-coded (with limited possibility to adapt the information process). This restriction was a design choice made by SIACAD to ensure a degree of consistency in the calculation of the Bscore. However, the interviewees argued that this was not considered a problem because SIACAD rapidly and frequently updated eBDAS BIM according to any general changes in the environment of the designers, such as updates to the building codes.

The interviewees argued that the reason as to why this approach worked was related to how the rules were translated. The rules were translated with the intent that they would be suitable for automation, with the result of potentially negating contextual requirements of the designers. The negation of the contextual requirements was criticized by an interviewee (Architect) who argued that the transformation of the rules has led to severe architectural issues because it removed the designer's ability to interpret what constitutes buildability in the specific project. Before the rule was made explicit, buildability could be assessed using the designer’s expert knowledge of various contextual aspects, and they would know it was formulated into the explicit value of the LSI score. The explication allowed for a more consistent and straightforward assessment of the Bscore, but it was considered highly constraining for the designer's ability to affect the buildability of the building designs. A concrete example was mentioned regarding the LSI score and bricks. The low LSI score of using bricks in the building designs restricted the use of bricks by disregarding any other possibility of using bricks in a more buildable manner. The interviewee (Architect) argued that this disregard leads to less innovation regarding buildability, which negatively affects the construction industry subject to these rules.

USING THE INSIGHTS FROM THE INTERVIEW TO CREATE A NEW METHOD OF TRANSLATING RULES

The insights from the interviews pointed towards specific aspects of translating rules from natural language into computer-executable rules for improving the practical use. These insights were applied to create a new approach to translate the rules, which is presented in this chapter.

Transparency precedes the ability to obtain the trust of the translated rules.

The interviewees pointed towards the need to improve the transparency of rules that are to be embedded in BMC systems. By emphasizing transparency in the process of translation, the user's ability to make a clear mapping between the functionality of the system and the user´s goals can be improved [31]. For example, when using an email client to send emails, the user must have a clear knowledge of how his/her email is processed. The interviewees voiced the need to establish trust in the systems they used. The trust would be obtainable through the ability to scrutinize the automation and achieve certainty in the results. The trust decreased when it was difficult for the designer to understand how the system acts (according to the rules). Moreover, an increase in transparency would also increase the designer's knowledge about how choices made in the design affect the BMC systems automated score assessment.

Transparency could assist the designers in improving their design choices according to the rules. The improvement occurs when the designer is aware of how the rules specify, for example, how a score is calculated in relation to room height. This enables the designer to make conscious choices to model the rooms in the BIM model in an improved way according to these rules. With a focus to make the rule translation as transparent as possible, it would be easier for BMC systems developers to embed the rules transparently into the system (e.g., through presenting a visualization of the processes or a standardized rule ontology).

The flexibility of rules at a business and project level

Transparency allows the designers to achieve trust and allows them to adjust the systems to improve its automation. The BMC systems embed a set of tasks executed in a checking process where both the rule translators and developers (often the same people) embed either conscious or unconscious logic. For example, when a rule specifies that if a room height is more than three meters, it gives the score of 5 (according to an assessment method). Specifying room height is highly contextualized and is based on how the room is formed in the design. Specifying how to assess a room height can be done in multiple approaches, but the chance to accommodate all possible scenarios of room height is not viable. Therefore, when developers specify the logic for assessing room height in a BMC system, they formulate the logic that is most sensible from their point of view.

When developers or rule translators embed the rules into the BMC systems, there can often be a divergence between the logic of how they interpreted the rules and how the rules can be interpreted in the context of the design project where these rules are applied. The developer's method of adapting eBDAS BIM to the contexts was handled in a top-down approach to ensure control and consistency. The developer was able to provide rapid and continuous updates. Whether this was successful due to the skill and rapid response rate of the developer, or to the limited scale of rules (Bscore assessment which had been revised to fit into automation), was not evident. Though limited in scale (compared to all the rules affecting building design), eBDAS BIM had a significant impact on the design practice by crudely limiting the use of certain materials (e.g., bricks). Herein lies the danger of attempting to translate rules from a top-down perspective with limited recognition of the practitioner's context, hence hindering the practice of design. This finding could potentially be a hint as to why the implementation of the larger and more ambitious BMC system, ePlanCheck, was challenged.

The insights from the interviewees who worked traditionally indicated the need for the designers to have flexibility in using the rules. The designers need to adapt the rules to their context if they can achieve the intent of the rules. In some cases, it requires that the rules be more liberally interpreted. The existing attempts to translate rules were conducted from a mainly top-down approach. The top-down approach of translating rules is when the translation is conducted from the rule enactor's perspective. This approach generally focusses on the absolute explication of rules that can be embedded directly in the software. The top-down approach requires that the designers abide by these rules, with limited to no possibility of exercising discretion. Instead, using an approach that accommodates the notion that rules must be translated with a certain level of vagueness allow the designers to specify their own interpretation.

Balancing the explication of the translated rules

A key aspect of translating rules is to deal with the confusing, ambiguous and inconsistent formulations that are created by the rule enactors, both deliberately and by accident. Such formulations have been conceptualized as business ramblings [22], which could exist as the term "often." "Often" does not contain any explicit logic. Instead, it could be interpreted in many ways, such as 1) more than 50 % of the time; 2) always, but in some instances, the rule could be circumvented; or 3) in 99 % of all cases. Such interpretations can be subject to even further scrutiny, such as number 2, which then leads to specifying in what cases. Formulations like "often" can be considered by the rule users (e.g. designers or developers) as a poor, faulty or unnecessary formulation. However, the intent of the business ramblings is often to embed interpretive flexibility for the users of the rules. The interpretive flexibility means that "often" allows the user to circumvent the rule if required by the context of the user. The flexibility formed by the business ramblings makes the use of rules easier in various situations that the rule-makers have not considered when conceiving the rules. If the rules were created to accommodate all thinkable scenarios, the formulation most likely would be highly exaggerated and complicated and thereby be impractical for humans to learn, apply, and maintain. To illustrate such relationship, Figure 1 shows four quadrants that translation could follow. When translating rules at the traditional atomic level, many scenarios are included in the automation, which also embeds a high complexity. When few scenarios are accommodated for, the complexity is typically low, unless the translation has been inefficient and therefore embeds unnecessary complexity. Translating rules with a low complexity that accommodate many scenarios is unrealistic and therefore considered a utopia.

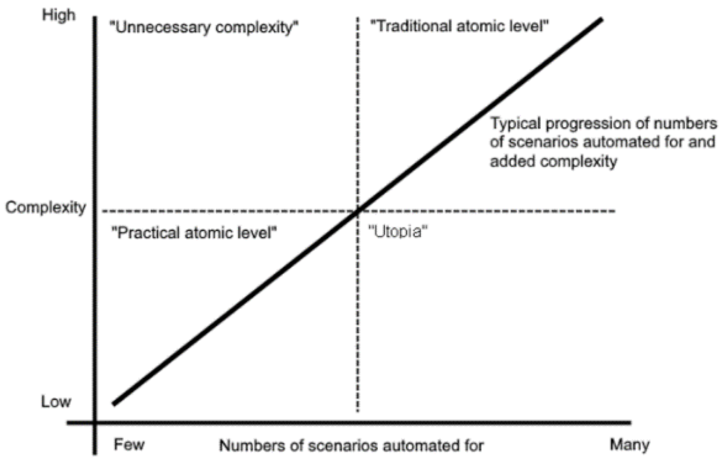

Figure 1: Relationship between complexity and number of scenarios automated for related to the translation of rules.

Instead of focusing on creating rules to accommodate too many scenarios, the focus must be on allowing businesses and projects to adapt the interpretation of the rules. Such an adaption requires the translation to be focused on a *practical* atomic level, as opposed to striving for an atomic explication of translating the rules to serve all scenarios. The *practical* atomic level is an approach to balance the translated rules to be less complicated by reducing the applicability of the rules to the practical level. What determines the practical level is based on the context of the business or project, which also dictates the specific interpretations of the rules.

USING BUSINESS RULES THEORY FOR TRANSLATING RULES

The results of the interviews indicate that the translation of the rules needed to improve with respect to transparency and better accommodate the business and project context in a balanced approach. This calls for a closer look at the traditional approach of handling rules. Rule enactors should specify rules that carry the intent of guiding positive behavior but embed enough leeway for the users of the rules to adapt them to their context and still fulfill the original intent.

In the domain of business rules theory, similar issues have been encountered. A business rule perspective makes the translation of rules business-centric, and such rules can be defined as "*a statement that defines or constrains some aspect of the business. It is intended to assert business structure or to control or influence the behavior of the business*" [22]. A business-centric approach to handling the rules requires that the rules are defined by what is essential for the business. Moreover, the businesses own the rules, not the enactors or software developers [32]. This perspective differs from previous research, which only diverges between the developers and the users, such as designers or process specialists [3,8,33].

In practice, the rule enactors still have ownership of the untranslated rules that contain the vaguely formulated rules. The practitioner's business takes ownership of how they translate the rules according to their business interpretation, and they make adaptions at a project level. The rule enactor formulates the rule statements that are concise enough to provide the intent but leave them loose enough to allow the designers to adapt it to their contexts. For example, stating that room height must be more than 3 meters high (as formulated in natural language) states the intent of the needed vertical space in rooms. However, it allows interpretation of what constitutes room height, which is not straightforward across potential scenarios. Since the intent is to ensure vertical space in rooms, is it only the room itself, or is it the functional space of a room (requiring that the space installations occupy are subtracted). At the business level, domain specialists translate the rules from the rule enactors into if-then-else statements that still contain leeway, but they also specify the assessment quality. For example, by specifying that room height will be determined by a parameter in a BIM data object specifying a room. These rules can be instantiated into the chosen BMC systems and, e.g., allow the designers to override the parameter specifying the height in the room manually.

Though it is a simple approach to assess the rule; it provides the designer with an easily understood assessment and enables the designer to override the parameter when needed. Other approaches to assessing the rule are conducted as complicated calculations to incorporate as many as possible scenarios of assessing the rule. A potential problem with this approach is that the rationale of how the model checking is conducted becomes hidden in its complexity and removes the designer's ability to conduct discretion by relying on the hidden mechanisms. Moreover, the comprehensive calculation will never be able to assess room height for all possible scenarios and will, therefore, embed uncertainty. If viewing the translation of such a rule from the perspective of business rules, the rule must strive to represent the business as much as possible and limit the constraints of the technology. The designers must be in control of the calculations to ensure certainty of the assessment. Therefore, it becomes an issue if too much information about the calculation is hidden. When incorporating the business layer in the translation, it improves the business ability to conduct efficient and continuous rule maintenance and improvement [32]. This approach reduces the risk of wrong or inconsistent rules because its translation is derived from the business itself and not by system developers with limited business knowledge [34].

Making the translation business-centric necessitates a clearer separation between what is important for the business (e.g. the business logic) and how it is represented in systems (e.g. the data models). Such separation yields flexibility by allowing the domain experts, like designers, to change the rules more efficiently because it improves transparency and flexibility. In general, structuring a system can be beneficial in improving [22,35]:

- a better understanding of what is relevant for the business,
- better capture of softer rules that make use of human judgment,
- tracking problems for the businesses,

- documentation of the business decisions (based on the business rules used for assessing),
- application maintenance costs,
- flexibility (because domain experts can easily change the rules using visual tools),
- integration of components from other systems that would be relevant for the business and
- reuse of business rules among a variety of systems.

Business rule ontology

The Business Rules Group (BRG) suggested an ontology (the conceptualization of terms and relations) to represent and reuse domain knowledge related to business, formalized in the business rules [36]. The use of the ontology is to ensure a rigorous basis for translating rules that are important for businesses and make the rules applicable to business rule checking systems [22]. The business rules are specified in statements that have the intent to control the behavior of people in business from filing documents to ensure alignment with the strategy of the business. The statements defining business rules can found in natural language text, which can be categorized into three types of business rules [22]:

- **Structural assertions**

  A structural assertion is a statement concerning static aspects of a business and is used to describe possibilities. Structural assertions can define aggregates (a room is a part of a building), roles (an auditor may document the score according to an assessment method) or association (mechanical ventilation with outdoor air may be used). It can also state facts relevant to the business such as, "Name is an attribute of the user" or generalizations like, "Designers optimize the building for DGNB." It specifies the businesses structures and paths of the business processes that are of importance.

- **Action assertions**

  An action assertion is a statement that concerns the dynamic aspects of a business and describing constraints. Often, action assertions are described as a "must" or "should," which impose constraints. For example, "A room must have a classification code." Here, the action is creating rooms in a BIM model and is subject to the action assertion business rule that rooms must have a classification code. Thereby, the action assertion is constraining the designer during the creation of the design.

- **Derivations**

  This is where inference or a mathematical calculation creates a derived rule:

  - Rules can also be created due to inference by logical induction or deduction. A rule defined by a deductive derivation could be, "All woodwork in the construction must be sustainable." Then it would be known that the wooden rafters must be made with sustainable wood.
  - A derived rule by mathematical calculation is produced according to a mathematical algorithm. For example, "You will get 100 TLP points if the LCC value is equal or lesser than 3000 USD per square meter of the buildings building area". A derived rule can be put into a mathematical formula and be calculated.

A business rule can be combined with one of the three rule types described above, and they are formulated in statements. These statements can be expressed in prose (i.e. natural language), formulas or figures. The statements contain terms and facts. Terms are the objects set in order by the facts. Terms are the parts of the business rules that specify and set information consistency. Terms are often specified in dictionaries or/and an entity-relationship model. Facts are the relationships between terms. Examples of terms could be "room," "has," or "height." Also, it could be a composition of terms such as sustainability assessment score. The terms are combined in an order that constitutes a phrase, which defines the facts.

The terms are divided into two categories: business terms and common terms. Business terms contain specific meaning in a specific context, whereas common terms are universally usable. Business terms are also characterized by being related to facts. An example of this could be the term "height." If not defined otherwise, industries like construction have cultural understandings of what defines "height," for example, in the context of rooms and the construction industry. In this context, it could be defined as the height from the top edge floor to lower edge ceiling. In rule translation, this needs to be specified to achieve the atomic level required for the rule to be computer-executable.

Using BPMN2 to express the rule process

When tasks are operationalized, the business rules are put into action and transformed into business processes. The business processes are tasks subject to the rules, which is made visual to improve the transparency for the users to enable continuous improvement of the process. Business Process Model Notation version 2 (BPMN2) can be used to express the connection between the business rule and the process. The rules are explicitly formulated in logical based language and portrayed in flow diagrams in BPMN2, which is a standard for process notation. TheBPMN2 approach can improve the communication of processes among business users and has previously been utilized to express and formalize rules in the construction industry domain (Dimyadi et al., 2014).

Figure 2 shows the basic modeling elements of BPMN2, including the event, activity, gateway, sequence flow, association, pool, lane, data object, message, and flow. The event is described when something happens, and the activity is a generic term for when work happens, such as a task. A gateway is used to control divergence and convergence of the process flow. The sequence flow dictates the order of activities in the process. The association links information with activities. The pools and lanes define collaboration between actors. The data object is a container of information produced or used by activities.

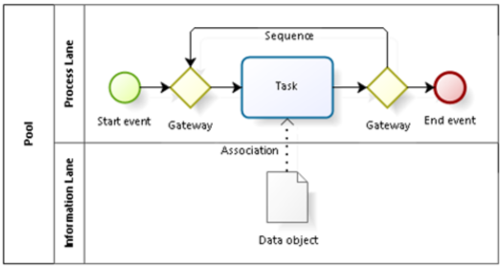

Figure 2: Basic modeling elements of BPMN2.

Expressing information requirements as BIM-information.

Using BMC systems entails using one of more BIM models as a repository for design information that can be used by a BMC system checking mechanism. The rules set requirements for the information needed to conduct the checking. For example, if a rule states that rooms need to be higher than 3 meters, the information "room" is required with attributes of "height." Each of the information requirements is related, which needs to be expressed and can be associated with a given BIM format like IFC or a proprietary format like the Revit. The required information, like "room" and its associated attribute "height" will be gathered from a BIM-model and when expressed be formalized according to the format's specifications. As a concrete example, a room in IFC2x4 is named IfcSpace where its attributes are related in, e.g., PropertySets. A traditional approach to describe information related to a business is the entity-relationship diagramming method [38]. Entity-relationship diagramming can assist in graphically expressing information with associations and dependencies.

BUSINESS-BASED RULE TRANSLATION METHOD

To improve the translation of rules we suggested an approach that differed from the current trends of normativity. Being informed by practitioners in how such improvements could be envisioned we identified the need for a more situated approach to conducting the translation based on the business to allow for a more contextualized translation. Using theories from both Business Rules, Business Process Model Notation, and Entity-Relationship Diagramming.

The translation is initiated through the identification of rules in the sustainability assessment methods specified as natural language text. In this text, the terms and facts analyzing the need to specify the rule were located and categorized as either business terms or business ramblings. The translated rules were expressed as If-then-(else) statements, which are known from conditional programming to express logic. Afterward, the *terms* expressed the information required in IFC. The formal rule statements will be organized into sequential steps illustrated in BPMN2, explicating the logical order of rule execution. Based on the insights from BRG [22], this method was developed to assist practitioners in translating natural language rules into If-then-(else) statements in the following steps:

1. **Identify rule statements (facts)**

   Identify the rule statements found in the rulebook as prose, tables, or illustrations.

2. **Identify terms (business and common)**

   Separating business and common terms and deriving business terms from making the rule atomic.

3. **Categorize rule types**

   Categorize if the rule is a structural assertion, an action assertion or a derivation.

4. **Address business ramblings**

   This step makes the business ramblings explicit and requires interpretation. This expectation means that unless the translator has contextual knowledge to address the business ramblings, contact is needed to the rule-makers who will assist in ensuring the intentions are translated best as possible by doing the following:

a. **Remove unnecessary ramblings**

What defines unnecessary is the context. If a rule is made for manual processing, specific manual characteristics can be removed in the case of automation.

b. **Interpreting business ramblings**

This step is related to the identification of business terms. However, if the logics are related to a business context, this is to be made explicit.

c. **Achieving a practical atomic level**

Emphasize simplistic translation of rules to reduce unnecessary complexity.

5. **Express the rule as a formal rule statement**

The rule will be expressed in a formal rule statement written with control flow statements.

6. **Identify information requirements**

Finding the needed information objects required for processing the rule assessment.

7. **Express the information requirements as an entity-relationship diagram**

Use entity/relationship diagram to express the relationship between objects in the rule

8. **Express the logical processing of the rules**

The processing of the rules will be expressed in BPMN2, and process function is identified.

TRANSLATION OF DGNB-DK FROM NATURAL LANGUAGE INTO FORMAL RULE STATEMENTS

To explore how the rules of sustainability assessment can be translated from natural language into computer-executable rules, the devised method was applied based on the BRG definitions. This example will be used as a proof-of-concept to how this applied when translating sustainability assessment methods, such as DGNB-DK. The example of DGNB-DK Office buildings 1.1. ECO2.1-2 Room height criterion was used, and the eight steps formulated in the previous section were done. The ECO2.1-2 Room height criterion was used due to its combination of explicit and implicit formulated rule statements and its scope being fit for translation in an article format. Moreover, it contains business ramblings necessary to filter to ensure consistent and precise translation of the rules.

Translating DGNB-DK Office buildings 1.1. sub-criterion ECO2.1-2.

The first steps were to identify the facts and terms of the rule. In Table , the text was extracted and translated from Danish to English, where the rule statements were identified. As indicated in Table , eight rules were identified. The rule statements were spread among the sections of the DGNB-DK Office buildings 2014 1.1., in the method, evaluation, and documentation sections [21]. Each rule was identified as natural language prose in sentences, except Rule 5, which was expressed as a logical statement.

Table 2: Identification of rules from ECO2.1-2 Room height criterion in DGNB-DK 'Office buildings' 2014 1.1.

	DGNB-DK natural language text	Identified rules
Method	Room heights were determined according to the current building codes. In connection with new construction, the height was determined using the sectional drawings and, in the case of existing buildings, also	1. Room heights were determined according to the current building codes. 2. In connection with new construction, the height was determined using the sectional drawings and

	by measurement. If the ceiling was not horizontal, the height was measured as average height. The room height was determined as the shell house measurements = top edge floor to lower edge ceiling.	in the case of existing buildings also by measurement. 3. If the ceiling was not horizontal, the height was measured as average height. 4. The room height was determined as the shell house measurements = top edge floor to lower edge ceiling. 5. Room height > 3,00 m = 10 TLP 6. To be interpolated between the specified values. 7. Criteria were relevant for all rooms, excluding toilets and similar secondary rooms. 8. Display of heights on extracts from section drawings.
Evaluation	Room height > 3,00 m = 10 TLP	
	To be interpolated between the specified values.	
	Criteria were relevant for all rooms, excluding toilets and similar secondary rooms.	
Documentation	Display of heights on extracts from section drawings	

The rules identified in Table were translated from the natural language text for interpretation into a formal rule statement. The natural language text was separated into the headlines of the sub-criterion chapter and was again separated into eight isolated rules. Each rule was then analyzed in relation to solving the challenges related to business terms and related business ramblings. Solving these challenges entailed removing unnecessary ramblings (e.g. ignoring that height must be determined using sectional drawings), interpreting business ramblings and translating the rules into a practical atomic level (e.g. both specifying that the business terms Room and Height were to be understood as a value found in the

BIM model like room_height). Moreover, one rule was derived based on a referral to an external rulebook, the Danish building code. Table shows the results of the translation into formal rule statements and the identified information requirements.

Table 3: Rules identified from ECO2.1-2 Room Height criterion in DGNB-DK 'Office buildings' 2014 1.1.

Number and rule category	Short text	Text	Interpretation	Information requirement	Formal rule statement	Function
Rule 1 (Action Assertion)	Are room heights gathered according to the current building code?	Room heights are determined according to the current building codes.	Current building codes are interpreted as "BR 2015" [1] Section of the building code relevant is named "3.3.1 Boligers indretning". Paragraph 5 is relevant to determine if the spaces are disqualified.	"Room height," "Current building codes."	See "Sub-rule 1.1."	Room filtering
Sub-rule 1.1 (Derivation)	Are the room floor areas > 3,5m² and Room Height > 2300mm?	If the ceiling is not horizontal, the height is measured as average height, and only free heights of 2.1 m and above are included. In rooms with slanted walls, the requirement may comply with a ceiling height of at least 2.3 m of at least 3.5 m² floor area.	If height varies in a room, then, do not include heights smaller than 2100 mm. If the room has slanted walls or roofs, rooms are included if room height is at least 2300 mm across 3.5 m² of the floor area.	"Floor area", "Room height"	If "Floor area" > 3.5m2 and "Room height" > 2300mm Then Include Else Exclude.	Room filtering
Rule 2 (Action Assertion)	Average room height	If the height of the room is not horizontal, the height is measured as average height.	If the ceiling height varies, the height is measured as the average height of the room.	"Room height."	If "Room height" varies Then use "average height" Else use "Room height."	Information gathering

[1] http://bygningsreglementet.dk/.

Rule 3 (Action Assertion)	Is room height measured from top edge floor to bottom edge ceiling?	Here, the room height is determined as the shell house measurements = top edge floor to lower edge ceiling.	Room height must be measured from the upper edge floor to lower edge ceiling.	"Room height."	If "Room height" = ("Base constraint" ="upper edge floor") and ("top constraint" = "lower edge ceiling") Then use Else reject.	Information validation
Rule 4 (Derivation)	Is room height larger than 3.00 m	Room height> 3.00 m = 10 TLP	Room height> 3000 mm = 10 TLP	"Room height"	If "Room height" > 3000 mm Then = 10 "TLP" Else 0 "TLP".	Score calculation
Rule 5 (Action Assertion)	Interpolate values	To be interpolated between the specified values.	The individual room heights are to be interpolated	"Room height."	Interpolate "Room heights."	Score calculation
Rule 6 (Action Assertion)	Is room type primary?	Criteria are relevant for all rooms, excluding toilets and similar secondary rooms.	All interior rooms must be assessed except for toilets and other secondary rooms.	"Room type."	If "RoomType" = primary (is not secondary) then Include Else Exclude.	Room filtering
Rule 7 (Action Assertion)	Generate documentation	Display of heights on extracts from section drawings	This Rule will be satisfied through digital documentation.	Na.	Na.	Documentation generation

To formalize the relationship between the information requirements (which can be used to express information requirements based one, e.g., IFC), an entity-relationship diagram was used.

The logical processing of the rules was then specified in the BPMN2 diagram illustrated in Figure 3. Here, the rules were specified into a BMC process, where each of the general BMC functionalities was expressed in dashed/dotted lines that framed the tasks to conduct the rule checks in a context of using the information. The process is then an instantiated suggestion of how best to execute the check using the results of the translation of the ECO2.1-2 criterion.

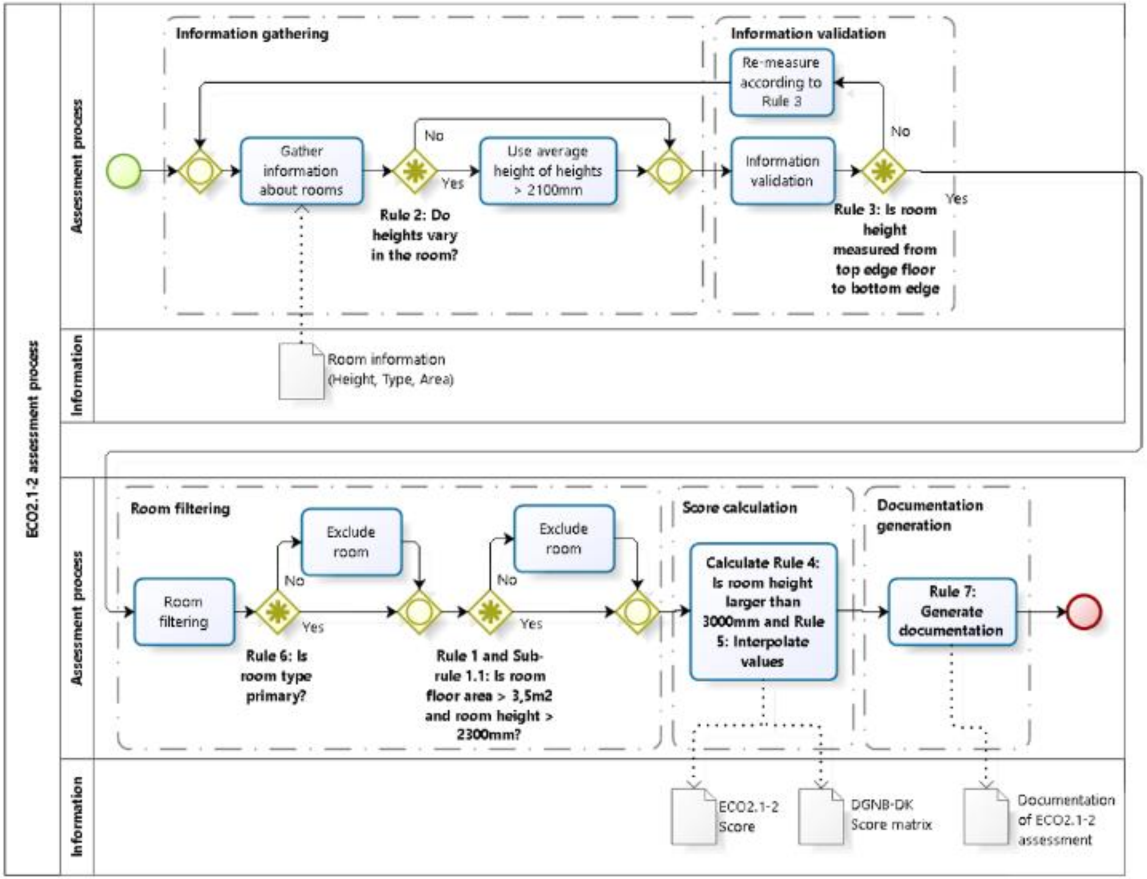

Figure 3: Assessment process of ECO2.1-2 Room height criterion.

DISCUSSION AND CONCLUSIONS

The exploration of the practitioner's experiences indicated a need for transparency, flexibility, and recognition of unique situated requirements in the project contexts when rules are translated and used in BMC systems. Also, the exploration of the Singaporean practices indicated existing challenges regarding the consequences of normative translations of rules that led to unwanted restrictions of the building design. The insights from the interviews led to the development of a business-based translation method that emphasized the local context of the businesses. The method was then exemplified with the translation of a sustainability assessment criterion ECO2.1-2.

The significant difference between contemporary methods of rule translation for BMC systems and the method presented in this paper is the focus on translating the rules in the business and not enforcing a normative translation upon the users that can lead to unwanted consequences as exemplified in the findings from the Singaporean practices. There would be substantial benefits of succeeding with a normative translation in that it would simplify the translation process by having one absolute interpretation that also would ease the verification of BMC systems results. However, while the normative-based methods have been recognized as the only approach used in BMC-systems it has not so far been successful as stated in the introduction. Potentially, a different focus is needed that shifts the research related to both translations of BMC systems rules and BMC systems in general. Instead of attempting to develop potential restrictive, inflexible and opaque normative translations, an alternative approach of supporting designers and their businesses by allowing them to make their interpretation. This would require a completely new approach levitating the practical flexibility and transparency of the BMC systems for the users and set many new challenges. For example, a business-based translation will require all businesses to conduct their interpretation that would require much more resources and complicate verification.

Looking at the traditional process of assessing designs using rules, situated interpretation (in the businesses and projects) is standard procedure, which allows the designers to make their interpretation and get it verified by the rule enactors (e.g., authorities). The legal ownership of how rules are interpreted traditionally is based on the users, but with a normative translation that limits the possibility for situated interpretation, the responsibility is moved to the translators (either developers or rule enactors), which is not necessarily desirable.

Allowing for business-based translation will allow the designers to conduct discretion, but are often perceived as being lazy or with maligned intentions of subverting rules [39]. Instead, discretion should be perceived as a sensible and practical approach to implementing rules into the complex context of building designs to fulfill the intent of the rules and goals of the design into the realities of the design practice. Also, using a business-based translation is not an approach where everything must be available for interpretation but can also contain normative aspects such as stated by explicit criteria. However, it opens the discussion about to what degree should an interpretation be normative or situated. One consequence of the business-based translation would be how best to allow the businesses to interpret the rules and another is how for rule enactors to verify the translations. Using the business-based method will not only enable the rules to be automated using BIM-systems; it also serves as documentation of how the rules were assessed. Where normative translations allowed to easy verification, the business-based makes that much more challenging. Reviewing a translation according to if it serves the rule enactors intent would require human intervention or new technological solutions. For example, application of machine-learning that could assist in recognizing patterns in the business-based interpretations that could classify them as verified or not.

Another challenge is how technologically the handling of the business-based translations. Other domains make use of business process management software can improve flexibility and transparency that enables businesses to continually improve the interpretations of the business rules and processes. Currently, BIM-based systems like Dynamo is popular in many companies, which allow the use of BIM-information to automate various processes according to business needs, which is highly transparent and flexible that are increasingly being used by practitioners.

While a business-based method of translation would complicate and lessen control of the interpretation is the upside that the individual business and project unique characteristic can be accommodated potentially leading to more flexible use of BMC systems, better buildings and more competitive businesses. As design businesses key feature is the ability to create knowledge-based on, e.g., efficient and effective assessment of buildings the businesses should be able to make their interpretations that match their context.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgments

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6. DEVELOPMENT AND TEST OF A FLEXIBLE AND TRANSPARENT BIM-BASED MODEL CHECKING PROTOTYPE (PAPER IV)

Paper III both empirically explored and suggested a method for how to improve the translation of natural language to computer executable language for practices. The article empirically explored practitioners' work regarding rules supported and unsupported by BMC systems. This was done to investigate the characteristics of the practitioner's environment and what Socio-technical experiences help to inform improved translation according to the requirements of DSR.

6.1 USING ACTIVITY THEORY CHECKLIST TO ASSIST IN OBJECTIVELY INDENTIFYING SOCIO-TECHNICAL CHALLENGES

Semi-structured interviews were used to explore the practices and an Activity Theory Checklist was used to assist exploring the practitioners' work. The Activity Theory Checklist assists in holistically covering the investigation of the phenomenon, following the Activity Theory framework previously presented. The checklist provided a space of context that assisted in clarifying the most important socio-technical factors of the inquiry.

Moreover, it assisted in making the interviews more objective, because the questions were based less on the interviewer's potentially biased questions, but instead on a structured list of questions drawn from the checklist adapted to the article's context. The results were framed according to the Activity Theory Checklist and afterwards the results were categorized and compared. Figure 5 illustrates the timeline of how the data was gathered and processed.

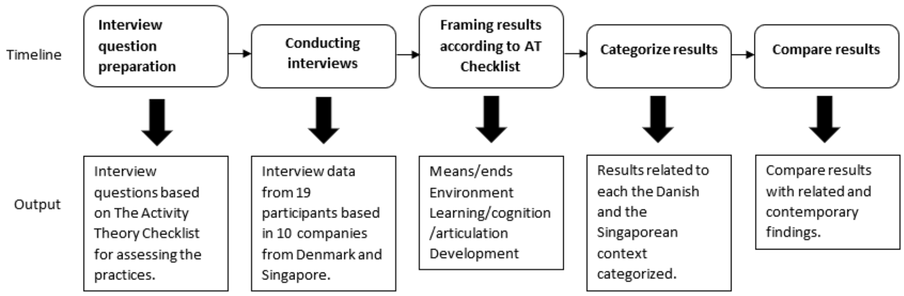

Figure 5: The timeline of research activities and their output of Paper III.

6.2 A BUSINESS-CENTRIC APPROACH TO IMPROVE TRANSLATION OF IMPLICIT RULES

The investigation led to suggestions for situating the translation in the building designers' businesses. Placing translation at the business level can potentially allow users to trust the localized interpretations more, due to the shorter distance between practitioners working with the rules and the people translating them. Allowing for more localized interpretation and flexibility, this also emphasizes "practical atomic levels" of translation. This perspective diverges from the traditional approach of translation, i.e., normative translation.

In an attempt to reduce the complexity of the world, standardizations are often used. While standardization is a reasonable approach in some cases to reduce complexity, in others it constrains practices. Translating rules at a national or regional level becomes normative of how rules are to be processed. In an attempt to create normative rules, Hörl (2017) argues that the rules become axiomatic. Rules become self-evident and cannot be rejected due to the limited formal, symbolic order of reason, which contains arbitrary connections between data.

Such rules carry the risk that the user's input in applying the rules will be limited, with the result that the system and its translation become negligent of the unique contexts of the projects. Translators cannot be objective but often carry imperceptible cultural, social, and economic patterns, which will manifest themselves in the normative translations (Kant 1800).

6.3 FORMALIZING KNOWLEDGE IN A SITUATED CONTEXT

Insights from other domains than construction have shown that formalizing knowledge in a situated context such as a business can work. There are several reasons why positioning formalization around businesses is more desirable than at national (e.g., Denmark) or regional (Scandinavia) levels. Formalizing knowledge at higher levels means that more of the commonalities between people's declarative understanding of what a concept is are challenged. Among nations, for example, the homogeneity of terms used for building materials can vary. However, businesses contain fewer people and have more streamlined cultures and policies that dictate processes and terminology by being more "limited domains".

The business-centric theories of formalizing knowledge as either process (Business Processes Theory) or rules (Business Rule Theory) are successful in other domains such as the banking and rental sectors (Gottesdiener 1997). These theories are built on the notion that the business is the natural place for creating, managing, and disseminating knowledge because it is a natural part of the business's competitive advantage.

Meanwhile, formalizing knowledge on a national scale has the potential to broadly assist an industry but is not limited enough for people to agree on concepts. In an attempt to do so, Sowa (2004) argues that such generalizations will fall short due to *"questions lurking in the penumbral background"* that might lead to over-generalizations, abnormal conditions, incomplete definitions, conflicting defaults, and unanticipated applications. eBDAS BIM was one example of a system that was created for the industry but was very limited in both its scope (explicitly transformed building codes regarding buildability) and industry (the city-state of Singapore). Using the method proposed in paper III moves the responsibility for translation to the business and suggests a practical approach to managing the formalization of knowledge regarding the rules.

6.4 A BUSINESS-CENTRIC APPROACH TO IMPROVE TRANSLATION OF IMPLICIT RULES

The next article, paper IV, investigates how are the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) and how they are experienced by practitioners using BMC systems. This is done to give insights of how to improve BMC systems can be improved to better support building designs with sustainability assessment. It makes use of rules translated using the method suggested in paper III. Here, the aim is to operationalize the BMC systems using the insights gathered from the previous articles presented in this thesis.

The prototype developed in paper IV is built on the notions of ecological rationality, which manifests itself in allowing rationality to be decentralized and thereby manifest such rationality at the business and the project level in interpreted rules. This decentralization enables users located in the contexts of the businesses and projects to employ discretion in the translation. The business formalizes general rules that the user of the BMC prototype it is permitted to adapt to project contexts.

Moreover, a business-centric approach emphasizes characteristics that allow the users to make such adaptations, including transparency, which embeds trust and flexibility in the structure of the prototype. More concrete theories are utilized in paper IV to include these characteristics, including the theory about process-aware information systems and business process management. The practical applicability of the proposed BMC prototype is demonstrated by allowing building design practitioners to use it to solve a building design task of assessing a sustainability assessment criterion.

The use of the prototype to assess the criterion was qualitatively and quantitatively measured to get insights into the effectiveness of the prototype. These results were used to discuss the potential benefits and challenges of adopting such characteristics in a BMC prototype. Therefore, the research question is *"How are the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) are experienced by practitioners using BMC systems?"*

DEVELOPMENT AND EVALUATION OF A FLEXIBLE AND TRANSPARENT BIM-BASED MODEL CHECKING PROTOTYPE

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SUMMARY: The use of BIM-based Model Checking (BMC) has the potential to improve building design processes by enabling the automation of building assessments. However, only a few BMC systems are being used in building design practice. The limited use is related to socio-technical challenges that have so far not received much attention in research regarding BMC systems. To explore these challenges, a Design Science Research methodology was used to design a BMC prototype to improve the socio-technical challenges of BMC systems, specifically challenges of transparency and flexibility. The prototype was evaluated by practitioners to investigate aspects of BMC systems that potentially hinder its use. The results were used to discuss the socio-technical challenges of using the prototype to assess a test case.

KEYWORDS: *BIM-based Model Checking, BIM, Flexibility, Transparency.*

1. INTRODUCTION

BIM-based Model Checking (BMC) is deemed one of the most promising technologies to support the design of better buildings (Refvik *et al.* 2014, Hjelseth 2015). In both research and development, BMC is used for various types of assessments ranging from building codes, safety, and sustainability (Ding *et al.* 2006, Zhang *et al.* 2013, Kasim 2015). The application of BMC in building design practice can potentially enable a faster, more precise, and more consistent assessment (Hjelseth 2015, Khemlani 2015). BMC has been a focus of research and development for years, but its practical use has been limited (Dimyadi and Amor 2013, Refvik *et al.* 2014, Kasim 2015, Dimyadi and Solihin 2016, Khemlani 2017). BMC is a relatively new term describing the automated processes of assessing BIM models during its entire life-cycle. There exist many terms related to this process, including rule checking, model validation, quality checking, automated code checking, BIM checking and code compliance checking, and many more. Hjelseth (2015) proposed BMC as a joint term to indicate the commonalities between these many terms and furthermore categorized BMC into four sub-types: validation checking (a comparison of the information in the BIM model against pre-defined rules), content checking (the right content and quality of information in the BIM model), smart objects checking (BIM objects that act upon predefined logic) and design options checking (which suggests alternative solutions using a knowledge database).

The main focus of BMC research and developed systems are aimed at the design phase. The BMC systems are developed as either commercially developed systems, like Solibri Model Checker, or large governmental projects like ePlan-Check (Dimyadi and Amor 2013, Refvik *et al.* 2014, Khemlani 2017). Currently, the main use of BMC in practice is focused on coordination, for example, the identification of collision between BIM objects (Hjelseth 2015). While BMC can improve various aspects of the design process, the adoption of the technology is slow and problematic (Refvik *et al.* 2014, Khemlani 2017, 2018). There has been identified as a lack of research concerning the role of the practitioners in the BMC processes (Dimyadi and Amor 2013). Despite a massive effort to develop and implement ambitious BMC systems like e-Plan Check, AutoCodes, and SmartCodes, they were discontinued (Refvik *et al.* 2014, Khemlani 2018). There are many reasons why the development ceased, but in a report by Refvik *et al.* (2014), it was indicated that one of the main challenges was of a socio-technical nature. *"The technology is mature and available; it is the soft human aspects of organization, culture, and adoption of the technology that are the real challenges."* (Refvik *et al.* 2014, p. 58). So far, there has been limited interest in investigating the socio-technical issues of BMC, but there are indications that some of these challenges are related to the BMC users' role, and their ability to understand and adapt the BMC systems. These challenges are being discussed as problems of hard-coding and black-boxing the information processes of the existing BMC solutions (Dimyadi and Amor 2013, Refvik *et al.* 2014, Preidel and Borrmann 2016, Kim *et al.* 2018, Fan *et al.* 2019a). Hard-coding means embedding data directly into the source code, limiting the users to make changes to the information processing. Black-boxing is when the users are unaware of how the information processes are conducted in a system.

Refvik *et al.* (2014) emphasize the importance of the user's ability to both understand (related to the issue of black-boxing) and to modify (related to the issue of hard-coding) the processes. Preidel and Borrmann (2015) explain that the lack of transparency detaches the user from the assessment process and creates uncertainty related to the correctness of the assessment, which can lead to legal issues. Lindblad (2018) also noted that the black boxing approach regarding BIM implementation resulted in several problems making the processes inflexible. The inflexibility is a product of the developers own preference of information processes, which typically is black-boxed in BMC systems. However, the practitioners need to adapt the information processes in order to ensure that the assessment is conducted according to their unique context (Reinhardt and Matthews 2017). The need to accommodate the unique context is also noted by Dimyadi *et al.* (2016) who notes that BMC systems need to handle the changes of new materials, performance requirements and contexts, which is challenging to manage in hard-coded or black-boxed systems.

The methodological approach to much of the contemporary BMC systems research is isolated and of technical character (Dimyadi and Solihin 2016). So far, no research has emphasized the practices of where BMC systems are designed to be used. Moreover, there is no dissemination of either experiences or surveys of practitioners using BMC systems (Preidel *et al.* 2017). Using a different methodological approach could contribute to explore some of the limited remarks about transparency and flexibility in regards to BMC systems. The existing research carries underlying ideas about the role of technology in organizations that currently have not been addressed. The common view of technology in BMC systems research is based on technological determinism. In essence, that technical logic determines the design of systems and social changes (Kline 2015). A concrete result of such technological view no research regarding BMC systems has emphasized the practitioner's experience. This presents a gap regarding BMC systems research and consequences about implementing BMC systems in practices remain largely opaque.

In order to start exploring the socio-technical challenges of BMC, Orlikowski (1992) states that by better understanding the technology and the environment in which it is used, it is possible to identify characteristics that both constrain and facilitate the development and use of technology. Aiming to consider the environment the Design Science Research (DSR) methodology is applied. DSR is suitable in information systems domains that are subject to changing and unstable requirements that require complex interactions among the sub-components of the problem (the design practice) and its solution (BMC systems). These interactions are dependent on the users' cognitive abilities (like creativity) and their social interactions. Such characteristics are found in the domain of BMC and the construction industry, which is characterized as being unstable, dynamic and unexpected (Bertelsen, 2003; Wood, Piroozfar, and Farr, 2013) and require complex social interaction (Cicmil and Marshall 2005, Kazi and Koivuniemi 2006). These characteristics make it difficult to apply BIM systems to be properly used in design practices where they do not always provide proper feedback (Gade *et al.* 2018). DSR emphasizes business needs (i.e., the practices) and knowledge base (e.g., BMC systems theory) into consideration in the development of new artifacts (i.e., methods or systems) built to address unsolved problems. The DSR methodology aims to create knowledge by a problem-solving paradigm that shifts perspective between the process of designing an artifact and the artifact itself. Also, it emphasizes the evaluation of the developed artifact´s utility for a better understanding of the problem (Hevner *et al.* 2004). DSR follows a pragmatic perspective where the utility is dependent on the context (design practices), and therefore, the evaluated prototype is not meant to be a perfect solution. Instead, it is meant as a mediating instrument built using theories to solve problems in order to discuss its utility or problems experienced in these practices.

In this article, the aim is accommodating the aforementioned gap in order to answer the research question of how the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) are experienced by practitioners using BMC systems. A holistic study is conducted using DSR to answer this question following the three steps based on DSR (Hevner *et al.* 2004): (1) The use of theory to solve existing challenges identified of BMC systems use. (2) Creation of a prototype using the previously identified theories (3) Practitioner evaluation of the prototype used to discuss the socio-technical challenges of BMC systems use.

2. METHODOLOGY

The use of new technology such as BMC systems will generate new practices, which entail that the technology must accommodate aspects of the existing practices. This relationship has been described by Orlikowski (1992) as the duality between the objective reality (the actual functions of the systems) and the socially constructed product (the uses that the users can imagine and apply in their practices). This duality necessitates a view of technology as interpretively flexible because individual users are subject to their socio-historical context. In other words, the use of a system is based on the individual user's historical context (e.g., education, project, company). Without recognizing that BMC systems need to accommodate existing practices, there is an inherent risk that unintended challenges will affect the practices that the systems aim to improve. *"The relationship between technology and society cannot be reduced to a simplistic cause-and-effect formula. It is, rather, an 'intertwining', whereby technology does not determine but operates, and is operated upon in a complex social field"* (Murphie and Potts 2017). Investigating how to better design and use BMC systems in practice necessitates an investigation of existing practices both with and without BMC systems to identify characteristics that need to be accommodated. The accommodation of such characteristics can potentially assist in the research and development of BMC systems that will be potentially more usable and less constraining for the practitioners.

The results of this process are used to disseminate insights that can be used to improve the functional performance of BMC systems. It is therefore not a study that sets out to focus on the specific individual aspects of BMC like interpretation, implementation, and validation, or the content of the BIM model or the prototype itself. Instead, it provides a holistic account of a BMC prototype evaluation that is used to highlight and discuss the socio-technical characteristics that potentially impair the functional performance of BMC systems.

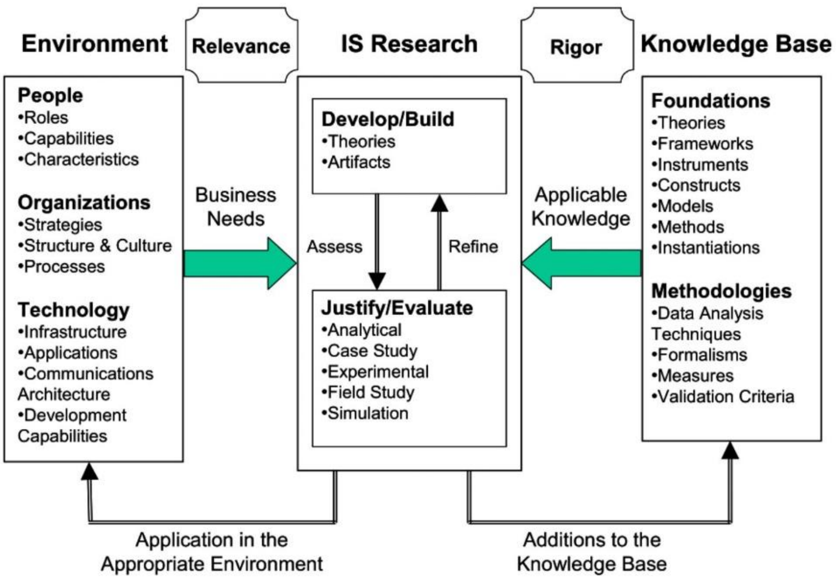

FIG 1: The DSR Information Systems Research Framework (Hevner *et al.* 2004)

According to the DSR methodology, knowledge is obtained through the developing/building the artifact and justify/evaluating it, see FIG 1. This entails that while it is not possible to find the best or optimal design for a realistic problem, it is possible to find an effective solution. Finding an effective solution is done by identifying the problems in the business, which sets requirements for the prototype. The prototype is then developed based on these requirements and evaluated in a realistic environment. While the process is iterative, a focus is based on simplifying the problem by representing a subset of the relevant problems (Hevner et al. 2004). This to answer the research question of the article, the cycle is conducted at the following steps earlier defined: (1) The use of theory to solve existing challenges identified of BMC systems use. (2) Creation of a prototype using the previously identified theories, (3) Practitioner evaluation of the prototype used to discuss the socio-technical challenges of BMC systems use. To fulfill the steps from DSR, the steps are translated into the following phases:

1. **Identification of requirements for the prototype (step 1)**
   Theories were proposed to improve the existing identified issues to allow better adaptation of BMC systems into practice.
2. **Creation of a prototype based on the requirements (step 2)**
   A prototype was created using readily available software tools that can accommodate the functional requirements identified in the previous step.
3. **Prototype evaluation (step 3)**
   The prototype was evaluated by practitioners and compared with their traditional approach to assessing.

3. RESULTS

3.1 Identification of requirements for the prototype

The requirements for the BMC prototype are based on the traditional BMC functionalities. BMC validation checking uses BIM to represent a designed building solution to verify if it complies with a set of rules (2016). Eastman *et al.*'s (2009) view of the process is more detailed, including steps of rule interpretation, BIM model preparation, rule execution, and report checking results. The notions from both Hjelset (2016) and Eastman (2009) have been used to formulate requirements for the BMC validation checking in the prototype. Also, we include functionalities to accommodate the socio-technical issues highlighted in the introduction, which include transparency and flexibility. These functionalities are based on solving two related issues of Black-boxing and Hard-coding. Black-boxing relates to the user's inability to comprehend the internal processes of the system (lack of transparency), and hard-coding is the user's inability to make adjustments to the systems processes.

3.1.1 Black-boxed BMC-systems

One of the dilemmas with BMC is the balance of transparency in the BMC systems. Users can be overwhelmed by the amount of complexity and comprehensiveness of the processes needed to be conducted by the BMC systems. However, the users still require a need to comprehend the processes in order to ensure trust in the system. A general tendency regarding BMC systems is that they are often regarded too complex for the users (Hjelseth 2015, Preidel and Borrmann 2016, Ghannad *et al.* 2019). So as not to overwhelm the users, the developers tend to black-box most of the processes, leaving a set of specific parameters open for adjustment. Cornelius and Borrmann (2016) argue that if users are not able to ensure the correctness of the BMC systems, this will lead to a lack of trust. Hoffman *et al.* (2013) argue that a lack of trust can result in the systems being rejected, and users will resume previous methods of working. Trust can be achieved through different means, including systems perceived competence, benevolence (or malevolence), understandability, and the degree to which it is possible to assert control when something goes wrong rapidly. Notably, a systems competency to solve the task at hand is required to be understood by the experts using the system which requires a level of transparency. This is because systems "*always hide things as much as it reveals them*" (Hoffman *et al.* 2013, p. 86). For example, sensors developed to prompt warnings might be miscalibrated. In relation to BMC systems that can be used to assess the room heights of a building, where the user is unable to scrutinize the assessment process, the user is not able to ensure that the quality is sufficient. The quality is defined by the quality standards of the contexts where the system is used, based on, e.g., localized standards, laws, technology, and culture (Reichert and Weber 2012).

3.1.2 Improving transparency

One of the possible solutions to improve transparency is the use of Visual Programming Language (VPL). Using VPLs for BMC systems can improve the communication of the information processes between the system and the users, thereby increasing the transparency. The improvements enabled by visual programming are that it makes use of higher-level operators such as nodes to conduct operations that are presented graphically. While visual programming can increase transparency, it also requires sound management of how it is applied. The poorly designed code in VPL makes it difficult for users to understand the information process and therefore requires structure, like coloring, commenting, grouping, and modularisation (Green and Petre 1996).

3.1.3 Hard-coded BMC systems

The majority of BMC systems (and information systems in general) are hardcoded (Preidel and Borrmann 2017, Fan *et al.* 2019b). Bell (1973) argues that the reason why developers tend to use this approach is that it is efficient for the developers to execute their changes in the system rapidly. However, this also embeds a disadvantage for the users because they must accept or circumvent the developer's processes. Findings (Dimyadi and Amor 2013, Beach *et al.* 2015, Preidel and Borrmann 2017, Fan *et al.* 2019b) indicate that there are issues related to the amount of hard-coding in BMC systems, which can indicate that the environment of BMC use requires an increased ability to adapt than the current systems allow. Reichert and Weber (2012) argue that information systems are subject to different types of change. For a system to provide relevant feedback (e.g., to assess a building design using the latest building codes), it needs to adapt to such changes. The changes arise from both external and internal drivers of change. The external drivers are the changing business and legal context, new technology, and system optimization due to organizational learning. The internal drivers are due to issues related to the development of a system, such as technical problems. The issue with BMC arises due to the different environments in which it is used. Each environment calls for a different adaptation to the changes, and the users must ensure that the BMC system processes the information with sufficient quality.

3.1.4 Improving flexibility

While some operations related to BMC are well-structured and highly repetitive, others are knowledge-intensive and highly dynamic. The latter is difficult to translate to fit all needs and contexts and imbue the translated processes with great complexity and comprehensiveness, which leads to difficulties of both maintaining and using it in practice (Reichert and Weber 2012). Research regarding the changes that users of BMC systems make is limited, and not much is known about what changes are required regarding effective practical use. However, to better adapt to the different practices, Reichert and Weber (2012) argue that it is necessary to implement a series of functionalities in systems that are subject to major change. To improve the flexibility of systems, they suggest considering the following:

1. **Separation between the logic and the data objects**
   Such separation will provide an additional architectural layer of the information processes that enhances the maintainability and traceability.
2. **Separation between run- and build-time**
   Providing a system architecture with a separation between run-time and build-time components emphasizes the user's possibility to change specific operations according to the specific context. The build-time components allow specialists to ensure certain aspects of the information processes' validity and permit continuous optimization.
3. **Loosely specified processes**
   When an information process is very comprehensive and detailed, it increases the chance that it is difficult to adapt. When it is loosely specified, an emphasis is put on making it as simple as possible. While it may not accommodate all situations of use, it provides the users with the ability to defer decisions made in the processes.
4. **Exceptions**
   Providing the user with the ability to deal with exception handling provided in the system code that will allow the user to adapt to the dynamic environments where a system is used.
5. **Performance analysis**
   Providing analysis of the information processes along with other performance insights that can encourage organizational learning to support the improvement of existing processes for both run-time and build-time users.

3.2 Creation of a prototype based on the requirements

The BMC prototype is created to accommodate the proposed requirements specified in the previous sections, including transparency, flexibility, and BMC system functionalities in relation to validation checking.

3.2.1 Prototype architecture

The prototype is based on three software components to accommodate the requirements; Revit, Dynamo, and Tableau. These software components were selected to accommodate the functional requirements (in TABLE 1) and based on familiarity with the industry where the evaluation was conducted. Autodesk Revit is the most used BIM authoring system in Denmark and was selected for BIM authoring. While Revit black-boxes many processes (e.g., calculation of quantities) it provides an interface many practitioners have become familiar with in Denmark. The limitations of the opaqueness can be managed using the visual programming competent named Dynamo (Dynamo BIM 2018), which is integrated into Revit. Dynamo can use information from the BIM models created in Revit and allows manipulation of the information through nodes and wires. Nodes are objects that perform operations, and wires connect those nodes. Dynamo contains a set of predefined nodes that can conduct basic operations, and it also allows the user to create customized nodes. Dynamo can be accessed either through the Dynamo player or as separate software. The Dynamo player is useful to execute the operations specified in Dynamo but does not present an overview. The data visualization software Tableau Desktop (Tableau 2018) was used to provide performance feedback to the user based on the BIM-based model checks conducted in Dynamo. The BMC-prototype architecture is illustrated in FIG. .

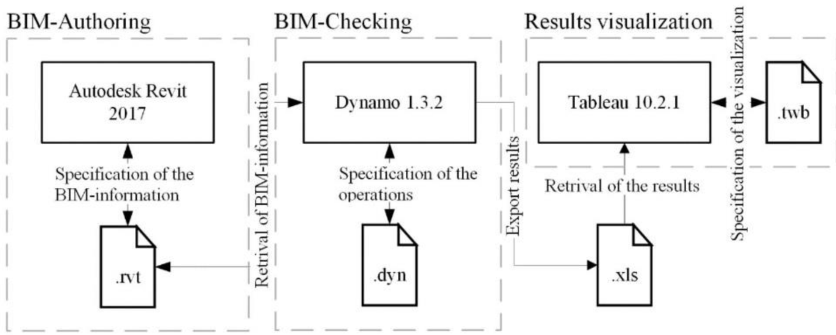

FIG. 2: The BMC-prototype architecture

The visual programming interface Dynamo allows both the run-time user and build-time user to achieve a visual representation of the operations of BMC. The prototype architecture is file-based and uses proprietary file formats for the sub-systems. The information from the project used in Revit is stored in .rvt. Dynamo uses .dyn to store the dynamo scripts and can export the results to .xls used by Tableau. Tableau stores its visualizations in .twb. Each of the software components fulfills a role related to the functional requirements (detailed in chapter 2.1) specified in TABLE 1.

TABLE 1: Functional requirements of the prototype

Theme	Requirement	Function	Software component
BIM-based Model Checking – Validation Checking	Rule interpretation	Formulation of rules in a programming language	Dynamo
	BIM-model preparation	Extraction of BIM-model information	Revit/Dynamo
	Rule execution	Apply the rules (in computer code) to the extracted BIM-model information	Dynamo
	Reporting checking results	Generate a report of the results from the execution	Dynamo
Flexibility	The separation between the logic and the data objects.	Separation between data objects and logic	Dynamo

	The separation between run- and build-time	Separation between the run-time and build-time users	Dynamo
	Loosely specified processes	Loosely specified processes	Dynamo
	Exceptions	Exception handling	Dynamo
	Performance analysis	Monitoring TLP score	Dynamo/Tableau
Transparency	BMC processing transparency	A structured visual representation of the automated processes	Dynamo

3.2.2 Structure of the information processes

The use of visual programming can be problematic due to the likely complexity of the comprehensive presentation of the code that makes it difficult for users to comprehend. Because of that, visual programming requires sound management of how the processes are structured and presented (Reinhardt and Matthews 2017). The processes are structured according to the hierarchical structure. The logic/data objects have been separated into individual nodes and as run- and build-time components. The separation of the run- and build-time users allows a better possibility to maintain the checking operations. The run-time user can alter operations and accommodate aspects envisioned by the BMC system developers or the build-time user. As an example, rulesets often contain measurements like room height without being specific about how such measurements are to be used in all possible scenarios due to practical considerations. Instead, it is the discretion of the users of the rules to provide details of how the rule is interpreted in the specific scenario. If room height is used to specify the flexibility of use of rooms, i.e., can a room be used as an office or a showroom, it is the room height clearance. However, is such clearance constrained by, e.g., lamps or HVAC equipment? Allowing the separation of both run- and build-time users allow aspects of the operations to be changed in order to make such decisions.

In the prototype, the separation will happen based on the operations (i.e., nodes) that are available for modification by the run-time. Nodes available for project-based adaptations will be denoted as P-nodes. For example, a P-node contains an operation regarding the retrieval of room-height information from a BIM-model. Operations that contain aspects that are important for a company are denoted as C-nodes and cannot be altered by the run-time user. An example of such a scenario is, e.g., when an operation is considered well-structured and highly repetitive. If the calculation of a score related to the building code is explicitly formulated, then it makes no sense to allow the alteration of this calculation by the run-time user. However, in some cases, companies find it important to exceed the minimum of such scores, and therefore, it is a company-specific operation that specifies when a score is acceptable according to their quality requirements.

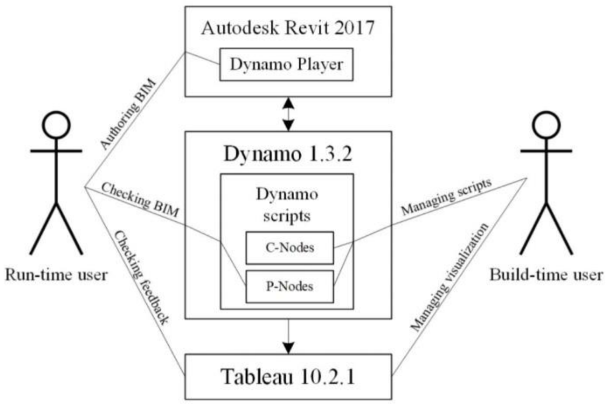

FIG. 3: Prototype use-case diagram

FIG. shows a use-case diagram illustrating the run-time and build-time users' interaction with the prototype. The run-time user authors the BIM-model and uses either the Dynamo player or the Dynamo stand-alone software to execute operations, while having the possibility to both scrutinize the operations and adapt the P-nodes in relation to the project-based requirements. The build-time user is responsible for managing the scripts in Dynamo that contain the nodes and the visualization of the results in Tableau. He aims to harmonize the scripts used by the run-time user to be as efficient as possible and aligned with the company's strategies and, e.g., updates to the rules.

The visualized processes can also benefit from an information structure. Preidel and Borrmann (2017) proposed the modularisation of the visual programming semantics and ontology. In this article, a focus will be put on a higher-level structure and modularisation due to the use of existing visual programming software that already provides a low-level structure (semantics and ontologies related to, e.g., the operations that nodes conduct). The structure used in this article will follow a hierarchal structure based on the fundamental steps of automation suggested by Parasuraman, Sheridan & Wickens (2000):

- **Acquisition** - Registration of input data, e.g., registration of the right definition of room height from a BIM model.
- **Analysis** - Analysis of input data through algorithms, e.g., calculating the average room height.
- **Decision** - Selecting a decision based upon the analysis, e.g., assigning the right score to the average room height.
- **Action** - Conducting the correct action based on the decisions, e.g., submitting the score to a score database.

This structure will assist the users in identifying specific parts of the information processes. If the user knows what aspect of the check he needs to scrutinize, e.g., what information the room height is based on, the user can identify that such information will be placed in the Acquisition node. The operations needed to conduct the Acquisition would include gathering the right data from the BIM model and assembling it for the Analysis, e.g., the process of obtaining the right room height data.

3.3 Prototype evaluation

3.3.1 Rules used in the prototype

The evaluation was conducted using rules translated from a criterion from the Danish sustainability assessment method Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB-DK) "office buildings" 2014, 1.1. (Green Building Council Denmark 2014) and a BIM-model of an office building. DGNB-DK contains 40 criteria to assess the sustainability performance of buildings. The third most impactful criterion responsible for 7.5 % of the total score is related to the flexibility and adaptability of the building and is named ECO2.1 Flexibility and adaptability. This criterion has seven sub-criteria, and each sub-criterion can achieve a varying amount of checklist points (TLP) that in total for the criterion can range between 0-100. The sub-criteria of ECO2.1 are listed below:

ECO2.1-1 - Use of area
ECO2.1-2 - Room height
ECO2.1-3 - Building depth
ECO2.1-4 - Vertical access
ECO2.1-5 - Flexible layout
ECO2.1-6 - Construction
ECO2.1-7 - Technical installations

The sub-criteria was translated from natural language into the visual programming code of Dynamo, in order to match the functional requirements specified in TABLE 1, including a separation of the data objects and logic, specifying C- or P- nodes, loose formulation, and inclusion of planned exceptions in the process. Because the translation of the rules is not the primary focus of the article, a brief example of how the sub-criterion ECO2.1-1 was translated is presented below (Green Building Council Denmark 2014, p. 143). The four operations were separated into both P- and C-nodes. The P-nodes specifies the operations that are editable by the run-time user and the C-nodes specify what is editable by the run-time user only. In this example, decision and action operations are specified as C-nodes because it is defined that the decision must be specified by the run-time user. In FIG 5, it is possible to see the four fundamental steps of automation by Parasuraman, Sheridan & Wickens (2000). The steps of automation have been separated into four colored boxes where dynamo operations are grouped. Each box has been marked with a P or a C to indicated if the box is open for a project or company-based changes. In this example, the run-time user is allowed to change how information is acquired (not only input but also how the BMC system interprets them) and analyzed but not how the information is decided upon or what action is made. The C-nodes, in this example, shows that decisions about how to score are decided upon is not for the run-time user to decide. However, it allows the run-time user to adapt the information used in this automation based on his/her interpretation of, e.g., quality of the information used.

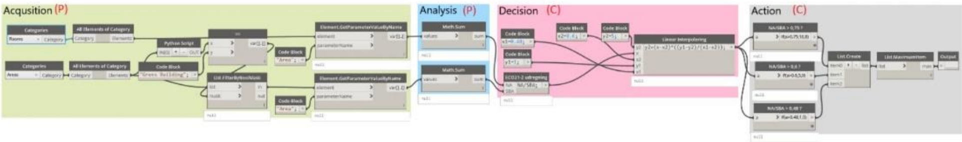

FIG. 2: A view of the contents of sub-criterion ECO2.1-1 separated into operations related to Acquisition (green), Analysis (blue), Decision (pink) and Action (grey). P- and C-nodes are marked in red text next to the operation name.

3.3.2 Evaluation case - Two-storey office building

The evaluation was conducted at the users' respective companies. Here a computer was set up with the prototype running and with the test building loaded in Autodesk Revit. The test building (see FIG. 3) represents a two-story office building in Denmark. The gross building area is 1128 m^2, and the building contains a large hall that separates sections in three directions. The building contains 29 different rooms with varying room heights from 2800 mm to 7100 mm. According to the Danish standards of information levels (Cuneco 2014), the building is specified as information level 3. The building was created for evaluation purposes, deliberately creating obstructions, e.g., varying room heights.

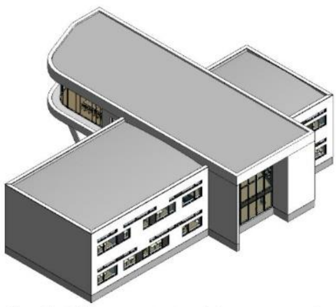

FIG. 3: The two-story office building optimized for user evaluation with the prototype

3.3.3 Participants in the evaluation

Nielsen (2000) suggests that 5 is the optimal number of users for usability testing. However, if either the domain is complex and comprehensive, or the users' background is diverse, more users could be included. Due to the difference in the backgrounds of the users for this evaluation, we have expanded the number from 5 to 8. The users were selected based on their professional experience with DGNB, BIM, and BMC, and from a range of small and medium-sized construction industry consultancy companies in Denmark. TABLE 2 shows the participants participating in a user evaluation.

User nr.	Education	Role	Company and size	BIM exp.	BMC exp.	DGNB exp.
1	M.Sc. in Construction Management	BIM Manager	Architectural Consulting Company 1 – Medium	15 years	0 years	0 years
2	B.Sc. in Architectural Technology and Construction Management	BIM Developer	Architectural Consulting Company 1 – Medium	2.5 years	2 years	0 years

3	Cand. Scient. Techn. in Building Informatics	BIM Process Developer	Engineering Consulting Company 1 - Medium	3 years	2 years	0 years
4	B.Sc. in Architectural Technology and Construction Management	DGNB Auditor	Architectural Consulting Company 2 – Medium	7 years	0 years	3 years
5	B.Sc. in Architectural Technology and Construction Management	BIM Manager & DGNB Consultant	Engineering Consulting Company 2 - Medium	3 years	0 years	3 years
6	B.Eng	DGNB Consultant	Engineering Consulting Company 3 - Small	0 years	0 years	2 years
7	B.Sc. in Architectural Technology and Construction Management	BIM Manager	Engineering Consulting Company 3 - Small	4 years	0 years	0 years
8	B.Sc. in Architectural Technology and Construction Management	BIM Manager & DGNB Consultant	Engineering Consulting Company 4 - Small	3 years	1 year	1 year

TABLE 2: Participants in the user evaluation and interviews

3.3.4 Data collection and analysis

The data from the process and results are obtained from three sources: semi-structured interviews, video observations, and performance metrics. Triangulation is used to ensure confidence in the evaluation and includes gathering data from various sources to establish confidence (Jick, 1979; Kaplan and Duchon, 1988). The data are analyzed by categorizing using affinity diagramming (Beyer and Holtzblatt 1997). The video observation was conducted to assess how the users interacted with the prototype during the automated assessment, and how they assessed the building traditionally without the support of the prototype. The interviews were conducted to enquire about how they perceived the consistency, precision, flexibility, and transparency and trust of the prototype. Quantitative metrics were gathered to assess the speed and precision of the ECO2.1 assessment. See TABLE 3 for an overview.

Topic	Description	Quantitative metrics	Qualitative metrics
Speed	Comparing the time used for assessment	Time deviation percentage between traditional and prototype evaluation case	Not relevant
Consistency	Comparing assessment results from the assessments	Score deviation between results	How the users experienced the quality of consistency
Flexibility	The ability of the user to adjust to changes in DGNB and the BIM-model	Not relevant	How the users experienced the ability to be flexible to unforeseen changes in DGNB and the BIM-model
Transparency and trust	The ability of the user to understand and trust BMC processing	Not relevant	How the users experienced the transparency and trust of each case

TABLE 3: Overview of metrics used to evaluate the prototype

According to Jewitt (2012), video recordings can support exploratory research and are a suitable complementary source of data. Video observations can contribute to how users interact with technology in a context (Nielsen and Kaufmann 1993). In this study, a total of 8 hours of video recordings were gathered. The semi-structured interviews were conducted to allow poor responses to be overcome, as well as further exploration of values and attitudes, and the opportunity to evaluate the validity of the respondents' answers (Barriball and While 1994). The questions were devised based on the theory presented earlier in relation to flexibility (Reichert and Weber 2012), and transparency and trust (Inagaki *et al.* 1998, Moray *et al.* 2000, Hoffman *et al.* 2013). The quantitative metrics were derived from Fish's (2012) theories of knowledge automation used to assess the quality of automation quantitatively. We compared the time taken for the traditional assessment of the building with the time taken for the automated assessment.

3.3.5 Quantitative results

The quantitative results disseminate the results regarding speed and consistency. Regarding speed, the results showed that the users spent an average of 29 minutes assessing the performance of the building traditionally according to ECO2.1. Regarding consistency, the users' and the rule developers' total scores differed, with total scores ranging from 25 to 50. However, the results from criterion ECO2.1-2 were consistent, as shown in TABLE 3. The rest of the users' sub-criteria scores varied and were different from those of the rule developers. User 5 did not find that the BIM-model contained enough information to assess sub-criteria 4 and 6.

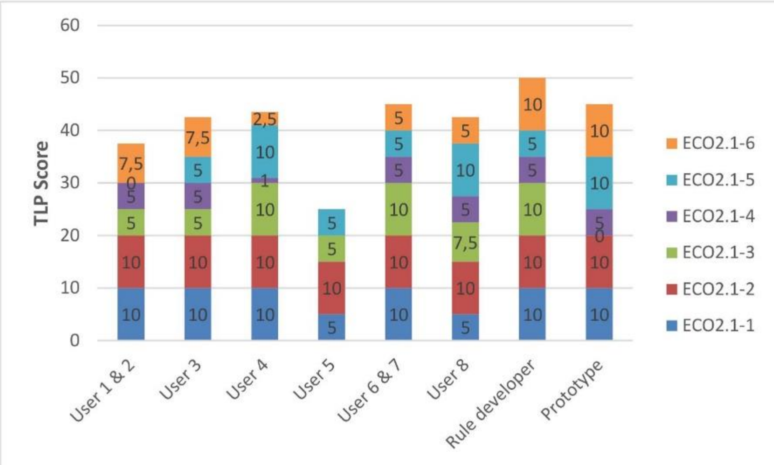

FIG. 4: Results from the traditional assessment of ECO2.1

The score results of the traditionally assessed criteria were on average 15 % lower than those of the rule developer. Only sub-criterion ECO2.1-2 matched the rule developer's score. ECO2.1-5 was on average 14 % higher than the rule developer's score, and the remaining sub-criteria scored lower. The prototype assessed the building within one minute, and the average score was 10 % lower than the rule developers. The individual sub-criteria scores from the prototype show that two sub-criteria differ from the rule developer: ECO2.1-3 and ECO2.1-5. The results are shown in TABLE 4. The results also indicate that users with DGNB experience scored lower (37.8 TLP points on average) than users without DGNB experience (40 TLP points on average).

TABLE 4: Results of the traditional and prototype assessments.

Metric	**Traditional assessment results (result on average)**	**Prototype results**
Speed	29 minutes	< 1 minute
Precision ECO2.1	85 %	90 %
Precision ECO2.1-1	83 %	100 %
Precision ECO2.1-2	100 %	100 %
Precision ECO2.1-3	71 %	0 %
Precision ECO2.1-4	84 %	100 %
Precision ECO2.1-5	114 %	150 %
Precision ECO2.1-6	55 %	100 %

3.3.6 Qualitative results

This section presents the results from the interviews and observations conducted with the users from the design practice. The first sub-section presents the results from the traditional assessment of the building. The next sub-section presents the results from the users using the prototype to assess the building.

3.3.6.1 Traditional assessment

The users had different approaches on how they used the BIM information for assessing the criteria. Their primary approach to gathering information was by creating schedules in Revit with quantities for ECO2.1. Others made use of the building's 3D visualization to assess specific sub-criteria, for example, assessing ECO2.1-4 vertical access. The differences between the users' results were mainly due to the different methods of assessing the building. An example of this difference was observed when the users assessed the ECO2.1-2 sub-criterion. In the description of ECO2.1-2, it was specified that the room height had to be measured from the top raw floor to the bottom raw ceiling. The definition "raw floor" is not a standardized term in Danish construction vocabulary but has connotations related to unfinished surfaces. This vague wording allowed the interviewees to define terms differently, such as, e.g., the raw top floor as the top finish of the floor, as the top core structure (such as a concrete slab), or as a top screed. Though this was a source of inconsistency, the interviewees argued that the vague wording allowed interpretations enabling the rules to be applied to the projects better while retaining the intent of the rules. In one example, an interviewee argued that the definition of the primary or secondary use of a room regarding sub-criterion ECO2.1-2 is open to interpretation. *"In a discussion between the Danish green building council* (DGNB-DK rule developers) *and me, in relation to a kindergarten, I made the argument that the lobby was a primary room because it had a pedagogical function for the children in relation to waving goodbye to their parents." (User 5).* Not only did the vaguely formulated rules allow the users to use their discretion, but they also served as a competitive factor. The same interviewee had experienced that a collaborator even misused the interpretations of DGNB to provide a better competitive factor. *"The interpretation of the criteria is a competitive factor. For example, a contractor asked if we could exempt the calculation of thermal bridges and linear losses in the energy calculation and only focus on u-values." (User 5).*

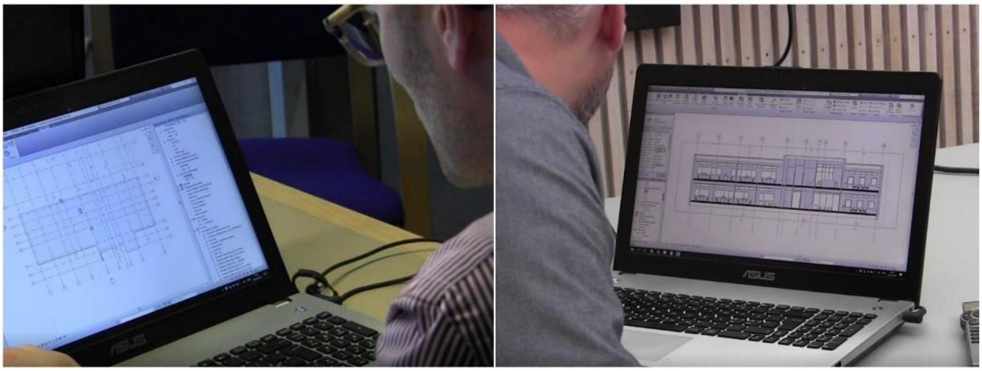

FIG. 5: Screenshots from the video observations showing two users assessing the building traditionally according to ECO2.1

The traditional assessment was conducted, and the users were able to assess the score of the building. The results from the traditional assessment showed that even the users with DGNB-DK experience applied different methods that led to different results. The observations showed that many of the users trusted the quantities seen from the sections in Revit's representation of the BIM-model. However, some of the rooms were not visible from the sections and would be left out of the user's traditional assessment, which affected their calculation of the score.

3.3.6.2 Using the prototype to assess ECO2.1

The interviewees expressed the opinion that the use of the prototype would support their practice and ease their workload related to assessing a building's performance according to DGNB. The interviewees agreed that the prototype could lead to increased consistency of the assessment due to the explication of the many vaguely formulated rules. Moreover, it would reduce the time, repetitions and effort spent on assessing the performance of the building, which could result in more regular assessments throughout the design process.

In all the interviewees' companies, Dynamo is increasingly used. However, Dynamo was considered a BIM specialist system that would be difficult for non-BIM specialists (e.g., engineers) to use. Moreover, Dynamo was perceived as being less stable than other software solutions. *"It is sensitive to wrong inputs; for example, if you were to use a symbol instead of a number it would crash completely." (User 1)*. One company that already used Dynamo to automate some aspects of their work argued that they consider using Dynamo to be better for tasks at hand that need automation, rather than tasks that require high certainty. *"Dynamo is a quick and dirty system that users can apply to automate tasks at hand." (User 1)*. Another interviewee argued that *"There is a certain degree of uncertainty associated with the user interface with Dynamo." (User 3)*.

3.3.6.3 Transparency

The interviewees all agreed that a key benefit of using the prototype was its transparency. *"It is easy to understand, and it is pedagogically expressed." (User 4)*. However, the interviewees stated that the prototype had to be evaluated by company specialists to review the BMC processing. The interviewees would use the prototype if they could review the processes and test it on various projects. One interviewee argued that the main uncertainty is the BIM-model.

One interviewee argued that, through the explicit management of the assessment process with the rules, it would allow for a more reflective interpretation for the company. The traditional assessment of a building is a highly individual process, making it difficult to share experiences among colleagues. The interviewees argued that the explicit and visual formulation of the prototypes processes allowed individuals to make their processes clear. This allows a clearer expression of how a score is achieved. If the designers authoring the BIM-model are aware of how their design choices affect the score of the assessment, they can design better for assessment performance. The interviewees argued that designers working on a building design (e.g., the BIM modellers) typically do not have much insight on the rules constraining the design. The prototype can assist designers to better understand the consequences of their design choices during the design, instead of later in the process when evaluated by, e.g., a DGNB consultant or auditor. *"It especially gives me a better platform for communication to allow the participants to see things in a context; this is done better in the prototype." (User 6)*. Not only does it communicate the processes of the assessment better, but it also highlights the information needed in the BIM-model to conduct such an assessment. A lack of information in the BIM-model is also an indicator of decisions that need to be made in the project. The prototype would be able to highlight such needs through notifications but would require that it be made transparent; otherwise, information missing from the BIM-model can result in the prototype calculating flawed results.

One interviewee argued that having more explicit information requirements by using a system like the BMC prototype would better highlight the exchange of information needed in a project. Also, it would specify what information is missing, increasing awareness of what information is needed and why. This is something that is largely missing at present. *"The use of a prototype like this would increase the quality of information in the BIM-model. In many cases, we receive information from the architect, which results in missing information in relation to our needs." (User 7)*. Another interviewee argued *"If information like the primary or secondary use parameter in rooms is missing, the prototype makes the designers notice that."*

3.3.6.4 The balance of accountability between the build- and run-time users

The interviewees argued that black-boxing, in general, was undesirable. It could be necessary to restrict and standardize some aspects of BMC processing to ensure consistency and validity. Most of the interviewees argued against black-boxing. They suggested better control of certain nodes in the prototype with the ability to either lock or lock with the possibility of override certain nodes and processes. However, one interviewee argued that *"For me, it was OK if everything was black-boxed in relation to if someone says that is OK, as long as the responsibility does not lie with me." (User 5)*. This comment was directed at whether it was possible for him to completely trust the prototype by having it, e.g., certified by the Danish green building council, so that he did not need to establish trust beyond that. The rest of the interviewees argued that there was a need to be able to manipulate the BMC-prototypes process to adjust to the needs of the projects and disagreed with the black-box approach. However, they expressed that it would be beneficial if there were more control of central nodes in the process. *"The prototype could benefit from a more central place to set up the rules." (User 3)*. One argued that it could improve maintenance to control the processes centrally, to update and lock the nodes better than with Dynamo in the prototype.

One interviewee (User 1) stated that it was of great importance to consider the balancing of benefits and trade-offs in accountability between the user and the organization. At both levels, the individual and the organization are accountable for the work they carry out, and at both levels, they have different objectives for when the system either constrains or benefits the projects. The interviewees added that it is the responsibility of the run-time user to manage a project's budget and the time to decide when, and if, to use a system. Understanding the BMC process is vital to assess if it would be of benefit in a certain situation. However, the interviewees explained that only a few people would make an effort to understand the BMC system completely. *"90 % of people are not interested in how things are executed in detail; it is only "the nerds" that would go into detail... The rest do not care about following the information from A to B." (User 1).* The interviewees argued that it would still be necessary to have manual validations by domain specialists of the automated processes to ensure that the automation is valid and/or for the Danish green building council to validate the system.

Other interviewees argued that for specialists like engineers to use the prototype, it would require them either to be fully able to scrutinize how the information is processed or to trust the developer or organization that is responsible for its implementation. *"In general, 70 % of all engineers would ask questions on how the prototype works and try to understand the smallest detail." (User 5).* The interviewees further added that it is considered essential that the users are in control. *"It is important for the users of the prototype to identify when the prototype automates critical tasks where the user is responsible for how it is processed and when it just gives a direction of the performance." (User 1).* This evaluation of the prototype was considered necessary to ensure certainty in the processes and for the user to decide if the quality of the automation adequately supports his/her work.

3.3.6.5 Understanding the limitations

The interviewees had previously experienced challenges with overtrust and argued that using the prototype would still require a certain level of domain-specific knowledge. The use of the prototype requires that the user can review the BMC processing and react to issues. The decoupling between the user's domain knowledge and the BMC processing can potentially lead to dangers associated with such automation. In the current practice, there have been examples of overtrust, and these had to be considered as a significant threat when integrating systems which automate a design practitioner's work. *"We created a prototype to calculate daylight, where we and the software did not communicate its limitations enough. This resulted in a user taking screenshots as documentation which was sent to the architect." (User 5).*

The interviewees expressed that the prototype allowed the user to understand its limitations because of the transparency of the processes to a certain degree. However, there is a need to communicate the limitations to the users further. One interviewee suggested that more notifications on the functionalities would help communicate the limitations of the prototype, for example, when the BMC processing is for purposes that require high certainty. *"It is important to make the users aware that it is only a simulation, what you get out is not the exact truth but a simulation, but to direct the design towards optimization. You have to be able to interpret this with your professionalism." (User 1).* Another interviewee argued that the prototype needed notifications when the performance of the building was close to achieving a point. *"If the calculation is close to achieving points or more points, there should be a notification from the prototype. For example, if the width of a building is 14.7 and not 14.5 that allows for points." (User 6).*

3.3.6.6 Project and organizational learning for continuous improvement

One interviewee argued that the use of the prototype would allow tracking of the evolution of the different BIM-models' performance, which would be difficult to achieve in a traditional approach. *"The use of the prototype is an advantage because it can spot issues that are difficult for me to find. It makes the user aware of underperforming aspects of the building design, which need action. For example, if the architect delivered a new model and the performance decreased in aspects of DGNB, I would be able efficiently to locate the issues and assess the causes and actions to counter the issues." (User 5).* Besides the score itself, one interviewee argued that the benefit was based on the user's ability to understand how the score was achieved. As an example, when a performance score is low in one criterion it provides the user with rationale for that score, e.g., that rooms in a certain area have a low room height.

The interviewees argued that the prototype needed functionality to better express the BMC-prototypes' performance history in terms of how both the BIM-models and assessments perform. *"It would be nice if it was possible to track the DGNB-DK performance history, which would allow us to identify reasons for the performance changes. We can use that for documentation both inside and outside the company. The way we do it now, we have difficulties gaining a historical perspective of how and what made our buildings perform." (User 4)*. Visualizing the performance throughout the design process would enable the user and the organization to learn how the different design choices affect the performance. This was an important issue for the interviewees, who also suggested that more notification was needed to identify aspects of the sub-criteria that could be improved with little effort but with a high impact on the performance. *"In some cases, I would have been able to achieve points with minor changes to the design, and the prototype does not notify me when this happens." (User 6).*

3.3.6.7 Flexibility

The interviewees argued that the prototype would provide users with the flexibility to interpret the criteria in the contexts of their projects as well as of the company. Though the prototype provided functionalities of flexibility, it raised concerns for one interviewee about handling the varying quality of the information of the BIM-model. *"It is a dangerous assumption for a system like a prototype to rely on a complete set of BIM-information. As an assessor, we often receive BIM-models we did not make ourselves. This can be a problem if there are inconsistencies in the BIM-model that lead to issues in the prototypes processing." (User 6).*

Design information evolves and the quality of the information from the BIM-model is often not of a high enough quality until the end of the project, when most of the decisions of the project have already been made. One example explained by an interviewee was: *"It can be a problem for the designers to properly classify objects in the BIM-model, which contain some uncertainty." (User 3).* Another interviewee argued that even if they attempted to specify the information needs, it would often not comply with these requirements. "*We see many examples in our work where we receive BIM-models of varying quality. Sometimes we get BIM-models where everything is created in generic models because it was easier for the BIM-modeller." (User 3).* Reasons for this were argued to be related to the often diverging goals of modelling. *"The reason why the quality of the BIM-model varies is that it is used to generate drawings." (User 3)*. Therefore, the interviewees argued that the BMC system must support the dynamic process of design better, which requires that the prototype must be able to use the information better at the various stages of maturity and quality.

However, people are often from different companies, as well as having different goals and responsibilities. Requiring a designer to create a BIM-model for another company's benefit, and a poor understanding of other designers' needs results in poor quality information, emphasizing the need for transparency of the processes. One interviewee expressed: *"There is a danger that the person who uses the prototype does not know the context of how the information is processed, which would be a source of uncertainty."* Previous attempts to counter this issue have been by specifying the information needs in detail. However, the interviewees argued that there were still embedded challenges in the use of systems using such information because designers from collaborating companies either put little effort into providing good quality information or still lacked a complete understanding of how the information is intended to be used. *"We prefer the BIM-model to contain DGNB specific parameters, like for rooms, specifying if they are for secondary or primary use." (User 7)* — referring to the ability to specify the role of the rooms ad hoc.

The interviewees expressed that the prototype allowed them to be flexible, both regarding BIM-models of varying quality, and relating to the specific processes of the project. *"The more simply the processes are formulated the better, because it allows the users to adapt to the changing building design" (User 4).* The interviewees argued that the approach to formulating the processes loosely would improve their understanding of the processes themselves, but also better enable them to adapt the processes to their project contexts. *"The prototype allows adapting to the real-world processes because of the many changes in, for example, the criteria." (User 4).* Moreover, the looseness of the formulated sub-criteria was experienced as a good approach from a cost-value perspective because it would lessen the resources otherwise required to create and maintain highly specific and detailed processes. *"It is important that the automated processes are loosely defined because the effort and complexity of specifying the automated processes require too many resources."*

Many of the interviewees argued that it was critical to ensure control of the maintenance of the rules. *"In other software, we are challenged by updates to the processes that in some cases significantly modify the results." (User 6)*. The versioning of the processes in the prototype had to be managed either through the custom nodes or through manual handling of the Dynamo scripts.

4. DISCUSSION

The prototype made use of modularisation to enable the user to more easily understand and adapt the processes according to the context and reduce the visual complexity of VPL in Dynamo. The modularisation was reported to be helpful for the interviewees to understand how the information was processed, allowing them to achieve a simplified overview. However, there are limitations in the available functionalities of Dynamo because its use is not directed towards model checking. It is possible to create custom nodes in Dynamo that are locked. However, efficiently managing how these nodes are maintained was reported as being sub-par. An interviewee argued that the use of Dynamo was a hazard for the company because it allowed too much alteration of the processes by the run-time users. Further control and separation seem to be required between the run-time users of BMC systems and the processes that the build-time users employed, as indicated by the interviewees.

However, as Reinhardt and Matthews (2017) note, the use of visual programming can be an efficient method of conducting BMC through good management. Whitley (1996) argues that the main challenge of using VPL is *"Given the range of information required in programming, can a VPL highlight enough of the important information to be of practical benefit?"*. The interviewees were able to scrutinize how the information was processed, even by users who had limited experience with BIM. A lack of looseness can result in comprehensive and complex processes that can potentially overburden the user with information that is not important and lead to rejection, as noted by the interviewees. The prototype was judged to require a better interface to communicate various notifications. For example, there needs to be an indication of when the performance of a building is close to obtaining points but does not comply. Dynamo does not provide many opportunities to control and constrain the run-time user or allow control functionalities of the build-time user compared to other systems like business process management systems (Koncevics *et al.* 2017). However, currently, no business process management solutions exist specifically for use in the construction industry.

The interviewees' TLP scores for the sub-criterion ECO2.1-3 were significantly different from the score of the rule developer and the prototype. The reason for this difference could be identified as the literal interpretation of the term *depth*. The sub-criterion is assessed based on the depth of the building. To understand this measurement, you have to understand its context, and the flexibility of the building's uses. This means that it is up to the individual assessor to subjectively formulate what that means and how it affects the measurement of the building depth. While standards can provide a uniform way of specifying the depth of a building, many scenarios can occur where strictly formulated rules neglect unique aspects of the building and cause potential issues. In our case, the rule was translated literally from the specifications stated in the DGNB-DK into the prototype, yet the different interpretations resulted in a different score in the traditional assessment.

The rule specifies that it is the complete depth of the building measured from outer wall to outer wall. Merriam Webster defines depth as "the direct linear measurement from front to back." The walls from the BIM-model were then transformed into 2D lines in a plan view, where the depth was measured as a direct linear measurement conducted from the front to the back. The front and back were defined as the narrowest points. In comparison with the traditionally assessed scores, this approach was different. The general approach would be to measure the front and back of the narrow "body" of the building and not the building per se. Since the building is T-shaped, the result was very different from the prototype. This is an example of a criterion that either needs to be very complex in the prototype BMC processing or provide the user of the prototype with transparent processing so that he can adapt the automation to the specific design where it is used.

The results of the interviews show that traditional methods of assessing buildings allow for a company-based interpretation of rules to both their own and the rule developer/enactor's advantage. The problem with hard-coded and black-boxed BMC systems is that they potentially restrict the users, preventing them from adapting the rules constricting their work of assessing the building. Adopting a BMC system then becomes a balance between the benefits and constraints of automation. The results from the interviews indicated that BMC systems like the prototype must give more consideration to how rules should be interpreted, allowing the users to make adaptations. It has previously been argued that construction projects are highly reliant on contextual knowledge, and for that reason often require that the processes can accommodate rapid changes (Demaid and Quintas 2006). For example, the knowledge that is created during the process of designing a unique building could affect how the rules are supposed to be used, such as re-interpreting the meaning of what a primary room is. The integration of rules in the prototype was an attempt to let the designers adapt the use of the rule while still achieving its intent. One of the results, an interviewee's "rule-breaking" in the definition of primary and secondary rooms in the traditional assessment, led to the designer's ability to adapt the rule in the context of its use. The goal of the rules in the criterion is to ensure that the design is flexible in its use. However, letting the users adapt the rules might result in inconsistent assessment and increase the need for manual labor. Additionally, it would be more difficult to control how the users conducted the BMC systems assessments.

Traditionally, the users have the main responsibility for correctly applying the rules, and they are required to present documentation on how the rules are interpreted. However, by using contemporary BMC systems, it is the system developers that specify how these rules are interpreted, but these are hard-coded and black-boxed, limiting the user's ability to understand and adapt the automated assessment according to her/his context. However, it is still the assessor who is liable for the correct assessment of the rules, whereas for BMC developers to take on such liability can be problematic. Allowing the users to understand and adapt the rules to their context would better align the responsibility with the users rather than the creators of BMC systems.

As the interviewees commented, unnecessary explication could remove competitive advantage and rule out contextual adaptations that could potentially spark innovative solutions while preserving the intents of the rules. Demaid and Quintas (2006) argue that the negligence of context-based knowledge has previously led to problems. They argue that the "holy grail" of converting all knowledge into explicit knowledge had historically failed on many accounts, including the failure of many promised expert-systems. In many cases, it is impossible to create rules for BMC systems that take into account all possible scenarios because this requires that the developers envision all possible contexts of use. Limiting the user's ability to adapt the rules could lead to unforeseen consequences that could potentially negate the upside of using BMC systems.

An example of disregard for context-based knowledge in the construction industry can be found in the Singaporean attempt to make the building code explicit (Building and Construction Authority, 2015). The Building Code of Singapore was changed to better accommodate the automated assessment of, e.g., a building's buildability. Buildability is now assessed with a formula where the materials' labor-saving index is specified. These rules specify that brick walls have a low score of buildability. Such value can be viewed as a general opinion that building with bricks reduces the buildability (because it is labor-intensive) and can lead to the avoidance of such material. Such changes to make the rules more explicit then negate the possibility of innovative approaches to make the use of bricks less labor-intensive or using them because their aesthetical value is of importance.

5. CONCLUSION

In this article, we aimed to answer the research question of how the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) are experienced by practitioners using BMC systems. This was conducting a holistic study using the DSR methodology that emphasizes the creation of knowledge through the development and evaluation of artifacts. This resulted in disseminating three different types of contributions based on (1) Identification of requirements for the prototype (2), Creation of a prototype based on the requirements and (3) Prototype evaluation.

The first contribution is the identification of the requirements of the prototype. Here existing challenges were explored theoretically to identify theories that could alleviate the challenges. Previously a lack of transparency was noted, which is suggested to be counted using structured visual programming language. The second contribution is the suggestion of a prototype accommodating better transparency and flexibility. The transparency is achieved through an emphasis on using visual programming language and a structure to manage the user's understandability of the processes used to perform the checks. The flexibility is achieved through an emphasis on separating the logic/data objects and run- and build-time use-cases. Moreover, an emphasis is made on loosely specifying the processes, including exceptions and enabling performance analysis of the checks conducted. In essence, it promotes a de-centralized BMC system that entails its use is centered around the business its projects. Familiar software components were used to accommodate the functional requirements, which was connected using primarily files.

The third contribution was user evaluation. Currently, no previous research has included practitioner evaluation of a BMC system quantitatively or qualitative. In this case, the developed prototype was evaluated by different practitioners to give voice to their practice-based experiences and measured their manual evaluation against the automated. The evaluation prompted a realistic case (rules and building) that all practitioners evaluated with the prototype. The practitioners' use of the prototype allowed us to explore the socio-technical challenges (i.e., transparency and flexibility) holding back the use of BMC systems and the use of considerations to relieve these challenges. Traditionally the interviewees indicated a need for contextual adaption of the rules which required them to be able to understand the adapt the formalized rules. Contextual adaptions were possible in the prototype that scored closer to the rule developers' assessment of the evaluation case. However, the prototype was limited by the lacking and ad-hoc nature of Dynamo. More control of the processes through logic and information was needed as well as better abilities to create notifications. In general, the interviewees did not like the black-boxed approach, but one argued that if he did not have any responsibility for the process conducted, he would allow for the black-boxed approach.

The interviewees indicated that by allowing them to scrutinize and adjust the processes, they would have more trust in the system. The more trust in the system, the more comfortable they are in using it for critical purposes such as assessing sustainability in a BIM-model. Moreover, it allows users to identify shortcomings of the processes in the context of their uses and to adapt them as needed. Equally important, it allows companies to enforce specific company-required behavior, with the ability to restrict specific nodes in the process.

6. FURTHER RESEARCH

We recommend that further studies are conducted to better understand the socio-technical characteristics of the use of BMC systems. While complete control over the BMC system might overburden the run-time user, there is a need to communicate the processes in the BMC system and to allow for certain flexibility, which requires further research. One possibility is looking for other domains that have emphasized flexible and de-centralized solutions like the domain of business process management systems. However, currently bridging such research into the domain of construction industry is limited.

The current approach to BMC systems has been limiting the transparency and flexibility offers easier development and control of the BMC systems and lessens the involvement of the users. The lack of involvement reduces the ability to apply the tacit knowledge often required to automate processes like assessment properly. A failure to recognize the need for tacit knowledge has previously been challenging for the expert systems movement. Demaid and Quintas (2006) noted that the primary failure for expert systems was the inability to involve the users and thereby embed their tacit knowledge into the systems without formalizing it into rules.

When rules are formalized in BMC systems that limit the user's involvement, this can reduce the user's ability to perform using his/her discretion. Rules were never meant to be too explicit in the first place, but as McLean (2003, p. 23) argues: *"Outputs of the political system include laws, rules, judicial decisions, and the like, regarded as the authoritative allocation of values."* Rules in the construction industry are intents of how we want the environment we live in to be, and when rules become formalized there is a risk that the values and intents are set aside by being too inflexible. Rule compliance is then for the sake of the rule. Allowing the users of BMC systems to adjust the interpretation of rules through the ability to understand how they are applied in the system (transparency) and how they can adjust them (flexibility) is one approach to balance the explicitness.

There is a strong need to investigate further the existing and potential future unintended consequences of automating rule assessment using BMC systems. Currently, most research is focused on creating a solution that dictates societal change (technological determinism) with little regards of the negative consequences implementation of BMC systems could have. Achieving a better understanding of the potential negative consequences could benefit future developments and potentially ensure better use of BMC systems in practice.

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7. BIM-BASED MODEL CHECKING IN A BUSINESS PROCESS MANAGEMENT ENVIRONMENT (PAPER V)

Paper IV presented the development and testing of a prototype that was built upon theories regarding how to improve transparency and flexibility. The test showed that the results were quantitatively closer to the results from the rule assessor and were produced within a minute. It showed that the translations and execution of the model checking using the BMC prototype results in this limited case could work. Moreover, the feedback from the interviews gave voice to how the interviewees conducted traditional rule assessment. Here, the importance of their ability to adapt the rules into the context of the project was clear.

7.1 AN EMPHASIS ON TRANSPARENCY AND FLEXIBILITY YIELDED IMPROVED RESULTS

While the prototype provided the interviewees with a level of transparency and flexibility, it had its shortcomings. Dynamo was the main component that restrained the possibility of having enough control over the processes. Dynamo is more of an ad-hoc data flow management and parametric programming system for the construction industry. While it is not a BMC system, Dynamo contains many features that BMC systems could adopt to improve transparency, for example, although it is a limited system for the task.

In Denmark, many companies have begun to adapt the tool to automate their work; a typical limitation is the amount of data it can process before it crashes. Another issue with the Dynamo-based prototype was that it was using proprietary systems. Currently, the construction industry is attempting to adopt open standards to improve interoperability with formats like Industry Foundation Classes (IFC). With the Dynamo-based prototype, it was necessary to create BIM model in Autodesk Revit.

7.2 BETTER FLEXIBILITY USING BUSINESS PROCESS MANAGEMENT SYSTEMS THEORY FOR BMC

Paper V aims to continue the exploration of "How is it possible to improve the flexibility of BMC in a Business Process Management environment?". However, in Paper V, the intention is to achieve even better flexibility by using Business Process Management systems instead of systems directly related to the construction industry.

One of the problems with the Dynamo-based prototype was the limited amount of data it could handle in the process. In the Business Process Management software, these limitations are accommodated due to its nature of dealing with large-scale businesses in regard to both processing information and controlling the processes.

the Business Process Management systems typically provide application programming interfaces that allow for connections to different databases, which means that such systems could provide better interoperability. This was emphasized in the new prototype, and therefore the prototype was connected with the BIMserver platform, which allows BIM information to be stored in IFC. This allowed the BIM information to be drawn from other sources and not only from Autodesk Revit.

There is a further need to provide the practitioners with functionalities that allow more flexibility in regards of integration of various systems and formats besides what was presented in Paper IV (Revit/Dynamo) and further investigation of how to structure BMC systems in order to allow for user flexibility. Because of that the research question in the next article is "How is it possible to improve the flexibility of BMC in a Business Process Management environment?"

BIM-Based Model Checking in a Business Process Management Environment

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ABSTRACT: BIM-based model checking has the potential to improve the building design process concerning efficiency and consistency by allowing for automatic assessment of BIM-models. However, BMC is infrequently used the building design practice. A fundamental challenge in applying BIM-based model checking in practice is the chaotic and dynamic nature of the building design process, which is subject to many changes, like changing requirements or constraints. BIM-based model checking systems have been criticized for having poor flexibility, as well as not being able to adapt to these changes sufficiently. To improve the flexibility, we developed a proof-of-concept prototype based on requirements of flexibility from process-aware information systems theory. The prototype was used to assess a sustainability criterion on a BIM-model to explore the possibilities of developing BIM-based model checking systems with improved flexibility. Based on this demonstration we discuss the limitations and opportunities for future research and development of more flexible BIM-based model checking solutions.

1 INTRODUCTION

The design of a building can be considered a composition of design choices optimized for satisfying the goals, requirements, and constraints in the environment of the design, as well as the technology used (Ralph & Wand, 2007). The designers are challenged to optimize the buildings in a process that is considered highly inefficient, due to complex rules and troublesome methods of organization (Kuben Management, 2016). The finished buildings contain many flaws due to design errors (Lopez & Love, 2012) and are poorly optimized (Flager, Welle, & Bansal, 2009). Cost of design errors is estimated to be approximately 6,85 % directly, or 7,38 % indirectly, of the total contract sum of building projects (Lopez & Love, 2012).

1.1 *BIM-based Model Checking*

Hjelseth (2016) defines Building Information Modelling (BIM)-based Model Checking (BMC) as a grouping of concepts that focuses on using BIM as an information source and algorithms for processing the information based on rules. The rules can be derived from various rulebooks, such as building codes or sustainability assessment methods. A rule derived from building code, for example, could be defining the width of hallways related to fire exits. BMC has the potential to improve designers work to ensure compliance with regulative or performance-based rules through enabling rapid, consistent, and precise feedback on compliance and performance (Dimyadi & Amor, 2013; Eastman, Lee, Jeong, & Lee, 2009).

Currently, BMC has found limited use in the design practice (Dimyadi, Clifton, Spearpoint, & Amor, 2014; Dimyadi & Amor, 2013; Hjelseth & Nisbet, 2010; Cornelius Preidel & Borrmann, 2015). Large, ambitious national BMC projects and commercial BMC-systems have proven difficult to integrate into the design practices (Khemlani, 2017; Refvik, Skallerud, Slette, & Bjaaland, 2014; Solihin & Eastman, 2016). Studies indicate that it is related to the “black-boxing” of the BMC-system´s processes (Beach, Rezgui, Li, & Kasim, 2015; Dimyadi & Amor, 2013; C. Preidel & Borrmann, 2017).

1.2 *A lack of flexibility challenges the practical use*

Many scholars have commented on the unpredictability and complexity of the construction projects, which are subject to many changes in scope during its progression (Bertelsen, 2003; Dubois & Gadde, 2002). These dynamics make it difficult to apply tools like BMC in the design practice because people improvise, make errors, and are subject to changing requirements. Bertelsen (2003) characterized the construction projects as: “a nonlinear and dynamic phenomenon, which often exists on the edge of chaos." The dynamics lead to changes that systems like BMC needs to accommodate. The changes are related to the evolution of the rules and the design.

One of the main challenges has been the lack of standardization of rule and design representation. An ongoing effort is made by the organization buildingSMART to develop open-standards for representing BIM-models to increase interoperability, lessening the need for managing information (Golabchi & Kamat, 2013). Moreover, various open-standards for rule formulations are available, but need to be manually updated (Dimyadi & Amor, 2013).

There exist attempts to automate the interpretations of rules using natural language processing techniques. Zhang and El-Gohari (2016) have attempted to improve the flexibility to changes of the rules by applying Natural Language Processing technology to automate a machines interpretation of rules. However, regulatory tests are not written for computer interpretation and have not been very successful (Dimyadi & Amor, 2013).

Dimyadi and Amor (2013) argued that there was a lack of research focusing on semi-automation in the domain of BMC accommodating both qualitative and quantitative aspects. Later studies attempting to close this gap has been conducted by Preidel and Borrmann (2017; 2015, 2016) by using visual languages to improve transparency of processes in BMC to allow for domain experts to easier adapt to the real-life changes. The emphasis of allowing domain experts to understand the automotive processes better has been suggested to ease the management of the information used in the BMC processes.

Preidel and Borrmann (2017) argued that the limitations and challenges of using visual languages are the complexity of the BMC process representation. Their findings indicated that the complex representation needs to accommodate better handling of the information involved such as errors and iterations. Handling such issues are related to changes happening in the construction industry that the BMC system needs to mimic in order to provide the users of BMC with reliable feedback. Therefore, BMC systems must be better to accommodate such changes and become more flexible.

1.3 *Improving the flexibility of BMC*

To improve the flexibility, we use theories related to Process-Aware Information Systems (PAIS) and Business Process Management (BPM). Both theories are interrelated, and emphasize improvement of productivity of business practices through a process-centered approach (Reichert & Weber, 2012b; Van der Aalst, 2013). These methods have been used to improve the structure of information related to handling processes to accommodate the challenges pointed out by Preidel and Borrmann (2017) that currently limits the use of visual language to improve the flexibility of BMC systems. The increased flexibility allows processes to easier and more rapidly be adapted to real-life changes. BPM systems have previously been applied to various practices that required information systems to respond effectively to changes (Van der Aalst & Basten, 2002).

We conducted a screening of the scientific litterature to identify previous research in relation to the construction industry, PAIS, and BPM, finding only a few studies. Few studies were found related to application of PAIS/BPM into the domain of construction industry, for example, Bergman, Gessinger, and Bergman (2016) used a PAIS approach to improve deficiency management. This approach was achieved by improving flexibility to handle actions related to assigning personnel to address the deficiencies. However, we were unable to identify any efforts of PAIS related to either BIM or BMC.

1.4 *The aim of the article*

In this article, we aim to explore how it is possible to improve the flexibility of BMC. To achieve this flexibility, we use the PAIS/BPM theories to set technical requirements for a prototype that integrates BIM-model information in a BPM environment. The prototype is tested to investigate the applicability of flexibility of BMC. The test case is a criterion from the sustainability assessment method Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB). The investigation is used to discuss the opportunities and limitations of improving BMC flexibility with PAIS and BPM.

2 THE NEED OF FLEXIBILITY IN THE CONSTRUCTION INDUSTRY

Reichert and Weber (2012b) argue that knowledge-intensive real-world environments, like building design, cannot be completely prespecified but require maneuvering room for the users, due to the drivers of flexibility. The need for flexibility stems from the relationship between the real world and the digital environment. In the real world, the designers need to get feedback on their design according to rules. When BMC needs to provide this feedback, it requires that both the rules and the design is represented in the digital environment. Asynchrony between the real world and the digital environment makes the feedback irrelevant. Additionally, the digital environment can cause errors on its own, and that system would require adjustment. Making the digital environment of BMC flexible to both changes will provide for more relevant feedback.

The digital environment of BMC is specified according to Eastman et al. (2009)´s defined classes of BMC functionalities: 1) translation of natural language rules into computer executable rules, 2) BIM-model verification, 3) BMC execution with a checking mechanism and 4) dissemination of the checking results. Each of these functionalities is subject to changes from the different organizational layers. At the company level, the steps must be aligned with the company's business goals and resources, for example, when a company has specified quality of documentation of the checking results. The BMC tools are operational at the project level, where it is subject to project-specific conditions and context-dependent rule interpretation. Figure 1 illustrates the relationship between the real-world environment of building design and the digital environment of BMC.

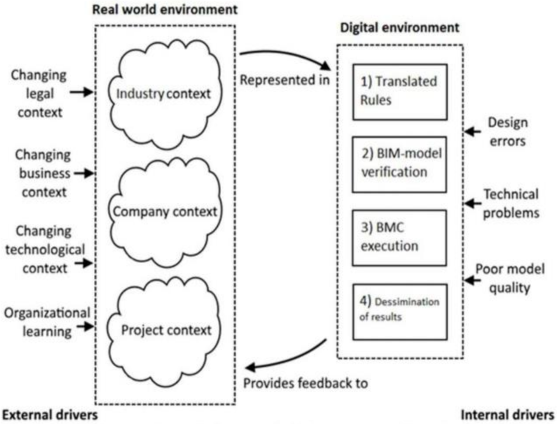

Figure 1: External and internal drivers are affecting the real-world and digital environment, adapted from (Reichert & Weber, 2012b).

The digital and real-world environment are affected by drivers of change. Van der Aalst & Basten (2002) argue that the drivers are caused by either ad-hoc or evolutionary change. Ad-hoc change is defined as the changes happening on a project basis, which is a result of errors, uncommon events or special demands from the customer. Evolutionary change is of more structural nature, related to changes in company policies, regulations, or a change in market demands (Van der Aalst & Basten, 2002). Reichert and Weber (2012b) separate drivers of changes to be either external or internal. The real-world environment is affected by changes in legislation, technology, and the context of business. When technology improves, new possibilities emerge for a new application of, for example, faster computers. Companies change due to the forces of the markets and changing needs of the customers. Customers' requirements shift along with, e.g., trends that can affect the choice of materials. Finally, the real-world environment can be affected by the organizational learning, for example, when learning creates opportunities to optimize the processes.

The digital environment is affected by internal drivers of change, which include design errors, technical problems, and poor model quality. Design errors can cause problems due to missing information in, e.g., either the BIM-model or in the checking mechanism. Technical problems could be performance degradation due to increasing amount of data. Poor model quality could either be related to the BIM-model or the process model. The process model is the steps of the digital process in the digital environment and can relate to the quality of processes, like amount redundant processes. Poor model quality can also relate to poorly created BIM-models due to inconsistencies in classification or collision of building objects.

The inability of the digital environment of BMC to adapt to external and internal changes can cause inconsistencies and flaws, making the feedback from BMC irrelevant to the design practice. We argue that addressing these dynamics of the construction industry is of importance to make BMC more practically applicable. This would thereby allow for more automation of the design practice and reduce inefficiencies and flawed building designs.

3 MAKING BMC MORE FLEXIBLE WITH A PROCESS AWARE INFORMATION SYSTEMS APPROACH

We suggest making BMC more flexible by applying a Process-Aware Information Systems (PAIS) approach to BMC. PAIS is used to increase flexibility in the development of information systems in complex and dynamic domains and is also used in workflow information systems, case handling tools, and service orchestration engines (Reichert & Weber, 2012b).

Key characteristics of PAIS are the separation of process logic (formalized in process models) and application code (formalized in data models). Also, by the separation of build-time and run-time components. Build-time components are used when the processes are developed and maintained by process specialists. Run-time components are used by the users like designers (not necessary process specialists) to execute the process models to obtain feedback on their building design. Reichert and Weber (2012b) argue that by splitting monolithic applications into smaller components, as well as a separation between build-time and run-time components can make information systems more flexible than traditional ones.

The application code is the statements of code formulated in applications specialized in executing certain functions. The processing logic is typically formalized in process modeling language such as Business Process Model Notation 2 (BPMN2) (Object Management Group, 2011). Formulating business processes with language like BPMN2 allows for more expressiveness of the processes that are used as reliable schemes of executions. It is through the process models that the logic is represented through control and data flow dependencies. These dependencies specify the dynamic behavior of the process, for example, visualizing the process of validating the information of a BIM model. This is done to ensure that the business processes are executed in a specified order and allow for easier development, maintenance, and monitoring of business processes (Reichert & Weber, 2012b).

4 REQUIREMENTS OF A FLEXIBLE BMC PROTOTYPE

We developed a prototype to explore and address the previously mentioned flexibility needs. This led to a three-part architecture that consisted of a BIM-model server platform, a Business Process Management platform, and a Custom REST service. The development of this architecture aimed to allow to conduct more flexible BMC. This architecture was created to accommodate the flexibility needs of BMC based on the PAIS theory (Dumas, Aalst, & Hofstede, 2005; Reichert & Weber, 2012a; Weber, Reichert, & Rinderle-Ma, 2008).

We focused on: 1) separation between logic and application code, 2) separation between build-time and run-time components 3) accommodation of looseness, adoption, and evolution. The logic and application code must separate in different data objects representing the logic of rules and represent the application code. The build-time and run-time components must be separated to allow specialists to manage information related to the data-objects representing specialized information not needed by the run-time users. The accommodation of looseness, adoption, and evolution is presented below:

4.1 *Looseness*

If changing processes become comprehensive and complex they require much maintenance to be kept relevant and still will they fail to match the uniqueness required in e.g., specific design projects. Moreover, can complex processes defer technical issues. A solution to this is the approach of looseness. Loosely specified processes that are made as simple and general as possible require more input by the run-time user but are both easier to maintain and applicable to more situations.

4.2 *Adaption*

A process of assessing the sustainability of a building, for example, must be able to continue even if not all required information is present in the BIM-model. In this case, it cannot provide comprehensive feedback on the performance of the design, but it must still give a partial insight of the BIM-models sustainability performance and score. If deviations are not permitted to the run-time users, it can lead to rejection of the system. Therefore, a PAIS must allow for ad-hoc changes for the run-time users and be able to handle exceptions in order for the run-time user to progress with executing the checking.

4.3 *Evolution*

A system will never reach perfection, but instead act as a continuous optimization and is subject to changes happening in the real-world environment such as changes in laws, materials and such. Changes of processes (due to the evolutionary changes) need to be supported for refactoring (the process of restructuring existing code for optimization) without the run-time users noticing and for users to apply older versions of processes. Especially older versions of such processes are necessary in the construction processes because building project typically span over a long period of time and often only needs to be assessed to a set of rules governing at the point of initiation. Such changes entail the need for the ability to make versioning of the processes and rules and the ability to manage to refactor the information used in the system. Moreover, the build-time users must be supported with feedback through monitoring, analyzing, and mining of process performance information, which can be used to improve the processes.

5 THE ARCHITECTURE OF THE BMC PROTOTYPE

We selected and developed different sub-systems components to accommodate the previously set requirements to create the architecture of the new BMC prototype. To address the main functionalities of flexibility, i.e., a separation between logic and application code, a separation between build-time and run-time components, and accommodation of looseness, adoption, and evolution, we applied a BPM system Bizagi Studio 11 (2017). The choice of BPM system was based upon a functional screening according to the requirements earlier specified. The screening included various software presented in a comparative study by Koncevics and Penicina (2017).

Bizagi Studio contains the functionality of separation of application and logic. Also, it allows a separation between run and build-time users. Moreover, it accommodates the requirements of looseness, adaption, and evolution through various functionalities.

Bizagi accommodates looseness by allowing BMC processes to be loosely formulated and require extensive but constrained user input. For example, by creating as simple and general as possible processes. This allows the run-time users to adjust the process to their specific contextual demands, thus requiring more run-time input.

Bizagi also accommodates adaption by making exceptions in the processes to the issues that are possible to foresee. Moreover, it allows evolution by handling versioning of the processes evolved over time and enabling refactoring of existing processes. It also supports organizational learning through extensive mining, analysis and monitoring elements of the processes.

Bizagi represents the business logic in both rule objects and the BPMN2 notation form, which is widely used by academics and professionals to express business processes visually. We created a process activity (expressed visually as rectangle that describes a task) for a web service to get the BIM information) named Service, and one process to assess the information named Assess. The information required in the processes was specified in the data model in Bizagi. The data in Bizagi Studio was connected with a custom-made web service to the BIM-model server platform. The data model from the BIM-model server was mapped to the data model in Bizagi Studio. The data were assessed according to logic translated from DGNB and specified in Bizagi Studio. Bizagi Studio then presented the result of the automated assessment of room heights of the building.

The BIMserver software parses IFC models and stores the data revisions in a non-relational database. The server can be accessed directly by the BIMserver software and the underlying web service implementation via the HTTP protocol. The data exposed by the BIMserver web service implementation are formatted as either JavaScript Object Notation (JSON) or Simple Object Access Protocol (SOAP) XML data structures.

In Bizagi Studio it is possible to model business processes and create a data-model that specifies the information containers needed for the automation. It is possible to integrate information from external sources through either REpresentational State Transfer (REST) or SOAP web services. We developed a RESTful web service that acts as middleware between our hosted BIMServer.org server and Bizagi Studio.

This web service makes it possible for Bizagi Studio to request data contained in the BIMserver-hosted IFC-models. We chose to implement a piece of middleware because the structure of the data exposed from BIMservers own web service implementation was unfit for direct integration with Bizagi Studio. Therefore, the custom web service acts as a data scrubbing middleware, which solves the structural mapping issues between Bizagi Studio and BIMerver data structures. The data scrubbing web service was implemented using Microsoft ASP.NET Web API 2.0, written in C#. The actual scrubbing of the JSON formatted BIM data consumed from BIMserver was done manually by querying BIMservers' API and using Newtonsoft.Json (de)serialization library. The main work of the web service is the querying for BIMserver data, deserializing the data and reconstructing it in an easily readable format, which is then serialized again, and exposed as JSON to Bizagi Studio.

The different tiers in the architecture can be geographically separated and are only communicating via message passing (HTTP requests). Building a middleware web service has the benefit of providing multiple numbers of clients with a shared interface, which exposes well-formed data to client applications. In our case, we have developed a system that can make BIM-model data available to a BPM system. The custom web service, however, is not limited to any client application, since it communicates over a standardized protocol, HTTP. The architecture is visualized in Figure 2.

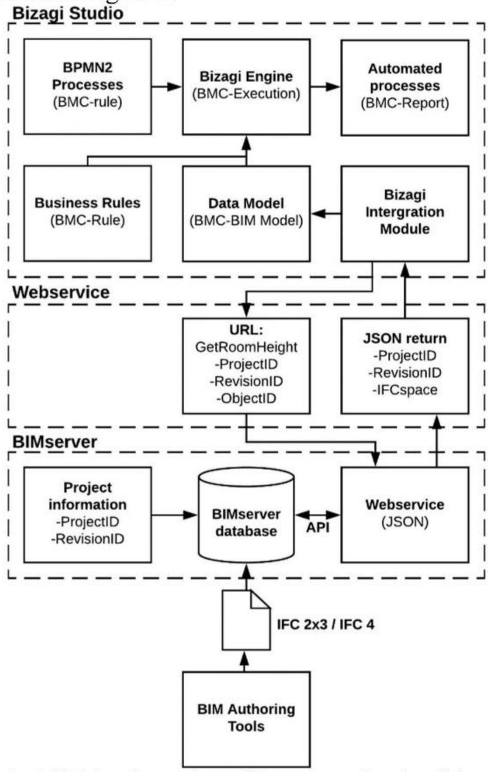

Figure 2. A high-level overview of the systems functionalities

6 THE CASE OF SUSTAINABILITY ASSESSMENT

We used the prototype to test its functionality of automatically assess a DGNB criterion. In Denmark, the preferred method for assessing sustainability is named "DGNB system Denmark manual for Office buildings 2016" (DK-GBC, 2016). The method is originally German but was adapted to a Danish context. It is a second-generation sustainability assessment method, which means that it contains a broader range of sustainability criteria than first generation assessment methods. The method is very comprehensive, containing 40 criteria with 140 sub-criteria covering aspects of social, economic, environmental, and process aspects of the design and construction of an office building. The criteria are weighted differently, and they vary in comprehensiveness and complexity. The designers struggled in handling the comprehensiveness and complexity of the sustainability assessment methods in general and this was a key reason why this was chosen as a case to test the prototype. The case tested a sub-criterion of the criterion ECO2.1 Flexibility and Adaptability named ECO2.1-2 Room Height. The sub-criterion is used to assess the possible flexibility of the rooms by measuring the height of “primary” rooms. However, this limited case is considered a test and example of the use of the prototype. The score of the criteria is given as checklist points, TLP (Danish: TjekListePoints). The description of the sub-rule is made both in prose and in a table, specifying the possible score according to the room heights of the building design. The sub-criterion specifies the following (important outtakes):

- The average height of the room is used
- Room height is defined as the distance between “top floor” and “bottom ceiling.”
- Room height is measured in meters
- The ECO2.1-2 score is named TLP and is calculated (average Room height => 3) = 10 TLP

We used Autodesk Revit (2017) to create a simple test model showed in Figure 3, containing walls, floors, ceiling, a roof, and three rooms. The ceilings restricted the height of the rooms and had various heights. One room had the height of 2600 mm; one had 3100 mm and one 3000 mm. The test BIM-model was exported in IFC version 2x3 – Coordination View 2.

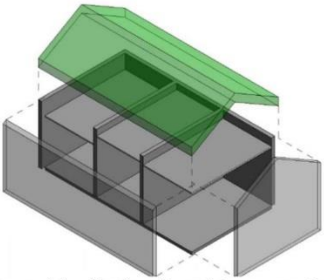

Figure 3: An isometric, displaced, and transparent view of the test model created in Autodesk Revit 17

7 TESTING RESULTS

We developed a prototype accommodating for the technical requirements regarding flexibility. This prototype was functional and was able to use the information from a BIM-model located at the BIMserver with the business logic represented in the BPM environment of Bizagi Studio. This connection allowed for a BMC check of the room heights in Bizagi Studio. The connection between the two servers succeeded with a custom-made web-service, wherein the data model requirements were specified (i.e., project information and room heights) and needed to be assessed according to the ECO2.1-2 criterion. The information was represented in Bizagi Studio and was automatically assessed based on the formalized logic. The logic was specified in a BPMN2 process diagram and the rules of ECO2.1-2 were specified in the "Actions & Validation" functionality, where control flow statements (If, Then, Else) could be represented. The test of using the information from the BIM-model resulted in the correct TLP score of 0. The logic successfully assessed the room heights and calculated the average room heights of three room´s which was lower than 3 meters. The results are shown in a screenshot from Bizagi Studio in Figure 4.

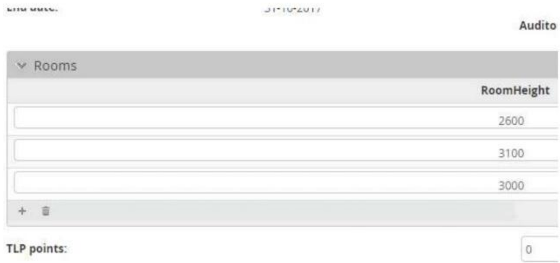

Figure 4: A screenshot from Bizagi Studio´s run-time web server showing calculated room heights and TLP score.

The processes formalized in Bizagi Studio was loosely formulated. This was done with a focus to simplify the process and rely on run-time user input. This meant that the method of assessment of the room height was measured based on the room height information in the IFC model, and were not conducted as a post calculation.

Also, we included exceptions to control the quality of information used both through BIMserver and Bizagi studio to ensure that the right information was present to conduct the assessment. For example, in Bizagi, the information was validated before the assessment commenced.

The process management functionalities of Bizagi Studio allowed for managing versions of the automated BMC-processes. In the BIMserver it was possible to manage the uploaded BIM-models through versioning, which can help manage the BIM-model evolution throughout the progress of the projects.

The prototype allows for versioning of the processes enabling the handling of deferred evolution due to the external drivers such as rule updating (e.g., new versions of DGNB). Updating the processes can be done real-time through refactoring in Bizagi Studio to continuously improve the quality of the process without making problems for the run-time users.

The versioning is especially important in building project cases, where the time determines, which rules are applicable, for example, if a project started in

2014, it is often the rules that apply to that year and not the most recent.

Bizagi Studio allowed for data mining for various process-related parameters, such as instances run, time to complete, errors, exceptions, and the possibility to include and integrate resource overview and management of the people executing the processes. These insights can be presented real-time for build-time users to enable integration of optimizations. The integration allows companies using such as setup to facilitate organizational learning by obtaining critical data about how the processes are executed and allowed for actions to be made for improvements.

8 CONCLUSION AND FUTURE WORK

In this paper, we explored the possibility to improve practical use of BMC by improving flexibility with the use of BPM software. We used PAIS theories to identify the functional requirements for BPM software in a BMC context. The requirements were used to create a prototype with BIMserver to host the BIM-model information and REST web service to enable a transfer of BIM data into the BPM software. With this prototype, we were able to assess a test BIM-model according to sustainability assessment method sub-criterion ECO2.1-2 from DGNB. Allowing to conduct BMC in a BPM environment provide several features of flexibility. Such environment could potentially improve the operationalization of BMC allowing to adapt better to the dynamics of the design projects, shifting business goals of the designer's companies and changing legislation of the industry. However, during our development and test of the prototype we discovered the following limitations of our prototype:

Poor integration of the BIM-model information

The integration of a data model from BIMserver requires that the webservice is required to be continuously adapted according to what is going to be checked in the BIM-model. Each adaption of the web service requires a specialist web service programmer, which complicates the maintainability and flexibility of the system. Instead, we suggest that future investigation on the use of BPM should emphasis better integration of BIM-model information enabling both the run-time and build-user on retrieving information from the BIM-model.

Lack of information processing transparency for the run-time user

The run-time user needs to understand how the information is processed to address potential adaptions. Instead, the run-time user is restricted to modifying certain parameters. The limitations of adapting the run-time processes could potentially hamper the practical use of such as system due to the large uncertainty in each project.

However, we suggest that future research should include further evaluation of the practical usability of flexible approaches to BMC in realistic settings. This would further explore the potential to utilize BMC in BPM environments.

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8. DISCUSSION AND CONCLUSIONS

This chapter will focus on discussing the main research question and the sub-questions asked in this thesis. The discussion will unfold various perspectives of the results of the studies conducted in relation research in the domain of BIM, BMC and beyond. Furthermore, limitations of the studies conducted will be commented upon and topics of future research will be suggested.

8.1 DISCUSSION

One of the biggest challenges related to the construction industry is the increasing complexity driven by the increasing demands on the performance of buildings, especially related to sustainability. The competitive market of the construction industry has made it difficult to create less flawed building designs within the constraints of time and money (Lopez and Love 2012).

The obvious approach to solve this challenge is by incorporating new technology such as BMC systems, which can automate design assessment to increase both the efficiency of the assessments process and quality. There have been successes in automating the processes digitally in other domains, but in the construction industry, and especially building design and its assessment, the digital automation of, e.g., BMC or BIM has proven highly challenging (Nawari 2012; Miettinen and Paavola 2014; Gandhi, Khanna and Ramaswamy 2016; Dainty et al. 2017).

The difficulty of using technology like BMC systems in the construction industry has been identified as being due to socio-technical challenges (Nawari 2012b; Refvik et al. 2014). In these works it is argued that the technology is mature, but that it is the human aspects of organization, culture and adoption that are problematic. Such difficulties arise due to wicked problems that are difficult to solve due to their characteristics of incomplete problem definitions, legislative issues and having changing requirements (Chachere and Haymaker 2008; Eng et al. 2011; Gero 1998). The construction industry as a whole is still rated as being the least digitized (Gandhi et al. 2016). Even in the design process, attempts to encourage the use of digital systems to provide feedback about design scenarios performance are often left out and the choices made are based on heuristics (Beamish and Biggart 2012; Buckley et al. 2018; Gade et al. 2018).

Without support from BIM and BMC systems, designers are subject to their cognitive capabilities, which in some cases results in flaws (Lopez and Love 2012) and inefficient processes (Flager et al. 2009b) in the design of buildings. With ever-increasing requirements based on, for example, the growing interest in sustainability, designers need assistance to provide society with better buildings designed more efficiently. Because of this, the research question *“How can BMC systems better support designers in complex building design practices working with sustainability assessment methods?”* was asked.

8.1.1 LACK OF PRACTICE INQUIRY IN BMC RESERACH

Answering the abovementioned question requires in dealing in how to answer the question methodologically. Previously, BIM and BMC research has been criticized for the lack of qualitative studies of how it is used in practice (Dainty et al. 2017; Koch et al. 2019; Miettinen and Paavola 2014). Miettinen and Paavola (2014) argued that the “utopia of BIM” was not sufficiently counterbalanced by studies that provided a more realistic conception of the complexity of how BIM systems are used in practice.

A similar notion was made by Dainty et al. (2017) that explain that a lack of such investigations is holding back essential perspectives that could improve the understanding of the barriers and challenges. Also, Koch et al. (2019) argue that in order to improve design practices by using BIM systems it is necessary to “dance across” interdisciplinary borders in research in order to reconceptualize and better understand the socio-technical aspects that are embedded in such practices.

Attempts to solve these socio-technical problems in BMC research are many, but the approach to solving these problems is often with a technological deterministic focus. The deterministic view is evident in how challenges are positioned as a separation of technology from the society using that technology. In many cases this has the result that little emphasis is put on understanding the society that is intended to use the technology.

This technological deterministic emphasis is evident in much research in the field of BMC and can be summed up by a quote from Refvik et al. (2014 p. 58): *"The technology is mature and available, it is the soft human aspects of organization, culture and adoption of the technology that are the real challenges",* effectively separating BMC from the users, stating that the technology is working and that it is the users who are generating the problems. Such a view of technology has been criticized by many for being overly technological deterministic, i.e., that it is the technology that must determine what is the most advantageous, not the users of that technology (Kline 2015).

While much research is aware of the practical implications of the use of BMC systems in practice, little effort is made to understand and make significant inquiries about the potential users and their environment. However, one example of achieving practical experience from users was conducted by Preidel and Borrmann (2017) using practical exercises of utilizing visual programming by students. Soliman and Formoso (2018) conducted an empirical study of a construction project using traditional and automated methods. However, the presentation of the findings of this study was very limited, with only six lines of findings based on these empirical studies. Another study by Guedes and Andrade (2019) that made an empirical inquiry into the construction of an Airport Passenger Terminal was related to the topic of BMC but only focused upon the traditional approach of rule assessment of the designers.

The emphasis in this thesis has been to include empirical inquiries from design practices into the research to allow practitioners to help inform the design-based research with their contextualized knowledge related to the use domain of BMC systems and gain insights to socio-technical challenges that occur. Moreover, this approach follows the pragmatic maxim of taking the practical effects of the research results into considerations (Peirce 1878).

8.1.2 USE OF DESIGN SCIENCE RESEARCH AND ACTIVITY THEORY TO EXPAND ON SOCIO-TECHNICAL CHALLENGES OF BMC USE

To continue the exploration of the socio-technical challenges in order to solve them better, the thesis presented a holistic, interdisciplinary, and empirically driven study using the DSR methodology. DSR is a methodology nested on an interdisciplinary approach that considers both behavioral and design sciences. It puts a strong emphasis on the exploration of business needs, e.g., through empirical qualitative studies of practices in order to provide insights into better ways of developing artifacts like information systems and BMC systems.

The business needs of the thesis have been explored using both observations of design cases (Paper I), interviews with design practitioners (Papers III and IV) and prototype user evaluation (Paper IV). Paper I reports on 30.5 hours of video recording of a design case where practitioners used BIM systems to design a building. In Paper III, 19 people working with BMC systems in Singapore and Danish design practitioners were interviewed, and in Paper IV 8 practitioners evaluated a BMC prototype.

DSR emphasizes the use of, e.g., theories and frameworks to ensure scientific rigor by using applicable knowledge in the development of the artifact. Theories were used to bolster the rigor of studies investigating human behavior and providing solutions to the findings of the practitioner inquiries. Behavioral science theories were applied to provide explanations of designers' behavior with an emphasis on holistic and social aspects.

This included the Activity Theory (Papers I and III) that was used as an analytical lens for holistically understanding social human activities of working with BMC. Bounded Rationality and Heuristics (Papers I and III) were used to provide insights into human cognitive capabilities or the lack thereof in making design decisions using BIM/BMC feedback.

Design science theories have also been used to suggest solutions to improve the development of the technical aspects of BMC. Besides BIM and BMC as the main theories, the thesis included Business Rule (Paper III), Business

Process Management (Papers IV and V), and Process-Aware Information Systems (Papers IV and V) theories.

Both the business needs and knowledge base (theories) have been used iteratively to justify functionalities in the development of BMC prototypes, which in turn were evaluated by the practitioners. The output of this work is insights into the socio-technical challenges in order to provide better BMC systems that are more applicable for building design practices. Thereby, DSR and associated knowledge and business needs were used to answer the thesis research question and contribute with additions to the existing knowledge base.

8.1.3 UNSUPPORTED HEURISTIC DECISION-MAKING IN THE BUILDING DESIGN PROCESS

The empirically derived findings indicated that when people make decisions in uncertain domains with little information, they often tend to use heuristics (Paper I). For example, when CEOs make essential decisions for their companies, they base them on heuristics and when decisions were made, they ordered an analysis or reports in an effort to justify the decision afterwards (Gigerenzer 2013). Similar studies are found in the construction industry (Buckley et al. 2018; Maqsood et al. 2004; Shelbourn et al. 2006; Sprinkle 2018).

The findings of Paper I were similar to Gigerenzer´s findings regarding CEO behavior. While there was much emphasis on setting up and using BIM systems to provide feedback about design performance, the feedback was not then used to inform any basis for making design decisions. Instead, it was used to gather some relevant information related to quantities in the model that was used.

The misuse of the BIM systems identified in Paper I exemplifies a discrepancy between how the BIM systems were applied and the intended use. They did not produce any feedback that was of relevance for the project participants to enable them to make decisions that were better informed than without, and they therefore resorted to the use of heuristics. As Refviks (2014) highlights, the technology is often viewed as being separated from society, so it is claimed that it is the people using the BIM systems who are the basis of misuse. However, looking at the mismatch from a socio-technical perspective, it must be attributed to the socio-technical system, i.e., both the technology and the people using it. Observing how the participants actually made decisions and how such decisions affected the design gave clues to what caused the mismatch.

The systems did provide feedback on, e.g., sustainability and cost, so why was it not used? There were indications from the observation that it was due to the participants' inability to understand the premises of how the BIM systems provided the feedback. Currently, little effort has been put into understanding the potential issues arising from the lack of user interactivity in BMC systems (Fan et al. 2019), although efforts have been made to enable users to better understand the premises embedded in the information processes through the use of visual programming language (Ghannad et al. 2019; Preidel and Borrmann 2015; Reinhardt and Matthews 2017). Nevertheless, the majority of commercially available BMC solutions provide only limited functionalities for users to understand and change the information processes (Lee et al. 2014).

Various studies have indicated that the majority of decisions made in the construction industry are based on heuristics (Daly et al. 2010; Flanagan and Norman 1993; Sprinkle 2018), and likewise in the design of buildings (Buckley et al. 2018; Gade et al. 2018; Maqsood et al. 2004; Shelbourn et al. 2006; Sprinkle 2018). The interviews in Paper III showed that designers working with sustainability assessment methods made decisions based on their experience, which allowed them to apply the heuristics to ensure that a design decision was made even though the decisions were often based on uncertainty.

The decisions made in the case of Paper III were not optimized decisions but satisficed decisions where the building's level of sustainability was good enough according to the client's requirements. Similar findings were reported by Dowsett and Harty (2013), who indicated that practitioners are encouraged to follow routines of compliance rather than innovative solutions. The findings of the papers indicated that the primary use of DGNB-DK was not to assist in making the decisions but rather to help in documenting the choices the designers had already made.

8.1.4 THE UNDERLYING "RATIONAL" PERSPECTIVE OF BUILDING DESIGN AND BMC SYSTEMS

Following the technological deterministic view of BMC systems risks neglecting the rationalities of the users and the environments they represent. The risk of neglecting situated user rationalities is due to the developer's inability to consider all potential scenarios that exist for the user. For example, assessing room height with BMC, the developers must imagine what room scenarios the users experience and how to assess the rooms height.

Even in simple scenarios accounting for such simple assessment is logically impossible and therefore, the developers must imbue constrictions to the scenarios of using BMC systems. Such as mismatch between the developers envisioned scenarios /imbued constraints with BIM systems was identified in Paper I. The users were not able scrutinize how the rationale (i.e., imagined scenarios) of the BIM systems to envision if the contradictions were satisfiable. Not knowing the rationale premises of how the BIM systems transformed information made the users reject the systems.

This lack of transparency and flexibility is supported by Fan et al. (2019), who state: *"Current interfaces of BIM-based rule checking systems are implemented without flexibility. They do not allow users to add, adjust or modify the rules in the system; neither do [they] reserve design intentions for higher rule classes compliance checking".* Regrettably, an old idea holds that it is possible to make rationality universal, in the sense of translating rules and developing BMC systems that have embedded in them the most rational premises for the information processes.

The current approach to solve these issues have been done from two perspectives. Either it has been counted by better integration of domain experts into the development process of BMC system/ rule translation or it has been seen as a technical challenge to be solved with e.g., semantic web technologies. One example of this is in Melsane (2015) and another by (Hjelseth 2015b; Lee 2011), who state that the translation process should include domain experts, which would entail that the invited expert can be considered a representative for the use and interpretation of the rules.

However, such normative approach can also be fallible along the same lines as the era of expert systems (Demaid and Quintas 2006; Leith 2016). Leith (2016) argues that there was a failure to recognize the users' context and requirements in the development of the systems, while Demaid and Quintas (2006) argue that it is the continual ambition to attempt to make tacit knowledge explicit that prompted the failure of expert systems.

These indications substantiate the need to change how BMC systems are developed. Is it possible to make a normative BMC system that can accommodate the users' contexts and requirements? So far, it seems very difficult. Similarly, the emphasis on eradicating vague rules (Dimyadi and Solihin 2016; Park et al. 2016) also can be viewed as a problematic approach, because in the tacit knowledge lies a situated rationality that it does not make sense to make normatively explicit.

Technically, there have been ambitious attempts to automate the adaptation to changes in rational systems using technologies like the semantic web that can, for example, then assist in updating the translation rules (Pauwels et al. 2011; Zhang et al. 2017), or machine learning that can further assist designers in creating BIM models that better fit the idealized scenario (Bloch and Sacks 2018; Sacks et al. 2017). When implemented, such an approach to BMC can potentially yield many improvements. However, the use of this technology is still in its infancy regarding BMC (Pauwels et al. 2017; Zhang et al. 2017).

Nevertheless, there also exist acknowledgments that such universal rationality is nonsensical (Sydora and Stroulia 2019), and there is little discussion about the degree to which, if at all, users define their own rationality by being allowed to make their own interpretation of rules in BMC systems and of how to apply these rules in practice. That is not to say that there is not a focus on practical BMC, and recently the flexibility and practicality of BMC systems have been addressed (Ghannad et al. 2019; Nawari 2019; Preidel and Borrmann 2016).

Flexibility is often suggested through various forms of modularization of translation processes, and visual representation. As concerns translation, Nawari (2019) proposes object-driven representation of building rules using a Transformation Reasoning Algorithm in order to provide a concise translation of vague data mapped into an IFC schema. Moreover, modularization has been suggested through visual programming language to ease user interaction with the systems (Ghannad et al. 2019; Kim et al. 2018; Preidel and Borrmann 2017).

Regarding the practicality of BMC systems, Solihin et al. (2019) conducted a subjective review of contemporary systems and languages. Their study emphasized assessing “technical” usability (ease of defining rules, requirements for logic or programming skills) and technical functionalities (technical interfaces, language expressiveness and standardizations). The review was not conducted by practitioners and it did not include any emphasis on transparency.

Such review reveals an underlying technological perspective that attempts to accommodate the complexity and rationality of rules in BMC: “…*complexity will be expected for complex rules*…”. The rationality of the rules is perceived to be captured in their entirety in the systems and therefore the systems and the rules become excessively complex. Again, the focus is then to open up such systems so that they can be adapted by the users of BMC systems. However, will the users ever be able to comprehend and adapt to such complexity with the limitations of bounded rationality? Findings from Paper I, III and IV, indicate that users that do not understand and are allowed to adapt the imbued rationality of BIM systems, will reject the systems. Thereby, the bounded rationality must be acknowledged in order to provide better BMC solutions.

The idea that people are rational and can rationally comprehend such complexity is considered a leftover from the perspective from the enlightenment era that probability theory and human reasoning are the same, even though this was rebutted in the early nineteenth century (Gigerenzer and Goldstein 1996). One of the potential issues of believing in rationality is the effort wasted on covering up the more “irrational” way of working and neglecting important characteristics about how people make decisions in practice.

While human behavioral history is full of instances of people not acting rationally, it is still a prevalent idea. People are not “rational” and have limited attention and cognitive capabilities (Miller 1956; Simon 1957). Typically, people will not even admit to the “irrationality” of their behavior because it can seem simplistic and lazy (Brighton and Gigerenzer 2015). This is also because there is a relevant and one-sided view of non-“rational” ideas such as heuristics as being generally a source of biased and error-prone decisions (Gigerenzer and Todd 1999), as seen in research conducted by Sujan et al. (2019) and Maqsood et al. (2004). For some reasons, people want to believe that they are acting rationally or that other people want them to act rationally. Moreover, the systems developed for these “rational” people also follow a rational viewpoint.

In all the accounts of gathering insights from the practitioner inquiries presented in Paper I, III, and IV, it was a general theme that they wanted more control over the rationality of the systems that they applied. Normative BMC systems come with a set of rationalities that often contradicts with the users set of rationalities. The users require to understand the rationalities and adapt the rationalities to their ecology.

8.1.5 TACIT KNOWLEDGE AND BMC

The construction industry primarily makes use of tacit knowledge to deal with its characteristics as a chaotic, situated and uncertain environment (Bresnen et al. 2003; Demaid and Quintas 2006; Pathirage et al. 2007; Woo et al. 2004). The extensive use of tacit knowledge in making design choices was also identified in Paper I. Moreover, many rulesets and rules are based on implicit formulations.

Paper II highlighted that from the sustainability assessment method DGNB-DK, 66% of rules were categorized as being implicitly formulated, weighting 40% of the possible score. The use of implicitly formulated rules in design projects requires the application of tacit knowledge. As Polanyi (1966) argues, tacit knowledge is highly personal, context-specific, and therefore hard to formalize and communicate. Moreover, there is the question of the degree to which it is even possible to formalize tacit knowledge because that would make it explicit by definition.

It is argued that the need for tacit knowledge arises from the project-based way of working, where the uncertainty of individual-based knowledge is the basis for how the individual exercises discretion sensitive to the project’s context (Koskinen and Pihlanto 2008). Translating rules is not only about looking at the text and translating it word for word, but also applying one's tacit knowledge in how that translation must be applied in an automated process.

Hjelseth (2015a) emphasized that translating rules for BMC systems had to be done by an industry professional (i.e., domain expert). In-depth reasons were left out, but this is most likely because an industry professional like a building designer has insights on knowledge that is not formalized in a natural language rule book (e.g., a building code book). When conducting translation of rules there are many information gaps, that are manifested in vague formulations or missing information.

Using DGNB-DK´s ECO2.1-2 criterion of assessing room height (Green Building Council Denmark 2014), little information is available in how to define room height. The use of industry professionals can apply his/her tacit knowledge to fill in the missing information using discretion. However, such knowledge is based on experience working with the rules in practice and is therefore derived from specific contexts. Can the use of such knowledge be used as a rationale for all possible scenarios?

The emphasis on making vague rules explicit also furthers the rational perspective, where an exploitation of rules can contain a precise and complex representation of the rule. However, this view that some people are capable of making such explication is rebutted in view of how "irrationally" and inconsistently people think and act (Davies and Harty 2013; Nørkjær Gade et al. 2018). As Smith (2003 p. 468) puts it: *"human institutions and most decision making is not guided primarily, if at all"*.

While, there are advantages of rationally explicating rules for, e.g., time spent on assessing building design rule conformity for the enactors of rules (like the building and construction agencies that enforce rule consistency), it can potentially have large unintended and undesirable consequences for the client, users and building designers. This is because within the "irrationality" there is embedded a contextual rationality that BMC system developers potentially cannot express in the then normative BMC systems.

8.1.6 RATIONAL BMC AND ITS IMPLICATIONS

If rational or normative BMC was implemented, there is no doubt that it would yield improvements - but at what cost? From a "narrow" perspective of looking at, e.g., cost benefits for, e.g., rule enactors administrative burden normative BMC would be beneficial. Highly explicit rules would be easy to ensure that the user's assessment would be valid, because no or very minimal interpretation would be possible. Also, the normative BMC carries the promise of easing the assessment process by providing rapid assessment of the design for the users.

Nevertheless, it could also neglect the hidden, unique and important aspects of individual projects and, for example, what a good building project actually is (Dowsett and Harty 2013). Such aspects were also identified in Paper I, where the participants often weighted aspects that was not present on the KPI board but was often weighted more than the KPIs. Such identifications bring forward the question of what a good building design is? Is that something that normatively conforms to an inflexible set of explicated rules established to improve an assessment process, or is a good building design something that is defined contextually by the individual clients, users and building designs? Or including subjective, vague (and nonetheless often considered important) ideas of wellbeing, safety, buildability and aesthetics?

Even though such ideas are integrated into assessment methods such as DGNB-DK these are often the highly implicit criteria, which require human intervention. There may be aspects of the building design that are unknown to the BMC development team and may be a constraining factor in how a scenario (e.g., a BIM model) can be created as identified in Paper I and III, IV.

The normative BMC systems are typically built to provide the most optimal response based on a set of premises. But again, these premises are manifested into the systems by a set of developers that often are dislocated from the context of use and can therefore must be questioned by the practitioners. However, on some occasions they include insights from a number of practitioners (Guedes and Andrade 2019; Hjelseth 2015a; Lee et al. 2019). Regrettably, as stated earlier, these insights are often very limited.

Another potential issue with rational and normative BMC systems is that the focus on improving very specific aspects (like specific sustainability performance indicators) of a very complex and chaotic building process can potentially result in damaging the design. However, so far, only limited aspects of BMC systems are being put into practice, maybe for a good reason. Solibri/Navisworks is applied by practitioners to very narrowly defined aspects of assessing a BIM model’s quality for either verification of information or collision control (Hjelseth 2015a). More advanced use of BMC systems for, e.g., assessing sustainability or building codes (only fragments of the codes in some cases) is not yet integrated into practice, which might be because the scope of knowledge leaves the “small world” characterization.

A transition from “small-world” successes with BIM and BMC systems for, e.g., specifying that one geometrical representation will collide with another geometrical representation can be specified explicitly in, for example, an algorithm. Such algorithms can be agreed upon between users and developers. When BMC systems move from the “small world” domain where more certainty exists into the “large world domains” of greater uncertainty it can cause the “soft” socio-technical challenges identified in Paper III and IV. Differentiating between these domains are necessary to provide with better BMC systems in order to not cause such challenges. This is similar to what Solihin & Eastman (2015) classify as handling class 4 rules where a knowledge base is applied. Potentially a new paradigm is needed to solve the challenges in the “large world” domain of building design.

8.1.7 AN ECOLOGICAL ALTERNATIVE TO NORMATIVE BMC

Based on the findings in Paper I and theories related to the findings, the author argues that an ecological rational approach to manage BMC systems could be beneficial to designers working in what could be described as a “large world” context. A “large world” context is one that is defined as being subject to much uncertainty (e.g., due to the implicit and vague formulations) and many alternatives (many potential solutions for design decisions), as with many aspects of rules as identified in Paper II.

The success of the heuristics used is based on the context in which they are applied. Currently, designers are not greatly assisted and rely mainly on internalized and tacit-based heuristics that they have developed based on their experience with projects (Gade et al. 2018; Gandhi et al. 2016; Koskinen and Pihlanto 2008; Shelbourn et al. 2006). In order to improve designers' practice, an ecological rational perspective was emphasized in order to better understand and develop BMC systems. Instead of attempting to create rational and normative BMC systems to automate the rules, the emphasis was on situating the translation (Paper III) and use (Papers IV and V) of the rule as practically close to the contexts of their use as possible, namely in the business.

8.1.8 ECOLOGICAL BMC IS NOT AN ANTITHESIS TO NORMATIVE BMC

The antithesis to the normative approach is one of anarchy, where everything is up for interpretation and without structure or order, and where the individual user or company is freely constituted without conforming to the intents of the rules. An ecological BMC approach is not an opposite to normative BMC but is a suggestion for a more balanced and situated approach of rationality. It is an approach that allows the users of BMC systems to exercise discretion in projects, with an emphasis on transparency and flexibility.

An ecological BMC system should still emphasize the use of standards and the explicitness of aspects of rules that can be deemed "limited" and relate to the "small world", meaning aspects about which it is practical and possible to find a shared consensus, such as specific formulas to calculate, e.g., sustainability assessment scores. However, it still emphasizes that the ownership of rule interpretation is situated with the users of the rules. This is often the case with traditional assessment, where it is up to the assessor to conduct and interpret the rules satisfactorily. Therefore, the user is responsible for a correct interpretation that satisfies the rule developer's intents.

Ecological BMC should emphasize a critical analysis of what makes sense and what does not make sense to be considered normative. For example, it can in many aspects make sense to use open standards as normative understandings of BIM models. So too can very explicit formulated aspects of rules such as formulas to calculate a sustainability score from DGNB be considered normative and standardized across businesses.

Such an approach was presented in Paper III, which applied the ideas of ecological rationality through the use of theories of process-aware information systems. This specified five requirements in order to improve the flexibility of the system and to make it more ecological rational. Here, the information structure was divided between logic and data objects and run- and build-time components. Specifically, project and company nodes are used to specify some form of normative control of the BMC processes. Similar suggestions have previously been made (Hjelseth 2015a; Nawari 2019; Preidel and Borrmann 2016). However, a limited use of business rule theory has previously been applied to the domain of BMC.

Besides the structure of the BMC, the concept of looseness was also applied. The ambition of loosely specified processes entails that the information processes must be formulated as simply as possible in order to ease the user's understanding of the rules and thereby their adoption. This also follows the ecological rational perspective, which doesn't aim to comprehend the more precise representation of BMC processes, but looks for processes that are satisficed (good enough). For example, the measurement of room heights was suitable to be determined crudely by relying on the specified information on the room height, though in some cases the information did not allow a correct representation.

In general, it provided a "good enough" estimation of the heights of the rooms of a building. It would provide a simple, easily maintained and communicative rule that also does not require much computational effort. Moreover, it would allow the users of the BMC system, through the ease of understanding of its computation, to override it in the specific projects where it is required.

Such an approach would not "over-rely" on the numerous parameters that could be embedded in the translation of such a rule, similar to the Markowitz example mentioned earlier in section 4.5 (Gigerenzer and Goldstein 1996). Moreover, in process-aware information systems, there is an emphasis on monitoring and analyzing the performance of the processes that were implemented in the prototype presented in Paper IV.

The prototype followed these requirements and was evaluated by various practitioners who made manual assessments of a test case. The results showed that, even though the processes of the prototype did not strive towards being complex or precise (but just good enough), the automated assessment of the prototypes came closer to the rule enactors' own assessment of the case than the manual assessment, but was conducted in just seconds.

8.1.9 COST EFFECTIVENESS OF ECOLOGICAL BMC

The ecological BMC approach will require new perspectives on how to develop and use BMC systems in design practices. The use of BMC systems will better mimic the existing use of rules in building design practices but significantly increase the effort required by companies to formalize their own rule interpretations. Such decentralized interpretations will set new requirements for the development of new systems socio-technically. Systems must be better able to provide easy-to-use systems that let users understand and change the interpretations and the current level of usability in, for example, the proposed prototype of the thesis.

At a glance, such an approach is considerably more inefficient than the normative BMC approach because it requires that the work of interpretation is distributed among the users (and businesses) and therefore not centralized. The distribution of interpretation would then necessitate that each business and potentially each project must, to a degree, make its own unique interpretations.

However, if the result of normative BMC systems is either that adoption will fail (through rejection by the practitioners) due to the constraints they put on the building design projects, or that the normative translations cannot cover all the contexts in which the rules are intended to be used, the constraints will be accepted but lead to unintended consequences for the construction industry, harming, for example, implicit but still important factors of buildings such as buildability, aesthetics and wellbeing. Maybe the businesses are acting in an ecological rational way, to the extent that rejecting or misusing the "optimized and normative BMC solutions" is better for the building design process and the product as a whole.

8.2 CONCLUSIONS

This section sums up the main conclusions in relation to the research questions and states the contributions of each paper. First the motivation of the research question is briefly presented. Then each sub-question is presented an answered upon and used to answer the main question. In the end of this section suggestions for future work is presented.

8.2.1 MOTIVATION FOR THE RESEARCH QUESTION

The motivation of this project was to improve the designers' challenged practices of creating building designs subject to sustainability assessment methods. The initial ideas stem from working in the architectural industry dealing with the often-chaotic processes of creating a satisfactory building design within limited resources. So far, BIM systems provide much help for designers in coordinating and documenting the building design, but it is difficult to provide further use of the BIM models for automating design processes like automated rule assessment.

Many BIM systems include forms of automation to provide various types of performance feedback to designers, but their impact is somewhat questionable. It was identified in Paper I that despite using BIM systems to provide feedback on sustainability and cost, it was not used actively as a basis for any design decisions. Instead, the designers used experience-based heuristics to assess the design and make decisions.

There is a constant increase in the requirements for buildings due to, for example, a more significant focus on sustainability, but designers are still making decisions largely unassisted as identified in Paper I. With BIM-based technology, like BMC, designers could potentially get better feedback about decisions made according to selected rules including building codes or sustainability assessment methods.

BMC has existed for many years, and BIM models are prevalent in design practices, but its use is relatively limited, and multiple large BMC projects have failed due to socio-technical challenges, which have so far not received much attention in research and have not been empirically investigated.

Still, the main use of BMC systems in design practice is focused on validation assessment and model coordination purposes, and not for assisting designers dealing with more complex requirements like sustainability. This resulted in the formulation of the main research question: "*How can BMC systems better support designers in the complex building design practices working with sustainability assessment methods?"*. In order to answer this research question, the next sub-sections will attempt to answer the sub-questions asked in the earlier chapters of the thesis to then provide a comprehensive answer.

8.2.2 WHAT ARE THE CONSEQUENCES OF USING BIM-TOOLS TO MEDIATE THE BUILDING DESIGN PROCESS IN A COLLABORATIVE DESIGN ENVIRONMENT?

Answering the research question and following the methodology of DSR entails that the problem domain itself is explored. Therefore, the first sub-question was: "*What are the consequences of using BIM tools to mediate the building design process in a collaborative design environment?"*. This sub-question was explored in Paper I, which focused on the user's design practice. Paper I investigated the practice through observation in a holistic study of a Danish case of designers working collaboratively to deliver a building design using Activity Theory.

The study showed that the design participants would bend and break the rules (like BIM modeling rules) to ensure the progress of the creation of the design according to the changing requirements and constraints of the project. While plans were made to ensure efficient use of BIM tools, the rules would be bypassed due to improvisations which ensured that the design would meet the deadlines, but be inconsistent according to, for example, the rules related to classification that would ensure proper use of the quantities in other BIM tools.

This indicated that while the processes were planned, the dynamics required the BIM tools used to be more flexible to accommodate the improvisations. The study also indicated that while BIM tools were used to provide indicators of design performance, these indicators were not used to direct the building design. The premises for such indicators and how they are calculated were not always self-evident, and the feedback was then left out of the design decisions made. This indicated that there was a greater need for the users of the BIM systems to assess and adapt the systems to their given context within a relatively small timeframe, which in the given case was not supported.

8.2.3 WHAT SUSTAINABILITY ASSESSMENT CRITERIA ARE BEST SUITED FOR AUTOMATION?

The second sub question was addressed in Paper II, *"What sustainability assessment criteria are best suited for automation?",* and revealed that the rules used in Denmark for assessing sustainability in buildings (DGNB-DK) were substantially of an implicit character, thereby emphasizing the need for BMC systems to be able to handle implicitly characterized rules.

The criteria from DGNB-DK to most easy translate are the explicit formulated, which accounts for 34 % of the criteria (weighted 60 %). Most implicit formulated rules were identified under the categories of social quality, technical quality and process quality and accounts for 66 % (weighted 40 %).

Dealing with the socio-technical challenges of using BIM/BMC systems in building design addressed in Paper I and handling the many implicitly formulated rules set new requirements and objectives for a BMC system. The first element of a BMC system is the translation of rules. Therefore, the results of Papers I and II were used to form the context for the next sub-question answered in Paper III.

8.2.4 HOW CAN THE TRANSLATION OF NATURAL LANGUAGE TO COMPUTER EXECUTABLE LANGUAGE FOR BMC BE IMPROVED FOR BUILDING DESIGN PRACTICES?

The third sub-question, "*How can the translation of natural language to computer executable language for BMC be improved for building design practices?"* was explored in Paper III. In this paper it was explore how users, both supported and unsupported, were challenged by assessing their design according to a set of rules. This exploration revealed that the users were restrained by normatively translated rules and required that they were able to exercise discretion. Instead, they required more flexibility in adapting the rules to their unique project context.

To alleviate the challenges of lacking flexibility, and the implicit nature of the rules, a business-centric method of translating natural language rules into computer executable language was suggested. This method emphasizes businesses instead of rule enactors as being responsible for conducting translations of rules for their BMC systems. The business-based method of translating rules emphasizes the descriptive translation of rules that embed transparency and flexibility by focusing on theories of business rules and business process modeling. The method's applicability was demonstrated by translating a sub-criterion from DGNB-DK.

8.2.5 HOW ARE THE SOCIO-TECHNICAL CHALLENGES OF FLEXIBILITY (HARD-CODING) AND TRANSPARENCY (BLACK-BOXING) ARE EXPERIENCED BY PRACTITIONERS USING BMC SYSTEMS?

The fourth sub-question is *“How are the socio-technical challenges of flexibility (hard-coding) and transparency (black-boxing) are experienced by practitioners using BMC systems?”.* This question was answered by developing a prototype that further made use of the results from Papers I, II, and III. Paper IV emphasized the execution of the rules translated with the business-based method presented in Paper III.

The prototype made use of systems already existing in the design practices Autodesk Revit, Dynamo, and Tableau. Autodesk Revit was used as the BIM-authoring component of the prototype. Dynamo was used to conduct and formalize the translated rules, and Tableau was used to visualize the results of the prototype.

The prototype followed the previously used theoretical perspectives and improved flexibility and usability using the theories of Process-Aware Information systems and Business Process Management. The prototype was evaluated qualitatively and quantitatively by design practitioners assessing a test building. The results indicated that the prototype provided the feedback on the Revit model’s performance regarding the sub-criterion from DGNB-DK.

The prototype results were closer to the rule developers’ own assessment of the building than the other practitioners’ assessment on several parameters.

Moreover, the prototype assessment was automatically processed within a minute. In the qualitative results, it was indicated that the flexibility and transparency that the prototype provided were of beneficial use. It was also reported that the BIM modelers could understand the information requirements and rule “behavior” better in the prototype because they were able to get instant feedback on their design choices and limitations of the system.

However, the use of Dynamo in the prototype was experienced by practitioners as a “quick and dirty” tool that also raised various issues. Dynamo was reported to be not ideal for handling large amounts of information and did not provide enough control to limit specific processes in order to manage maintainability and accountability, this meaning maintainability in relation to changes in interpretations and version control, and accountability for who interpreted what and what was allowed to be interpreted and changed in the processes. Also, Dynamo as a platform was experienced as being difficult for non-specialists to use, though various possibilities of Dynamo players and interfaces can be used.

8.2.6 HOW IS IT POSSIBLE TO IMPROVE THE FLEXIBILITY OF BMC IN A BUSINESS PROCESS MANAGEMENT ENVIRONMENT?

The limitations of the previous prototype led to the fifth sub-question: “*How is it possible to improve the flexibility of BMC in a Business Process Management environment?”.* While the prototype demonstrated various limitations, specialized systems for Business Process Management do exist. Although such systems have not been used in the domain of the construction industry, they can provide better handling of more significant amounts of information and also the ability to exert more control of the processes.

Based on such insights, a new prototype was developed using Bizagi Studio to conduct the model checks. Bizagi Studio does not natively provide any connections to BIM information, but can connect to external databases using an API. A connection to BIMserver hosted IFC information and was accessed through a webservice connected with Bizagi´s API and JavaScript Object Notation (JSON).

The prototype was tested in a limited experiment highlighting the possibility of using Business Process Management software. The prototype successfully assessed the building according to the ECO2.1-2 rule from DGNB-DK and in some respects provided a more user-friendly experience, with extended possibilities to control and present information. However, because Business Process Management software like Bizagi is scaled to much larger and less dynamic contexts, it presented challenges.

The Bizagi-based prototype also suffered from poor integration of the BIM model information, which made it cumbersome for users to adapt the rules for specific purposes. Also, the user’s ability to view and understand the information processes was limited compared to, for example, Dynamo because it did not provide enough transparency on how the information was processed.

While the experiment suffered from limitations, it provided insights into the potential advantages of applying Business Process Management software systems to conduct automated rule assessments using BIM information. Various concepts related to Business Process Management software can potentially be further incorporated into the domain of BMC systems alleviating issues of scalability and transparency.

8.2.7 HOW CAN BMC SYSTEMS BETTER SUPPORT DESIGNERS IN THE COMPLEX BUILDING DESIGN PRACTICES WORKING WITH SUSTAINABILITY ASSESSMENT METHODS?

In this section the main research question, “*How can BMC systems better support designers in the complex building design practices working with sustainability assessment methods?*“ is answered using the results from the papers that were used to answer the sub-questions. Diverging from the traditional approach of developing and using BMC models, the results from the investigations indicate that it is possible to promote and conduct a more ecological rational and thereby bottom-up approach. The following sub-sections summaries the conclusions to the main research question.

8.2.7.1 USING BUSINESS RULES TO SIMPLIFY RULE TRANSLATION RETAINING THE RULE INTENT

The results presented in the thesis indicate that it is possible to make BMC solutions that are simpler by relying on formalizing heuristics (i.e., simplified rule translations). The use of adaption of BMC can happen on a business scale where the ownership of rules is shared between the rule enactors and the businesses as traditionally.

The more explicit a rule is formalized, the less able are the rule user to conduct the discretion required to successfully adapt the rule. Not only to the benefit of the rule enactors perspective (retaining the intent of the rule) but also the rule user (fitting the rule into the context) and the building client (ensuring a feasible adoption of the rule).

Expressing the intent of the rules and embedding the knowledge about how a rule could be applied in a practical scenario will always run the risk of not being able to handle a specific scenario. The irrationality of creating complex systems that can handle the unfathomable complexity and comprehensiveness is rarely addressed in contemporary research.

However, few scholars have advocated for lessening the utopian dream of rationality and certainty in “large worlds,” domains like building design in the construction industry. In this thesis, a focus is emphasized on dealing with the complexities and comprehensives by applying an ecological rational perspective and the use of heuristics.

8.2.7.1 ECOLOGICAL BIM-BASED MODEL CHECKING

Ecological BMC emphasizes adaptive behavior acknowledging the limitations of human cognition and the structure of the environment and can provide with quick results that satisficing and easy to maintain, understand, and adapt. Not perfect, but good enough to be better than the traditional manual approach in their ecology of the businesses and projects. The suggestion to approach BMC from an ecological rational perspective is an alternative to the normative and technological deterministic solutions in contexts of much uncertainty.

The idea of finding optimal solutions using complex models are challenged by often being intractable and out of reach computationally. Currently, AI advancements have proven worthy in beating chess and go masters but is far from being able to find people a spouse. Some domains are limited in nature and give the possibility for complex models to optimize decisions.

Finding a spouse is more difficult. It is an ill-defined question that defies optimization because there are too many variables and is highly based on the individual's preferences. The same could be said for building designs which are subject to a multitude of unique preferences even for many minuscule design decisions. What is the optimal window to choose?

One might reduce the parameters to, e.g., cost, longevity, co2 footprint. However, what about aesthetics, ease to install, trust, and other subjective criteria? Also, what parameters weight more than others? Does it change? Moreover, are people able to express the parameters? Will an optimization of "objective" and generalizable parameters maybe not be overfitted and there not relevant for the people making the decisions?

The use of complex models for optimizing solutions are continually improving as well as computational capacity and are well suited to deal with finding optimal solutions in limited domains. However, when using complex models to optimize decisions in domains that are not limited, such an approach is often cumbersome to develop and maintain and produce wrong results and can even cause harm. Users then reject the use of such tools as identified in Paper I.

While a typical development strategy of BMC systems is to handle as many scenarios as possible makes systems complex, cumbersome, and often inflexible. Instead of focusing on handling as many scenarios, which can restrict flexibility, an approach of Ecological BMC systems can potentially improve the practical applicability, which sets higher requirements of functional flexibility of the system. However, using heuristics and understanding in which contexts heuristics work, or do not, offer new potential to automate and improve aspects of the design process and the construction industry in general as exemplified in Paper IV.

Where traditional building design assessment are nested and conveyed situated so are Ecological BMC, it diverges new challenges of how efficiently to handle the situated interpretations and implementations of rules. A situated approach of automating rule assessment is a part of the business's value-generating processes and is what gives them their competitive advantages.

The results from this thesis indicate that it is possible to follow the methodology to translate rules from the method proposed in Paper III and formalize the rules in the prototype presented in Paper IV. Given that one follows the principles of practical atomic translation and looseness to make it as easy as possible for users to comprehend the processing and to make the necessary adaptations, this approach would be practical.

There is potential for the prototype presented in Paper IV, but Paper V and the use of Business Process Management theories can potentially assist in formalizing more efficient information architecture. The results of Ecological BMC will never yield the most precise feedback, but it will instead rely on contextual, understandable, adaptive, and rational feedback.

The author suggests an ecological rational perspective to better develop and use BMC systems in “large world” domains of building design, and to better accommodate the unique practices subject to the comprehensive and complex requirements found in, e.g., sustainability assessment methods. To describe this ecological rational approach to BMC, the author suggests the term “Ecological BMC”.

The results of this thesis suggest that, to conduct Ecological BMC, the following must be accommodated: (1) the systems must be situated in the business; (2) the rules are based on heuristics; (3) the rules are transparent for the users; (4) the users can adapt the rules; and (5) it is possible to track the performance of the rules.

8.3 FURTHER STUDIES

The findings in this thesis open up a wide range of suggestions for further studies. The exploratory and theoretically induced results give insights into socio-technical challenges and potential solutions through Ecological BMC. However, these findings are yet to be generalized. Therefore, further studies of a quantitative nature could assist in identifying how generalizable the results of the thesis are, and specifically the user needs for transparency, flexibility and trust in the use of BMC systems.

It was indicated earlier that the ambition of Ecological BMC was not to neglect everything normative but instead to find a better balance of what should be normative and what not. Further research could help identify the rules and sub-rules that are best suited to be normatively translated without restricting the BMC system users too much. Following the Ecological Rationality perspective, an emphasis should be put on contextual factors that determine how and why the rules are best translated.

Similarly, how can rules be better translated into heuristics that provide simple but effective assessments? Such investigation should again follow the Ecological Rationality perspective in understanding the contexts in which such heuristics are relevant. As an example, how can limited information from a BIM model be useful in order to assess specific rules?

Such insights could potentially assist in better use of standardized information from such BIM models and improve the use of open standards. By limiting the amount and quality of information, fewer requirements are needed in the information exchange between participants, and this would allow for easier and faster BMC system assessment processes, while still yielding useful results.

Allowing the users of BMC systems more control of how rules are interpreted will make it difficult for the rule owners to validate how the users made their interpretations. In traditional and normative BMC systems with limited scope for rule interpretation and validation of the rule adjustment, the use is easier because the rules are typically hard-coded and black-boxed. So, the premises of how the rules are used in the BMC systems are embedded in the system, and the rule owners are assured that the results are consistent with the embedded premises.

However, when Ecological BMC systems are “open” for users to adjust how rules are interpreted and processed, it is more problematic for the rule owners to ensure that the intent of the rules is retained. While it is possible to log the interpretation and processing of the rules in Ecological BMC systems, this would require the rule owners to assess every individual log to ensure the validity of the intent. Such an approach will generate much more work for the rule owner to assess every single log but allow the users much more flexibility.

A potential solution to improve the rule owners' work of assessing the log validity of Ecological BMC systems is to apply technologies to assist in this assessment. Various machine learning technologies could potentially use the many logs and follow the data created using Ecological BMC systems. This would allow machine learning algorithms to identify patterns of rule intent retainment and thereby lessen the assessment burden for the rule owners.

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SUMMARY

This thesis presents a novel approach to conducting BIM-based Model Checking (BMC) named Ecological BMC. Ecological BMC emphasizes ecological rationality, which emphasizes that it is the context (business and project) that determine the rationality of the statements formalized in the rules used by a BMC system. BMC systems can provide with automation of the design assessment process and yield both more precise and quicker results than traditional design assessment using BIM-models. However, the use of BMC systems in design practices is limited, and many large BMC system developments have been abandoned. The limited use has been identified to be related to socio-technical challenges of how people use the technology, not the technology being unable to conduct the automated assessment. The Ecological BMC approach is a alternative to the traditional developments of BMC systems that suggests letting businesses and their users make their interpretation of the formalized rules and processes. This sets new functional requirements to the BMC systems and emphasizes effectiveness over precision, transparency, flexibility, and trust. The relevance of the Ecological BMC approach was substantiated by empirical studies of building design practitioners conducted in Singapore and Denmark, which has been used to the development of two prototypes. The prototypes were moreover tested by practitioners to general practical knowledge about the use of Ecological BMC systems in practice.

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