Methods for implementing Building Information Modeling and Building Performance Simulation approaches

PhD Thesis

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Cover photo: Autodesk Vasari Beta 3, wind simulation.

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Preface

This thesis is submitted in partial fulfillment of the requirements for the PhD degree in Civil Engineering at the Technical University of Denmark (DTU).

Thesis studies were carried out at the Section for Building Design, Department of Civil Engineering, DTU, and were partially funded by the Department of Civil Engineering, DTU, the Interreg IV A Öresund Programme "Integration of Sustainable Construction Processes – by the use of Information and Communication Technology", the Gate 21 project "Building Envelope Retrofits", and the cuneco project "cuneco classification system (CCS)".

The principal supervisor was Associate Professor Jan Karlshøj, Section for Building Design, Department of Civil Engineering, DTU; the co-supervisor was Associate Professor Flemming Vestergaard, Section for Building Design, Department of Civil Engineering, DTU.

The thesis is built on a multi-paper structure, covering five scientific papers, plus two thematic studies.

Kgs. Lyngby, Denmark, October 2014

Thomas Fænø Mondrup

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Acknowledgements

During the years leading up to the completion of this thesis, I have benefited from the inspiration, wisdom, and help given by many people.

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My friends and colleagues in the Section for Building Design, Department of Civil Engineering, DTU have willingly given their help and professional input, and I sincerely thank them for their insights and suggestions. My fellow Ph.D. student Niels Treldal deserves a special mention here.

I am also grateful to DTU, Interreg, Gate 21, and cuneco. Their financial support made this thesis possible.

I would especially like to thank my family and friends for the constant support and backing they have given me. Their encouragement and faith in me has helped me overcome the challenges I faced along the way. Finally, I am deeply grateful to my girlfriend Ditte Marie for her confidence, understanding and patience.

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Abstract

This thesis reports on a number of studies into the adoption of Building Information Modeling (BIM) and Building Performance Simulation (BPS). The thesis has two main goals. The first is to explore the benefits and challenges of adopting (a) BIM as a platform for Architecture, Engineering, Construction, and Facility Management (AEC/FM) communication, and (b) BPS as a platform for early-stage building performance prediction. The second is to develop (a) relevant AEC/FM communication support instruments, and (b) standardized BIM and BPS execution guidelines and information exchange methodologies.

Thesis studies showed that integrated BIM approaches have the potential to improve AEC/FM communication and collaboration. BIM is by its nature multidisciplinary, bringing AEC/FM project participants together and creating constant communication. However, BIM adoption can lead to technical challenges, for example, getting BIM-compatible tools to communicate properly. Furthermore, BIM adoption requires organizational change, that is changes in AEC/FM work practices and interpersonal dynamics. Consequently, to ensure that the adoption of BIM is successful, it is recommended that common IT regulations and standardized information exchange formats, and in-depth preparation and training of AEC/FM project participants are given a high priority. It is essential that this preparation and training are supported by common BIM standards and execution guidelines.

Thesis studies also showed that integrated BPS approaches have the potential to improve early-stage building performance prediction. However, because of complex BPS information exchange structures, the BPS process is not always practical, highlighting the need for these structures to be simplified and more, clearly articulated.

In the present thesis, buildingSMART standard approaches, such as the Industry Foundation Classes (IFC), Information Delivery Manual (IDM), and Model View Definition (MVD), are proposed to provide clarification and consistency for BIM and BPS adoption, particularly, for BIM and BPS information exchange.

As part of the thesis, a modular IDM Framework to define and organize generic, decomposed IDM Packages was developed. Each IDM Package represents a specic

AEC/FM process and a set of information exchanges. The IDM Framework, which, ideally, should consist of appropriate number of IDM Packages to support all main processes of the AEC/FM project life cycle, is particularly effective at providing the basis for developing an IDM Project Plan. The IDM Project Plan is created by selecting the specific IDM Packages required for the specific AEC/FM project. In this approach, the IDM Project Plan can help communicate the overall scope of the AEC/FM project, processes to be carried out, organizational interactions, and required information exchanges.

This thesis concludes that common BIM and BPS execution guidelines and information exchange methodologies, such as the modular IDM Framework and generic IDM Packages, generate value by providing a shared understanding and a unified platform for BIM and BPS adoption.

Resumé

I nærværende afhandling betragtes en række studier målrettet implementering af Bygnings-Informations-Modellering (BIM) og Bygnings-Performance-Simulering (BPS). Afhandlingen har to hovedmål. Det første er at udforske fordele og udfordringer ved at implementere (a) BIM som platform til kommunikation i byggeindustrien, og (b) BPS som platform til forudsigelse af bygningsperformance. Det andet er at udvikle (a) relevante kommunikationsinstrumenter målrettet byggeindustrien, og (b) standardiserede BIM- og BPS-implementeringsguidelines og -informationsudvekslingsmetoder.

Afhandlingens studier viste, at integrerede BIM-metoder har potentiale til at forbedre kommunikation og samarbejde i byggeindustrien. BIM er i sin natur tværfagligt, hvorfor BIM bringer projektdeltagere sammen og skaber konstant kommunikation. Dog medfører BIM-implementering ofte tekniske udfordringer, såsom at få BIM-kompatible værktøjer til at kommunikere korrekt. Desuden efterspørger BIM-implementering organisatoriske ændringer, herunder ændringer i arbejdsvaner og interpersonelle dynamikker. Det anbefales derfor, at BIM-implementering understøttes af fælles IT-regler og standardiserede udvekslingsformater, samt at der fokuseres på forberedelse og træning af projektdeltagere.

Afhandlingens studier viste ligeledes, at integrerede BPS-metoder har potentiale til at understøtte forudsigelse og evaluering af bygningsperformance. Dog fremstår BPS-processen ofte problematisk og tidskrævende, dette blandt andet på grund af komplekse informationsudvekslingsstrukturer. Det anbefales derfor, at der fokuseres på forenkling og specificering af disse strukturer.

I afhandlingen foreslås det at benytte buildingSMART-metoderne Industry Foundation Classes (IFC), Information Delivery Manual (IDM) og Model View Definition (MVD) til at skabe klarhed og sammenhæng for BIM- og BPS-implementering, særligt i henhold til BIM- og BPS-informationsudveksling.

Som led i afhandlingens studier blev der udviklet et modulært IDM-Framework til at definere og strukturere generiske IDM-Pakker. Hver af disse IDM-Pakker repræsenterer en specifik byggeproces og et sæt informationsudvekslinger. Ideelt set bør dette IDM-Framework indeholde IDM-pakker tilsvarende samtlige hovedprocesser i hele

byggeriets livscyklus. IDM-Frameworket er særligt effektivt til at danne grundlag for en såkaldt IDM-Projektplan. IDM-Projektplanen skabes ved at vælge de specifikke IDM-Pakker, der kræves af det givne byggeprojekt. Ved at benytte denne metode kan IDM-Projektplanen hjælpe til at kommunikere og formidle byggeprojektets overordnede mål, dets specifikke processer, indbefattede organisatoriske interaktioner, samt forskellige informationsudvekslinger.

I afhandlingen konkluderes det, at fælles BIM- og BPS-implementeringsguidelines og informationsudvekslingsmetoder, såsom det udviklede IDM-Framework og tilhørende generiske IDM-pakker, skaber værdi ved at tilvejebringe en fælles forståelse samt en fælles platform for BIM- og BPS-implementering.

Contents

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List of scientific papers

During PhD studies, six scientific papers, namely two journal papers and four conference papers, were written and made available to the scientific community. The corresponding author of this thesis is also the responsible author of all these scientific papers, with the exception of "Scientific paper #4", which was produced with equal contributions from the first two authors. Note that "Scientific paper #6" is not part of this thesis.

Scientific paper #1
Mondrup, T.F.[1], Karlshøj, J., Vestergaard, F. Communicate and collaborate by using BIM. In *Proceedings of 29th International Conference on Applications of IT in the AEC industry, CIB W078, 2012, Beirut, Lebanon.*

Scientific paper #2
Mondrup, T.F.[1], Karlshøj, J., Vestergaard, F. BPS tools for planning of energy efficiency retrofits. In *Proceedings of 10th Nordic Symposium on Building Physics, NSB, 2014, Lund, Sweden.*

Scientific paper #3
Mondrup, T.F.[1], Karlshøj, J., Vestergaard, F. Exploring IFC interoperability between BIM and BPS tools. Submitted to *Automation in Construction, 2014.*

Scientific paper #4
Mondrup, T.F.[1], Treldal, N.[1], Karlshøj, J., Vestergaard, F. Introducing a new framework for generic IDMs. In *Proceedings of 10th European Conference on Product and Process Modeling, ECPPM, 2014, Vienna, Austria.*

Scientific paper #5
Mondrup, T.F.[1], Karlshøj, J., Vestergaard, F. Information exchange structures for early-stage BPS. Submitted to *Energy, 2014.*

Scientific paper #6 (Not part of this thesis)
Mondrup, T.F.[1], Karlshøj, J., Vestergaard, F. IDMs to facilitate IT supported energy analysis. In *Proceedings of 29th International Conference on Applications of IT in the AEC industry, CIB W078, 2012, Beirut, Lebanon.*

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Part A

Introduction

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A1. Introduction

A1.1 Background to thesis

Well communicated information is at the core of a successful Architecture, Engineering, Construction, and Facility Management (AEC/FM) project – "the right information at the right time oils the machine of progress" (Socha & Lanzetti, 2012). However, because the AEC/FM industry is fragmented and discipline-oriented, communicating AEC/FM information efficiently and effectively remains a challenge (Berard & Karlshoej, 2012). Communication support approaches are therefore needed.

Building Information Modeling (BIM) represents a new approach within the AEC/FM industry, one that brings to life interactions between AEC/FM project participants and organizations, and between each AEC/FM project element (Beaven, 2011). Although opinions differ among AEC/FM professionals and researchers on a definition of BIM, in the context of this thesis, it is defined as the process of development and use of a computer-generated model to analyze the planning, design, construction, and operation of a building. The resulting product, a Building Information Model (BIM model), is an information-rich, object-oriented, digital representation of the building, from which different views and information appropriate to various needs can be extracted (Cidik et al., 2014). Ideally, the BIM model should carry information related to the complete building life cycle, both physical and functional characteristics. A BIM model can be used for a number of purposes, such as building layout and component/system visualization, fabrication/shop drawing production, material information extraction, conflict and collision detection, cost estimation, and facility management (Azhar et al., 2008). Among the leading BIM model authoring tools (BIM tools) in current use are Autodesk Revit Architecture (Autodesk, 2014b), Graphisoft ArchiCAD (Graphisoft, 2014), Nemetschek Vectorworks (Nemetschek, 2014), and Bentley MicroStation (Bentley, 2014).

In response to continuing BIM adoption, together with ever-increasing energy efficiency and environmental awareness, Building Performance Simulation (BPS) approaches are increasingly being used to virtually explore the performance of a building (Attia, 2012). BPS can be used for many purposes, but in this thesis, the focus is on the use of BPS to predict energy consumption and indoor environmental quality. It is widely claimed that a significant portion of a building's life cycle performance is determined by decisions taken in the early stages of building design. Consequently, early-stage performance prediction is an essential first step towards developing high-performance building design (Lin & Gerber, 2014) (Kanters et al., 2014). BPS tools in current use include Autodesk Ecotect Analysis (Autodesk, 2014a), IES Virtual Environment (IES, 2014), IDA ICE (EQUA, 2014), EnergyPlus (DOE, 2013), and more.

Despite some progress, the rate of adoption of BIM and BPS has been relatively slow. Key reasons include: (1) complexity in accessibility and usability of BIM and BPS tools, that is complexity in BIM and BPS Human-Computer Interaction (HCI), (2) complexity in BIM and BPS information exchange structures, that is complexity in information needed by and resulting from BIM and BPS, and (3) poor efficiency in BIM and BPS interoperability solutions, that is poor efficiency in BIM and BPS information (data) transformation and export/import capabilities (Laine et al., 2007) (Attia et al., 2009) (Venugopal et al., 2012) (Hiyama, et al., 2014).

The above factors inevitably challenge AEC/FM project participants' day-to-day BIM and BPS activities. In particular, these factors challenge the ability to communicate and exchange information between different BIM and BPS-based AEC/FM processes, to the point where information gaps and losses occur (see Figure A-1) (Pazlar & Turk, 2008).

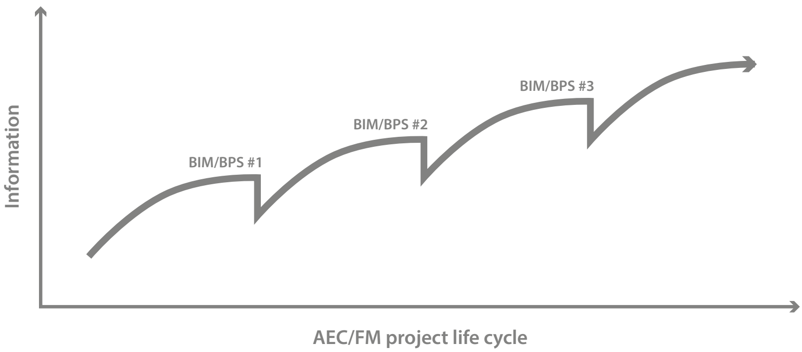

Figure A-1. BIM and BPS-based AEC/FM information flow.

To bridge AEC/FM communication and information gaps, and to promote the adoption of BIM and BPS, there is a need to improve the specification and structure of the content of certain BIM and BPS-based AEC/FM processes and information exchanges (Aram et al., 2010) (Karlshoej, 2012).

Here, buildingSMART standard approaches can be supportive. The buildingSMART alliance, which is an international organization driving the development of open standards to support BIM adoption, provides open standard, consensus-based methodologies to facilitate AEC/FM information exchange (buildingSMART, 2008). The buildingSMART standard approaches include: (1) Industry Foundation Classes (IFC), (2) Information Delivery Manual (IDM), and (3) Model View Definition (MVD).

In summary, the IFC provides a common data model standard for describing and exchanging AEC/FM information in a neutral file format; the IDM provides a collaborative standard for specifying and displaying AEC/FM process flows and associated information exchanges; and the MVD provides a technical standard for documenting IDM-specific IFC information exchanges (Wix et al., 2009) (See et al., 2012).

A1.2 Hypothesis

This thesis is based on a double hypothesis:

“It is hypothesized that Building Information Modeling (BIM), supported by standardized execution guidelines and information exchange methodologies, leads to improved Architecture, Engineering, Construction, and Facility Management (AEC/FM) communication”.

“It is hypothesized that Building Performance Simulation (BPS), supported by standardized execution guidelines and information exchange methodologies, leads to improved building performance prediction”.

A1.3 Thesis goals

This thesis has two main goals. The first is to explore the benefits and challenges of adopting (a) BIM as a platform for AEC/FM communication, and (b) BPS as a platform for early-stage building performance prediction. The second is to develop (a) relevant AEC/FM communication support instruments, and (b) standardized BIM and BPS execution guidelines and information exchange methodologies.

The study goals are addressed by: (1) a series of high-level studies, Part B of the thesis, which characterize and explore general issues of AEC/FM communication and BIM and BPS adoption, and (2) a series of detailed studies, Part C of the thesis, which explore in-depth issues of AEC/FM communication and BIM and BPS adoption.

NOTE: The primary purpose of this PhD study is to improve the processes for AEC/FM communication and building performance prediction by using BIM and BPS, with the ultimate goal of enabling better, high-performance building design.

A1.4 Motivations

This thesis deals with both BIM and BPS because of the relationship between: (1) current AEC/FM trends, (2) PhD funding issues, and (3) the corresponding author’s educational background and interests.

A1.4.1 AEC/FM trends
The adoption of BIM is gaining momentum as more and more AEC/FM project participants and organizations discover its advantages (Gonchar, 2009). Furthermore, an increasing number of clients and building owners, both public and private, require that BIM be used on their AEC/FM projects (Zeiss, 2013).

A1.4.2 Funding issues
As previously mentioned, PhD funding has been provided by the Interreg IV A Öresund Programme "Integration of Sustainable Construction Processes – by the use of Information and Communication Technology". The primary purpose of this programme was to support Öresund cross-border AEC/FM communication and collaboration, particularly by means of effective BIM adoption (Karlshoej, 2009). In addition, supplementary funding has been provided by the Gate 21 project "Building Envelope Retrofits" (GATE 21, 2013), where the primary purpose was to investigate the potential of adopting BPS as a performance-based building design decision-making tool, and the cuneco project "cuneco classification system (CCS)" (cuneco, 2013), where the primary purpose was to develop a common, BIM-compliant space classification and identification system.

A1.4.3 Educational background
The corresponding author of this thesis holds an MSc in Civil Engineering, with specialization in Architectural Engineering (AE) and Integrated Energy Design (IED). During engineering studies, BPS was used as an integral part of the performance prediction and benchmarking process of different building design alternatives.

A1.5 Methodology
This thesis utilizes an integrative, combined methodological framework of: (1) applied qualitative research, and (2) experimental development.

A1.5.1 Applied qualitative research
Applied qualitative research is concerned with "production of knowledge that is practical and has immediate application to pressing problems of concern to society at large or to specific public or private research clients", and it is research that is designed "to engage with people, organizations, and interests, and is aimed to inform human services, public policy, and other local, national, and international decision makers" (Given, 2008). In the present thesis, the applied qualitative research approach provided the methodological basis for data collection and analysis. Data was collected through multiple AEC/FM, BIM, and BPS studies, with each study making use of one or more of the following:

- Review of current approaches to BIM and BPS
- Semi-structured interviews of AEC/FM industry professionals
- Mapping of relevant AEC/FM standards

- Case studies of selected BIM and BPS uses

Embedded in applied qualitative research is the perspective that "researchers cannot set aside their experiences, perceptions, and biases, and thus cannot pretend to be objective bystanders to the research" (Harwell, 2011). The same applies to this thesis, in which the corresponding author's educational background and personal experience with, for example, specific BIM and BPS procedures unavoidably influenced data collection and analysis.

A1.5.2 Experimental development

Experimental development is concerned with "systematic applications of knowledge or understanding directed toward the production of useful materials, devices, and systems or methods, including design, development and improvement of prototypes and new processes to meet specific requirements" (NSF, 2010). In the present thesis, the experimental development approach provided the methodological basis for support instrument and methodology development. These developments included the following:

- Development of AEC/FM communicative website
- Development of space and thermal zone identification concept
- Development of methodology for BPS-based retrofit design processes
- Development of modular IDM Framework for generic AEC/FM processes
- Development of façade performance engineering IDM Package

A1.6 Thesis structure

This thesis builds on a multi-paper structure, as recommended by the PhD School of the Department of Civil Engineering, Technical University of Denmark (DTU, 2014). This means that the thesis studies are presented as a collection of scientific papers, covering a total of five scientific papers, plus two thematic studies. This structure differs from the "traditional" monograph structure in format rather than content.

In the present thesis, the thematic studies and scientific papers represent actual thesis chapters. Therefore, each thesis chapter, that is each thematic study/scientific paper, is written and organized in the general format of scholarly, scientific papers (title, abstract, introduction, methodology, etc). However, the layout of the scientific papers has been adapted to the general layout of the thesis without changing their original content.

The multi-paper structure inevitably leads to repetition, as specific concepts, definitions, and methodologies are described in several thematic studies and scientific papers. Another challenge to the multi-paper thesis is the ability to create coherence between included thematic studies and scientific papers, and to document a cohesive, unified thesis focus. However, a common feature across the thematic studies and scientific papers is that they all deal with issues of AEC/FM communication and BIM/BPS adoption.

Figure A-2 shows a model of the structure of the thesis, which has four parts: (1) Part A – Introduction, (2) Part B – High-level studies, (3) Part C – Detailed studies, and (4) Part D – Conclusions.

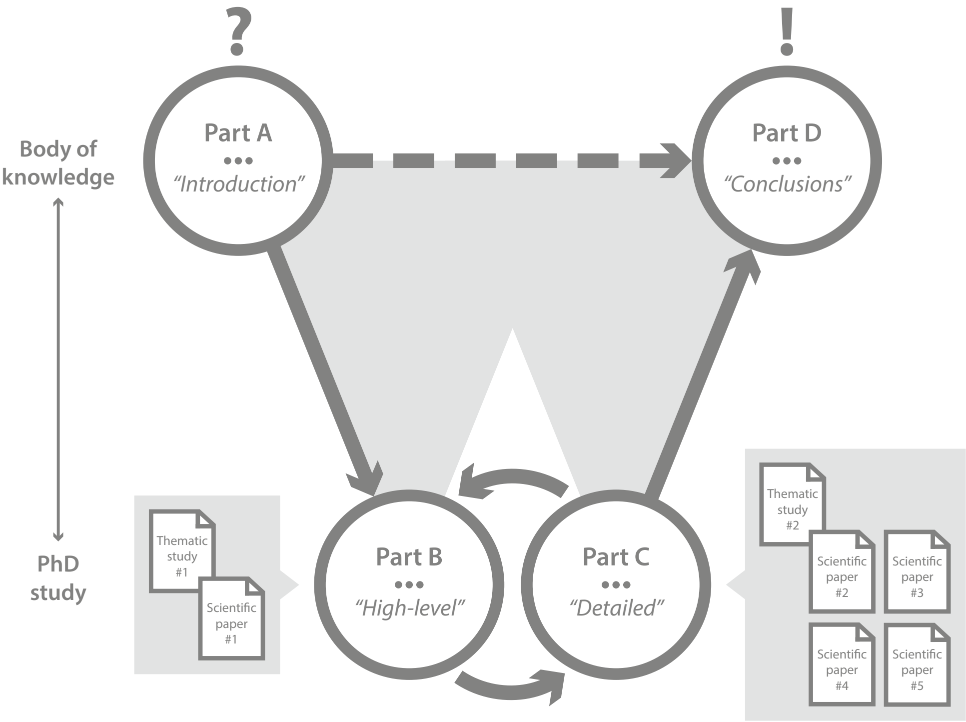

Figure A-2. Model of thesis structure.

A1.6.1 Part A – Introduction
The Introduction includes information on background, hypothesis, study goals, objectives, and limitations, methodological framework, and thesis structure.

A1.6.2 Part B – High-level studies
The high-level part contains studies of general issues of AEC/FM communication and BIM and BPS adoption, and includes one thematic study and one scientific paper.

<u>Thematic study #1</u>
Study title: "Exploring cross-border Architecture, Engineering, Construction, and Facility Management communication".
Relevance to thesis: Focuses on AEC/FM communication and collaboration efforts, and the harmonization of selected BIM and energy and indoor environmental quality standards
Primary contribution: AEC/FM communicative website.

Scientific paper #1
Study title: "Communicate and collaborate by using Building Information Modeling".
Relevance to thesis: Focuses on BIM as a platform for AEC/FM communication and collaboration, and exploration of social and technical BIM issues.
Primary contribution: Insights into overall benefits and challenges of BIM.

A1.6.3 Part C – Detailed studies
The detailed part contains studies of in-depth issues of AEC/FM communication and BIM and BPS adoption, and includes one thematic study and four scientific papers.

Thematic study #2
Study title: "Introducing a new space and thermal zone identification concept".
Relevance to thesis: Focuses on communicating space layout plans and thermal zoning definitions, and linking of the space and thermal zone identification concept with digital BIM approaches.
Primary contribution: Space and thermal zone identification concept.

Scientific paper #2
Study title: "Building Performance Simulation tools for planning of energy efficiency retrofits".
Relevance to thesis: Focuses on BPS approaches to support building performance prediction, and identification and specification of BPS information exchange structures.
Primary contribution: BPS-based building design decision-making methodology.

Scientific paper #3
Study title: "Exploring Industry Foundation Classes interoperability between Building Information Modeling and Building Performance Simulation tools".
Relevance to thesis: Focuses on IFC geometry exchange between BIM and BPS tools, and evaluation of geometry conversions and building modeling approaches.
Primary contribution: Insights into practical challenges of BIM-to-BPS IFC exchange.

Scientific paper #4
Study title: "Introducing a new framework for generic Information Delivery Manuals".
Relevance to thesis: Focuses on AEC/FM communication and information flow management, and identification and specification of decomposed AEC/FM processes and associated information exchanges.
Primary contribution: IDM Framework for generic AEC/FM processes.

Scientific paper #5
Study title: "Information exchange structures for early-stage Building Performance Simulation".

Relevance to thesis: Focuses on early-stage BPS adoption, and the identification, specification, and simplification of information exchange structures for early-stage façade performance engineering.
Primary contribution: IDM Package for early-stage façade performance engineering.

A1.6.4 Part D – Conclusions
The final part includes a summary of information and contributions contained in Part B and Part C, as well as overall conclusions and discussions of future studies.

As shown, Part B and Part C represent the main body of the thesis – the actual PhD study, including case studies and scientific papers. It is important to note that the structure of Part B and Part C does not represent the structure and process of the PhD study. Part B and Part C studies were performed iteratively, from data collection and analysis to support instrument and methodology development.

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Part B

High-level studies

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Thematic study #1

Exploring cross-border Architecture, Engineering, Construction, and Facility Management communication

STUDY INFO

Relevance to thesis: Focuses on AEC/FM communication and collaboration efforts, and the harmonization of selected BIM and energy and indoor environmental quality standards.
Primary contribution: AEC/FM communicative website.

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Exploring cross-border Architecture, Engineering, Construction, and Facility Management communication

Abstract

In this study, the benefits of harmonization efforts and support instruments to facilitate improved cross-border and cross-organizational Architecture, Engineering, Construction, and Facility Management (AEC/FM) communication and collaboration are explored.

Keywords: AEC/FM communication, BIM, information sharing, standardization

B1. Introduction

B1.1 Background to study

Many cities and regions are located along international borders, and therefore collaborating with cross-border neighbors may offer innovation-driven opportunities (OECD, 2013). The Öresund Region, centered on the metropolitan area around Copenhagen (Denmark), and the cities of Malmö, Lund, and Helsingborg (Sweden), is a well-known example of European cross-border collaboration. Over the years, several Öresund cross-border innovation and collaboration activities have been initiated, for example, the Öresund Bridge (see Figure B-1) (Skanska AB, 2009).

Figure B-1. The Öresund Bridge.

The framework of this study is directed towards the Öresund cross-border initiative Interreg IV A Öresund Programme "Integration of Sustainable Construction Processes – by the use of Information and Communication Technology". The primary purpose of this programme is to support the emergence of Architecture, Engineering, Construction, and Facility Management (AEC/FM) collaboration across the Öresund Region, and also to support a region-wide adoption of Building Information Modeling (BIM) approaches (Karlshoej, 2009).

Generally, the Danish and Swedish AEC/FM industries have many similarities. However, due to differences in design and construction traditions, organizational structures, and national regulations, Öresund cross-border AEC/FM communication and collaboration remains a challenge. Therefore, if AEC/FM organizations are to collaborate across the Öresund Region, regional network and common translators of national systems are needed.

Ideally, an integrated Öresund cross-border AEC/FM industry should be able to reach a broader range of global collaborators (OECD, 2013). This concept is shown in Figure B-2.

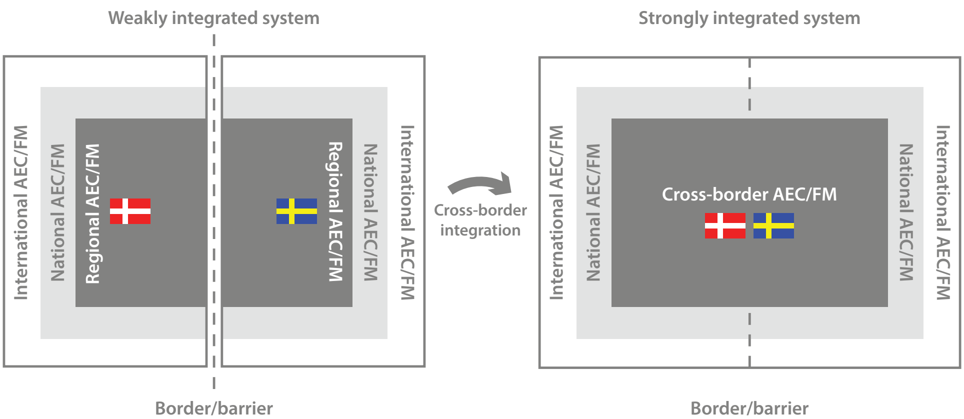


Figure B-2. Cross-border AEC/FM integration [Inspired by (Lundquist & Trippl, 2013)].

B1.2 Study goals

This study has two goals. The first is to explore specific border issues for AEC/FM project participants and organizations that interact across the Öresund Region. The second is to develop common guidelines and a support instrument that contribute to increasing mainstreaming Öresund cross-border AEC/FM collaboration.

The study goals are addressed by: (1) a survey of Danish and Swedish AEC/FM industry professionals to gain an understanding of their knowledge and expectations from Öresund cross-border communication and collaboration, including their knowledge of

BIM approaches, (2) the mapping of selected Danish and Swedish AEC/FM standards to produce an overview of existing guidelines, and (3) the development of an advisory website to support Öresund cross-border AEC/FM communication and collaboration.

B2. Methodology

B2.1 Survey of industry professionals

A series of semi-structured interviews of Danish and Swedish AEC/FM industry professionals has been conducted. Interviews were carried out to gain industry input, and to understand expectations and concerns about Öresund cross-border AEC/FM collaboration and BIM adoption.

The selection of participants was based on *purposive sampling* (Denscombe, 2007), in other words, the participants were *handpicked* based on both their organization's experiences from Öresund cross-border AEC/FM communication and collaboration, and their knowledge and use of BIM. The survey sample consisted of three consulting architects and six consulting engineers, representing an architecture organization, an engineering organization, a construction contractor, a BIM consultancy, and a software vendor. Table B-1 shows the structure of the survey sample.

Table B-1. Overview of survey sample.

Juul & Frost Architects, Copenhagen, Denmark * One consulting architect (Department of BIM)
Grontmij, Glostrup, Denmark * One consulting engineer (Department of Building Energy)
Tyréns, Malmö, Sweden * One consulting engineer (Department of BIM)
NCC, Copenhagen, Denmark * One consulting architect (Department of VDC/BIM)
MT Højgaard, Søborg, Denmark * One consulting engineer (Department of Construction)
PEAB, Solna, Sweden * One consulting engineer (Department of Real Estate Development)
E Pihl & Søn, Lynbgy, Denmark * One consulting engineer (Department of BIM)
ProjTools, Malmö, Sweden * One consulting architect (Department of BIM)
Vico Software, Solna, Sweden * One consulting engineer (Department of Virtual Construction)

The interviews were structured around a list of questions, with sufficient flexibility to allow questions to be modified depending on the situation. All interviews were conducted by an interviewer fluent in Danish and Swedish, and took place in the offices of the selected participants.

B2.2 Mapping of standards

Mapping of Danish and Swedish AEC/FM standards has been conducted. Covering two main areas of AEC/FM, the mapping was carried out to identify similarities and differences that exist for particular AEC/FM standards:

- Buildings and BIM
- Energy and Indoor Environmental Quality

The mapping was structured around a qualitative research methodology, the Grounded Theory approach, using *constant comparisons* to analyze the data (Denscombe, 2007).

Two kinds of correlations have been mapped. *Mapping via a direct link:* indicates issues directly present in both Danish and Swedish AEC/FM standards. *Mapping via a missing link:* indicates issues only present in either Danish or Swedish AEC/FM standards. In the latter case, the mapping points out possible deficiencies and standardization gaps.

B2.3 Development of website

A website, www.bygbygg.org, to display survey and mapping results and to function as an online translator of Danish and Swedish AEC/FM approaches has been developed. A key feature of this website is that it functions as an online lookup tool for Danish and Swedish AEC/FM standards. This tool could benefit AEC/FM project participants and organizations collaborating across the Öresund Region, as it enables direct comparisons of Danish and Swedish AEC/FM standards in current use.

Figure B-3 shows the website design. Danish guidelines are shown on the left; Swedish guidelines on the right. The website provides direct links to external websites, from which the described standards can be downloaded. The website name www.bygbygg.org is a combination of “byg” and “bygg”, Danish and Swedish for “construct”, respectively. The content of the website is written in Danish and Swedish, as required by the Interreg IV A Öresund Programme (Karlshoej, 2009).

[See Figure B-3 in next page] →

bygbygg

DANSK | SVENSKA | ENGLISH | SITEMAP

START | NYHEDER | BYGBYGG | MAPNING | INTERVIEWS | DOWNLOADS | KONTAKT

BIM-arbejdsmetode

Ved BIM-samarbejder forekommer det vigtigt at definere rammerne for BIM-processerne og samarbejdet heromkring.

Anvisninger Danmark

Herunder følger en mapning af danske anvisninger målrettet emnet *BIM-arbejdsmetode*.

MAPNING

1. bips fokuserer på implementering af BIM og brugen af digitale værktøjer.
2. bips tilbyder online-tilgængelige anvisninger og værktøjer til 3D og BIM-arbejdsmetode.

bips (BIM-arbejdsmetode)

Herunder følger en gennemgang af danske anvisninger målrettet *BIM-arbejdsmetode*. Der tages udgangspunkt i bips og dennes hjemmeside (BIM-arbejdsmetode).

Foreningen bips er en medlemsdrevet non-profit forening. Det er byggeriets virksomheder, der via deres medlemskab driver bips. Foreningen bips udvikler fælles digitale strukturer og standarder for sprog, begreber, udvekslingsformater og arbejdsmetoder, herunder BIM-arbejdsmetode.

Implementeringen sker gennem anvisninger, konkrete værktøjer og de facto standarder, der tilbydes til medlemmer på foreningens webside.

bips

Kilde: bips 2011
Link: www.bips.dk
Direkte link: www.bips.dk
Opdateret: 30.11.11

Anvisninger Sverige

Herunder følger en mapning af svenske anvisninger målrettet emnet *BIM-arbejdsmetode*.

MAPNING

1. openBIM fokuserer på implementering af BIM og brugen af digitale værktøjer.
2. openBIM indeholder ingen konkrete anvisninger til BIM-arbejdsmetode.

openBIM (BIM-arbejdsmetode)

Herunder følger en gennemgang af svenske anvisninger målrettet BIM-arbejdsmetode. Der tages udgangspunkt i openBIM og dennes hjemmeside (BIM-arbetsmetod).

Det svenske openBIM er et treårigt udviklingsprogram, der har til formål at teste nye digitale muligheder og udvikle fælles løsninger for IKT. Programmet , der særligt fokuserer på implementering af BIM, drives og financeres af medlemmer af foreningen. Strategien er at tage fat i de teknologier, standarder og software, som allerede eksisterer og så komme i gang med at afprøve dem.

Implementeringen sker ved at indhente praktisk erfaring og løse udfordringerne i forbindelse med de praktiske afprøvninger. På nuværende tidspunkt tilbyder openBIM ingen anvisninger eller værktøjer.

openBIM

Kilde: openBIM 2009-2011
Link: www.openbim.se
Direkte link: www.openbim.se
Opdateret: 30.11.11

Figure B-3. AEC/FM communicative website design.

B3. Survey

B3.1 Interview analysis

Interviews were analyzed using a thematic approach, dividing the data into identified key issues. Key issues include: (1) cultures and traditions, (2) roles and responsibilities, and (3) BIM adoption.

B3.1.1 Cultures and traditions

All surveyed participants, irrespective of professional background and nationality, highlighted the potential of expanding business activities and knowledge networks. However, due to differences in culture, tradition, language, and work environment, Öresund cross-border AEC/FM communication and collaboration appears problematic, often creating misunderstandings. Figure B-4 shows selected Danish-Swedish differences.

	Denmark	*Sweden*
Language	Vindue (Window)	Fönster (Window)
Cultural differences	Trading nation	Industrial nation
Construction traditions	Brick	Wood
Building planning	Building designer	Construction contractor
Building construction	Sub-contracting	General contracting
Building management	Lawyer	Client

Figure B-4. Danish-Swedish differences.

Because of these differences, Peab, Sweden's third largest construction contractor, deliberately avoids expanding AEC/FM project activities to Denmark, despite being located in Förslöv, approximately 100 km from Copenhagen (Peab, 2014).

Clearly therefore, before Öresund cross-border AEC/FM opportunities can become more common, a better understanding of nation-specific cultures and traditions, as well as nation-specific decision-making and collaboration methodologies, is required.

B3.1.2 Roles and responsibilities

Interviewees highlighted the issue of understanding organizational roles and responsibilities across Öresund cross-border AEC/FM project collaborations. For example, the role of a building designer or architect is not the same in Denmark as in Sweden. In Denmark, the building designer is responsible for planning and managing the early stages of the AEC/FM project. In Sweden, these processes are controlled by the construction contractor.

B3.1.3 BIM adoption

All survey participants highlighted the potential of adopting a BIM approach as an AEC/FM communication and collaboration platform. In particular, the participants mentioned improved in-house communication. However, based on survey responses, BIM collaboration across organizations, and across national borders, appears problematic. For this reason, survey participants pointed out the need for common BIM standards and coordination/harmonization of Danish and Swedish BIM approaches.

Note: The complete survey is available at www.bygbygg.org/interviews.

B4. Mapping

B4.1 Buildings and BIM

The "Buildings and BIM" mapping process included comparison of standards and guidelines issued by Dansk Standard, Energistyrelsen, Bygherreforeningen, Dansk Byggeri, Byggecentrum, bips, Svensk Standard, Boverket, Föreningen för Förvaltningsinformation, Sveriges Byggindustrier, Svensk Byggtjänst, Bygghandlingar 90, and others. Particular focus was given to bips and Bygghandlingar 90 standards, which respectively represent Denmark's and Sweden's most important guidelines for BIM implementation (bips, 2012) (SIS, 2008). Figure B-5 shows bips and Bygghandlingar 90 standards.

Kilde: bips, C102 CAD-manual 2008
Link: www.bips.dk
Direkte link: www.bips.dk/cad-manual-2008
Opdateret: 24.09.13

Kilde: SIS, Bygghandlingar 90 - Del 8
Link: www.bygghandlinager90.se
Direkte link: www.bygghandlingar90.se/del-8
Opdateret: 24.09.13

Figure B-5. bips and Bygghandlingar 90 standards.

Generally, bips and Bygghandlingar 90 include guidance on many of the same BIM issues, for example guidance on object-based BIM-models, classification systems, and open source formats. However, while bips covers all audience levels, and includes comprehensive guidelines, functional templates, and concrete examples, Bygghandlingar 90 covers administrative aspects only.

An example is the bips and Bygghandlingar 90 guidance on Model Progression Specification (MPS), also referred to as Level of Detail/Level of Development (LOD) specification or BIM-model "information richness" (Vico, 2014). Here, bips makes available detailed specifications – detailed LOD specifications specifically designed for the Danish AEC/FM industry – whereas Bygghandlingar 90 makes available simple and broadly defined recommendations. Different definitions put the emphasis on either *Level of Detail* or *Level of Development* (depending on author perspective). The details of defining the difference of emphasis are, however, out of the scope of this study.

Note: The complete "Buildings and BIM" mapping is available at www.bygbygg.org/byg.

B-4.2 Energy and indoor environmental quality

The "Energy and indoor environmental quality" mapping process included comparison of guidelines within the Bygningsreglement, BR 2010 and Regelsamling för byggande, BBR 2012 (Danish and Swedish Building Regulations, respectively) (Energistyrelsen, 2010) (Boverket, 2011). Figure B-6 shows BR 2010 and BBR 2012 standards.

Kilde: BR 2010, Energistyrelsen
Link: www.bygningsreglementet.dk
Direkte link: www.bygningsreglementet.dk/br10
Opdateret: 29.07.14

Kilde: BBR 2012, Boverket
Link: www.boverket.se
Direkte link: www.boverket.se/BBR-2012
Opdateret: 29.07.14

Figure B-6. BR 2010 and BBR 2012 standards.

Generally, BR 2010 and BBR 2012 include guidance on the same energy and indoor environmental issues, for example, energy consumption requirements, indoor environmental quality requirements, and documentation procedure requirements. However, the mapping showed significant differences in specific calculation and documentation procedures.

An example is the BR 2010 and BBR 2012 guidance on energy consumption requirements. Here, BR 2010 defines consumption requirements based on "building type" and "classes", whereas BBR 2012 defines consumption requirements based on "building type", "climate zone", and "with/without electric heating" (see Figure B-7). The likely reason is that Denmark is a smaller country than Sweden (43,094 km2 and 449,964 km2, respectively) (Nations, 2014a) (Nations, 2014b). Therefore, Denmark constitutes a single climate zone, whereas Sweden constitutes three climate zones (north, middle, and south). Consequently, due to differences in Danish and Swedish climatic conditions, BR 2010 and BBR 2012 energy consumption requirements are difficult to compare.

Other BR 2010 and BBR 2012 energy consumption requirements dissimilarities include differences in defining which specific parameters are to be included in consumption calculations and simulations, and how to specify the heated floor area/volume (gross versus net).

Denmark

BR 2010 - Part 7.2
[Type: Residental]
Class 2010 = maximum 52.5 + 1,650/A
Class 2015 = maximum 30 + 1,000/A
Class 2020 = maximum 20

BR 2010 - Part 7.2
[Type: Non-residental]
Class 2010 = maximum 71.3 + 1,650/A
Class 2015 = maximum 41 + 1,000/A
Class 2020 = maximum 25

(1) "A" represents the heated floor area
(2) Consumption in kWh/m²/year

Sweden

BBR 2012 - Part 9:2-9:3
[Type: Residental]
North 2012 = maximum 130
Middle 2012 = maximum 110
South 2012 = maximum 90

BR 2012 - Part 9:2-9:3
[Type: Non-residental]
North 2012 = maximum 120
Middle 2012 = maximum 100
South 2012 = maximum 80

(1) For buildings without electric heating
(2) Consumption in kWh/m²/year

Figure B-7. BR 2010 and BBR 2012 energy consumption requirements.

Another example is the BR 2010 and BBR 2012 guidance on documentation procedure requirements. Here, BR 2010 invites AEC/FM project participants to follow energy consumption documentation procedures described in SBi-Anvisning 213: Bygningers Energibehov (in English, SBi-Direction: Energy Requirements in Buildings) (SBi, 2013). This publication includes the Building Performance Simulation (BPS) tool Be10 (SBi, 2012). In Denmark, a Be10 simulation (energy consumption calculation and simulation only) to demonstrate compliance with prescriptive BR 2010 energy consumption requirements is required from any AEC/FM organization *before* construction permits are issued.

In Sweden, no such requirements exist as the building's energy consumption is measured and evaluated for compliance *after* constructing the building. Energy consumption should be measured over a 12-month reference period, and should be conducted within the first 24 months of the building's life cycle. If the measurements do not meet prescriptive BBR 2012 energy consumption requirements, the client – in collaboration with responsible AEC/FM project participants – should improve the building's performance, if necessary, by reconstructing/correcting the building (Boverket, 2011).

BR 2010 and BBR 2012 energy and indoor environmental issues, in principle, build on selected international CEN standards. However, BR 2010 and BBR 2012 customize CEN methodologies and procedures to specific national cultures and traditions.

Note: The complete "Energy and indoor environmental quality" mapping is available at www.bygbygg.org/energi.

B5. Website

B5.1 Online lookup tool

The www.bygbygg.org website was designed to function as a shared knowledge base for Öresund AEC/FM project participants and organizations, helping them to better understand, process, and communicate Öresund cross-border information.

Besides functioning as an online lookup tool for Danish and Swedish AEC/FM standards, the website also makes available a number of printed publications. These include "Survey of industry professionals", "Buildings and BIM mapping", and "Energy and indoor environmental quality mapping" (see Figure B-8).

Publication: Survey of industry professionals
Link: www.bygbygg.org/downloads

Publication: Buildings and BIM mapping
Link: www.bygbygg.org/downloads

Publication: Energy and IEQ mapping
Link: www.bygbygg.org/downloads

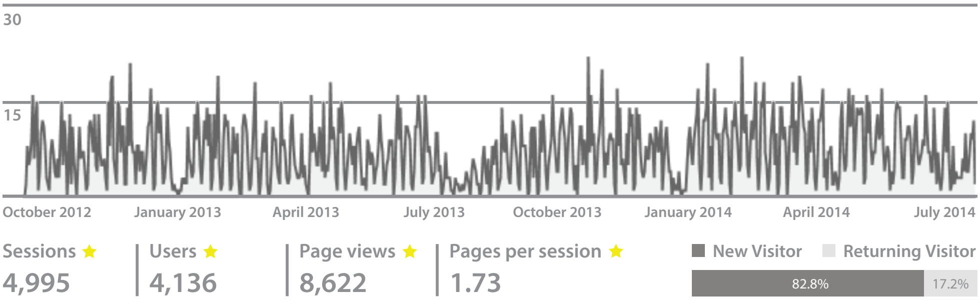
Figure B-8. Interreg IV A publications.

Note: The Interreg IV A publications are available as pdf documents at www.bygbygg.org/downloads.

B5.2 Website statistics

Since the www.bygbygg.org website was launched in October 2011, it has had more than 4,000 users and 8,000 page views with, not surprisingly, the majority of users from Denmark and Sweden. Figure B-9 shows selected statistics.

[See Figure B-9 in next page] →



	Nation/Country	Sessions	% Sessions
1.	Denmark	4,147	83.02 %
2.	Sweden	434	8.69 %
3.	Norway	63	1.26 %
4.	Brazil	52	1.04 %
5.	Germany	41	0.82 %

Figure B-9. Overview of website statistics (Google Analytics).

B6. Conclusions

B6.1 Conclusions

In this study, the benefits of Öresund cross-border AEC/FM communication and collaboration were explored. Generally, the Danish and Swedish AEC/FM industries have many similarities. However, differences in design and construction traditions, organizational structures, and national regulations create complexity and border barriers. Harmonization efforts and support instruments that take advantage of Danish-Swedish AEC/FM complementarities are therefore needed.

The www.bygbygg.org website presented here attempts to alleviate Öresund cross-border AEC/FM barriers by making available an overview of Danish and Swedish AEC/FM approaches and standards in current use. The website has three merits:

1. It reduces Öresund cross-border misunderstandings and communication malfunctions, as AEC/FM project participants and organizations will gain a better understanding of selected Danish-Swedish AEC/FM relationships.
2. It saves labor and time for AEC/FM project participants and organizations, by providing an online lookup tool for selected Danish and Swedish AEC/FM standards.
3. It provides a basis for harmonization of Danish and Swedish AEC/FM standards, as it identifies similarities and differences that exist.

Based on the Öresund example, harmonization efforts and support instruments, such as the www.bygbygg.org website, are generally evaluated as useful methodologies to support both international cross-border, and national cross-organizational, AEC/FM communication and collaboration.

Acknowledgements

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Scientific paper #1

Communicate and collaborate by using Building Information Modeling

STUDY INFO

Relevance to thesis: Focuses on BIM as a platform for AEC/FM communication and collaboration, and exploration of social and technical BIM issues.
Primary contribution: Insights into overall benefits and challenges of BIM.

Submission
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Communicate and collaborate by using Building Information Modeling

Abstract

Building Information Modeling (BIM) represents a new approach within the Architecture, Engineering, Construction, and Facility Management (AEC/FM) industry, one that encourages collaboration and engagement of all participants on a project. In this study, we discuss the potential of adopting BIM as a communication and collaboration platform. The discussion is based on: (1) a review of the latest BIM literature, (2) a qualitative survey of professionals within the industry, and (3) mapping of available BIM standards. We present the benefits, risks, and overarching challenges of adopting BIM, and makes recommendations for its use, particularly, as a tool for collaboration. Specifically, we focus on the issue of implementing standardized BIM execution guidelines across national borders (in this study Denmark and Sweden), and explore the challenge of developing a common standard applicable and acceptable at both national and company level.

Keywords: BIM, communication, collaboration, socio-technical system

B7. Introduction

B7.1 Background to study

Building Information Modeling (BIM) affects all project participants supporting the Architecture, Engineering, Construction, and Facility Management (AEC/FM) project life cycle – BIM is by its nature multidisciplinary (NIBS, 2007) (Kennerley, 2012). Furthermore, AEC/FM processes, and buildings in general, are considered to be unique on every AEC/FM project (Hartmann et al., 2009). Consequently, the BIM process requires a high level of communication and understood workflows to support its fullest capabilities.

The framework of this study is directed toward the Interreg IV A Öresund Programme "Integration of Sustainable Construction Processes – by the use of Information and Communication Technology" (Karlshoej, 2009). The primary purpose of the Interreg IV A Öresund Programme is to enhance AEC/FM collaborations across the Öresund Region (transnational region centered on the cities of Copenhagen, Malmö, Lund and Helsingborg), and also to enhance a region-wide implementation of BIM. In principle, the

Danish and Swedish AEC/FM industries have many similarities. However, if AEC/FM organizations and project participants are to collaborate across the Öresund Region, regional network and common translators of national systems are needed.

B7.2 Study goals

This study has two goals. The first is to explore the benefits and possible risks connected to BIM adoption in the Öresund Region. The second is to develop recommendations to support Öresund cross-border AEC/FM collaborations through the use of BIM.

The study goals are addressed by: (1) a review of relevant BIM literature to understand the background, (2) a survey of Danish and Swedish industry professionals to gain an understanding of their knowledge and expectations from the BIM approach, and (3) mapping of Danish and Swedish BIM standards to get an overview of existing guidelines.

B8. Methodology

B8.1 Review of current approaches

A review of BIM has been conducted. The review included research conducted by academic institutes; articles on the practice of BIM, and guidelines generated by government institutions. The review was chosen to develop an understanding of the current BIM status in the AEC/FM industry. For the purpose of this study, the review focuses on BIM as a communication and collaboration tool, and also discusses the issue of BIM as a *socio-technical system* (Harty et al., 2010).

B8.2 Survey of industry professionals

A series of semi-structured interviews of AEC/FM industry professionals have been conducted. Interviews were carried out to gain industry input, primarily, on BIM being a platform for AEC/FM collaboration. The interviews were structured around a clear list of questions, with, however, sufficient flexibility to allow questions to be modified depending on the situation. All interviews were carried out in the offices of the selected participants, placing the interviewee in a comfortable environment.

The selection of participants was based on *purposive sampling* (Denscombe, 2007). More specifically, the participants were *hand-picked* with a purpose in mind. In this study, the participant selection was based around the participant's organization's knowledge and use of BIM. The survey sample consisted of one consulting architect, two consulting engineers, four construction contractors, one BIM consultant, and one software vendor. The diverse backgrounds of the participants provided a rich context for their input. For the purpose of the Öresund cross-border study framework, the participants represented AEC/FM organizations from both Denmark and Sweden. The interviews were conducted by an interviewer fluent in both Danish and Swedish.

B8.3 Mapping of BIM standards

Mapping of Danish and Swedish BIM standards has been conducted. The mapping aims to highlight similarities and differences that exist, and to identify potential deficiencies. By mapping existing BIM standards, improved approaches for developing common BIM execution guidelines can be realized. The mapping involved data collection from Danish bips (bips, 2012) and Swedish Bygghandlingar 90 (SIS, 2008). The mapping was structured around a qualitative research methodology, the Grounded Theory approach, using *constant comparisons* for analyzing the data (Denscombe, 2007).

B9. Review

B9.1 BIM communication

BIM "describes the process of designing a building collaboratively using one coherent system of computer models" (Kennerley, 2013). More precisely, BIM is a marriage of both technology and processes. BIM can be viewed as a digital process that includes all aspects, disciplines, and systems of a building (from design development to operation and maintenance), in this way allowing AEC/FM project participants to communicate and collaborate more accurately. Furthermore, BIM is a multidisciplinary process, which brings the project participants together. Any modification one project participant makes affects the entire BIM process, as well as the entire BIM model, creating constant communication (Caramona & Irwin, 2007).

B9.2 BIM is a socio-technical system

The idea of BIM being an integrated process is an issue of increasing interest within the AEC/FM industry. As mentioned above, BIM is as much about people and processes, as it is about technology. Therefore, BIM is a *socio-technical system* (Harty et al., 2010). In Figure B-10, BIM is shown as a multilayered system with a technical core (technical parts) and layers of social practices (social parts).

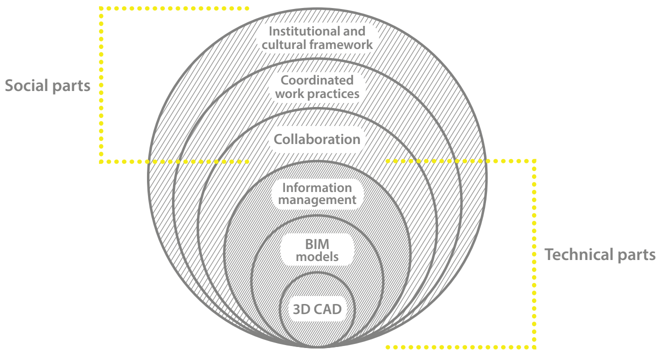

Figure B-10. BIM as a socio-technical system [Inspired by (Kennerley, 2012)].

B9.3 BIM adoption

Despite some progress, the rate of adoption of BIM has been relatively slow (Ning et al., 2008). Key reasons include: (1) lack of initiative and education, (2) inability to change existing work practices, and (3) lack of clarity on the roles and benefits of using a BIM approach. In other words, BIM adoption takes time, creating an unavoidable learning curve (Oakley, 2012). This process is shown in Figure B-11, presenting the expected, actual, optimal, and inexpedient path.

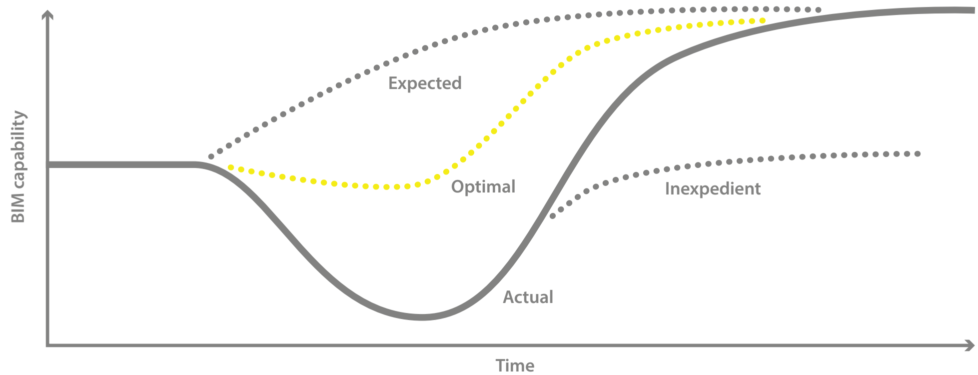

Figure B-11. BIM learning curve [Inspired by (Oakley, 2012)].

The learning curve is the picture of what many AEC/FM organizations experience when implementing BIM. As shown, the learning curve can be described through four stages:

- Expected Path: Many AEC/FM organizations rush into BIM adoption, expecting great benefits immediately.
- Actual Path: BIM adoption comes with a learning curve, imposing additional stress on AEC/FM project participants.
- Optimal Path: Sustainable BIM adoption requires extensive preparation, training, and guidance.
- Inexpedient Path: Unsuccessful BIM adoption may occur, downgrading the expected BIM level.

B10. Survey

B10.1 Interview analysis

Interviews were analyzed using a thematic approach, dividing the data into identified key issues. Based on survey responses, utilizing BIM as a communication and collaboration tool, and BIM adoption in general, involves functions of both social and technical matter. Therefore, the interview analysis can be summarized into social and technical issues. For the purpose of the Öresund cross-border study framework, both issues were discussed in a cross-border and cross-organizational perspective.

B10.1.1 Social issues

The social issues identified are summarized in the following:

- All survey participants, irrespective of professional background, highlighted the potential of adopting BIM approach as a communication and collaboration tool. In particular, the participants highlighted improved in-house communication.
- Most of the participants used BIM as a tool for producing visualizations (3D, 4D, and 5D), thereby communicating the entire building.
- However, BIM collaboration across AEC/FM organizations appears problematic, creating misunderstandings and communication malfunctions. Therefore, BIM collaboration requires focus on adapting common methodologies and work practices.
- Another issue that was highlighted was that of collaboration between AEC/FM organizations with different BIM profiles. All participants described this as a common issue, often resulting in misunderstandings. This process is shown in Figure B-12. Therefore, sustainable BIM collaboration requires that everyone involved possesses the BIM capabilities needed.
- Although participants in the survey were generally interested in and enthusiastic about implementing BIM, they stressed that adopting BIM takes time and resources, creating an unavoidable learning curve. The process of BIM adoption places particular demands on project participant training.
- Due to differences in language, culture, and work environment, Öresund cross-border BIM and AEC/FM collaboration often fails. For this reason, all survey participants highlighted the need for common BIM standards and coordination of Danish and Swedish work practices in general.
- How AEC/FM organizations implement BIM depends on the type of organization and the type of individual projects, as well as the individual project participant. Consequently, BIM execution guidelines should be flexible, with the possibility of being adapted to the given project, especially, when implementing BIM across national borders.

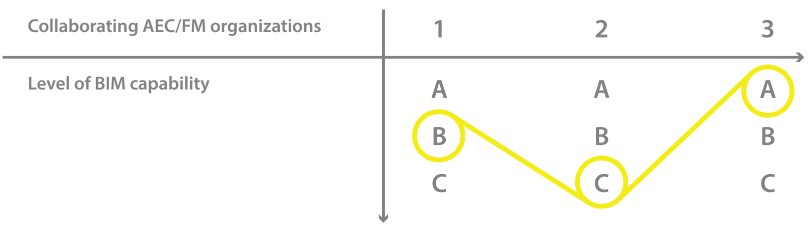

Figure B-12. Various levels of BIM capability.

B10.1.2 Technical issues
The technical issues identified are summarized in the following:

- Based on survey responses, BIM adoption and digital collaboration leads to a number of technical challenges, for example, getting BIM-compatible tools to communicate properly. The development of shared IT regulations and standardized exchange formats here appears valuable, allowing information to flow freely, particularly, when collaborating across national borders.
- In addition, all participants highlighted the issue of using neutral file formats such as the Industry Foundation Classes (IFC) data model standard (ISO, 2010b).
- The BIM model can be used as an information/database throughout the life of the building, communicating digital information to all project participants involved. From this perspective, several participants highlighted the potential of an Öresund BIM model server as a shared collaboration platform.

B11. Mapping

B11.1 Danish and Swedish BIM standards

Based on the Öresund cross-border study framework, we compared BIM standards issued by Danish bips (multiple documents) and Swedish Bygghandlingar 90 (a single document). The bips association is a member-driven association, representing organizations within the Danish AEC/FM industry. The association focuses on developing digital standards and guidelines for implementing BIM in connection with AEC/FM projects (bips, 2012). Bygghandlingar 90 represents Sweden's most important guidelines for delivering digital information within AEC/FM projects. Bygghandlingar 90 provides recommendations for managing building information, but requires some development in a number of areas, including that of BIM (SIS, 2008).

B11.2 Patterns of mapping

Two kinds of correlations have been mapped. *Mapping via a direct link:* indicates BIM issues directly present in both bips and Bygghandlingar 90. *Mapping via a missing link:* indicates BIM issues only present in either bips or Bygghandlingar 90. This relationship is shown in Figure B-13.

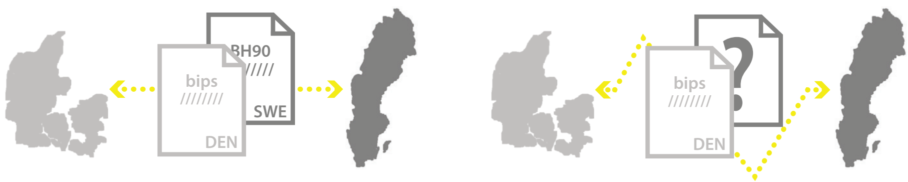

Figure B-13. Mapping via a direct or a missing link.

By mapping these correlations, similarities and differences were demonstrated, and deficiencies were identified. The mapping included comparison of various BIM issues, such as “3D Working Methodologies”, “ICT Agreements”, “Object Structures”, “Exchange Formats”, “Model Progression Specification (MPS)”, “Classification Systems”, and similar elements.

B11.2.1 Similarities

The similarities identified in the mapping are summarized in the following:

- In the mapping process, we found that bips and Bygghandlingar 90 in general include guidance on more of the same issues. For example, both bips and Bygghandlingar 90 cover the issues of implementing object-based BIM models. From this perspective, shared building object model libraries are a potential part of an Öresund cross-border BIM environment.
- In addition, both bips and Bygghandlingar 90 highlight the issue of linking BIM models together with national classification systems (Danish CCS and Swedish BSAB). For the purpose of improving Öresund cross-border BIM and AEC/FM communication and collaboration, a common classification system appears beneficial.
- Another issue that was identified was the use of neutral file formats. Both bips and Bygghandlingar 90 highlight the issue of using Industry Foundation Classes (IFC) data model standard, providing the basis for achieving full interoperability between BIM-compatible tools.

B11.2.2 Differences

The differences identified in mapping are summarized in the following:

- Whilst bips includes a comprehensive package of multiple BIM documents, Bygghandlingar 90’s BIM guidance is represented in a single document.
- In addition, bips covers all audience levels, providing all-inclusive guidelines, applicable templates, and real practice examples, whereas Bygghandlingar 90 covers issues for administrative purpose only.

B11.1.3 Deficiencies

The deficiencies identified in mapping are summarized in the following:

- In mapping, we demonstrated that Bygghandlingar 90 lacks strategic insight and concrete examples. Here bips may be able to bridge the gaps.
- During mapping, bips at times appeared incalculable. The likely reason being that bips involves multiple documents (possibly too many), suggesting the importance of simple, and clearly articulated BIM standards.

- Both bips and Bygghandlingar 90 lack digitalization of guidelines. Most guidelines are communicated as printed publications. The absence of digitalization encourages the development of online guidance, in this way supporting digital approach and automated workflows/information flows.

B12. Summary

B12.1 Literature review

Technology and processes were the most prominent points in the literature review. Here, we demonstrated that BIM is a socio-technical system, combining man-made technology with associated behaviors, social norms, and work processes. In other words, BIM is far more than a suite of AEC/FM software tools. This becomes clear as the technical issues begin to shape social practices by expanding possibilities. However, BIM adoption comes with a learning curve. Therefore, sustainable BIM adoption requires extensive preparation and training of project participants. If done well, expanding BIM across the AEC/FM organization will become an organic process. Eventually, this leads to improved communication, allowing different disciplines to collaborate effectively.

B12.2 Interview survey

Though many issues discussed echo the key points from the literature review, the survey gave greater insight into the practicalities of BIM adoption. Here, survey participants highlighted the potential of implementing BIM as a communication and collaboration platform. In particular, all participants highlighted the potential of improving in-house communication. BIM collaboration across AEC/FM organizations, however, appeared problematic; in particular, in collaborations between organizations representing different approaches and varying levels of BIM capabilities. In other words, when organizations do not speak the same language, misunderstandings and difficulty in communications occur. Therefore, BIM collaboration requires focus on adapting skills, methodologies, and work practices. Another issue that was highlighted was getting BIM-compatible tools to communicate properly. Here, model information/data import and export presented difficulties and frustration. This brings focus to the development of shared IT regulations and standardized exchange formats. Following this, all participants highlighted the issue of using neutral file formats and BIM model servers as collaboration platforms.

Note: The survey is presented on the website www.bygbygg.org with the purpose of functioning as an online translator of Danish and Swedish BIM approaches. This may appear beneficial, when collaborating across the Öresund Region.

B12.3 Mapping of BIM standards

In the mapping process, we demonstrated that bips and Bygghandlingar 90 in general include guidance on many of the same issues (e.g. guidance on object-based BIM models, classification systems, and neutral file formats). However, while bips covers all audience levels, containing comprehensive guidelines, templates, and concrete examples, Bygghandlingar 90 covers administrative aspects only. This encourages Swedish AEC/FM organizations to build up customized in-house BIM standards, resulting in conflicting approaches within the Swedish AEC/FM industry.

In contrast, Danish AEC/FM organizations tend to simplify bips standards. The likely reason behind this may be that bips involves multiple documents. Therefore, there is a need for simple and clearly articulated BIM standards. It is worth noting that bips, and Danish BIM adoption in general, is supported by the Danish government, whereas Swedish BIM adoption is developed within private AEC/FM organizations.

Note: The mapping is presented on the website www.bygbygg.org with the purpose of functioning as an online translator of Danish and Swedish BIM standards. This may appear beneficial, when collaborating across the Öresund Region.

B13. Conclusions

B13.1 Conclusions

BIM has emerged with substantial improvements in recent years, permitting development of digital AEC/FM communication and collaboration. However, to achieve potential benefits, one has to get through the many difficulties of BIM adoption. In this study, we presented benefits and challenges of adopting BIM as a communication and collaboration platform. In addition, Öresund cross-border perspectives were presented, discussing the issue of implementing BIM across national borders.

B13.1.1 Key benefits

The key benefits of BIM adoption are summarized in the following:

- Sustainable BIM adoption will improve AEC/FM project communication, allowing stakeholders to collaborate more efficiently and more accurately.
- BIM is by its nature multidisciplinary. Therefore, BIM brings project participants together, creating constant communication.
- BIM model servers can be used as online information/databases throughout the life of the building, communicating information to all project participants involved.

B13.1.2 Key challenges

The key challenges of BIM adoption are summarized in the following:

- BIM is a socio-technical system. Therefore, sustainable BIM adoption requires an integrated approach, combining technical structures and social practices.

- Adoption of BIM comes with a learning curve. Consequently, sustainable BIM adoption requires extensive preparation and training of project participants.
- BIM collaboration between AEC/FM organizations (and across national borders) appears problematic. Therefore, there is a need for common standards and documented procedures.
- Interoperability between BIM-compatible tools appears problematic. Consequently, shared IT regulations and standardized exchange formats are needed.
- BIM adoption leads to organizational change. For example, changes in work practices and interpersonal dynamics. For changes to be adopted, managers and leaders must engage.

B14. Recommendations

B14.1 Recommendations

Although solutions in the market are continuing to evolve, BIM is still in its formative stage. To make full use of BIM, a more integrated and collaborative approach must be adopted. The recommendation is to develop common BIM standards and execution guidelines that: (1) cover all audience levels and communicate with all disciplines, (2) provide guidance on both social behaviors and technical issues, (3) consist of concrete examples and adaptable templates, (4) are simple and clearly articulated, and (5) available online. Such standards represent a tool for collaborative improvement.

However, the potential benefits do not lie in simply setting common BIM standards. Rather, the benefits lie in the implementation and continuous development of the standards by AEC/FM project participants. To develop common Öresund BIM standards, it is recommended that European or International standards be used as a foundation. Furthermore, BIM standards should be flexible enough to allow adaption at both company and national level.

Acknowledgments

The authors would like to thank all the people and organizations involved in this study, particularly, the survey participants. The work presented in this study was performed in the scope of the research project “Integration of Sustainable Construction Processes – by the use of Information and Communication Technology”, funded by the Interreg IV Öresund Programme.

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Part C
Detailed studies

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Thematic study #2

Introducing a new space and thermal zone identification concept

STUDY INFO

Relevance to thesis: Focuses on communicating space layout plans and thermal zoning definitions, and linking of the space and thermal zone identification concept with digital BIM approaches.
Primary contribution: Space and thermal zone identification concept.

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Introducing a new space and thermal zone identification concept

Abstract

In this study, a space and thermal zone identification concept is presented. The space and thermal zone identification concept is particularly effective at communicating space layout plans and thermal zoning strategies between Architecture, Engineering, Construction, and Facility Management (AEC/FM) project participants. Further, the identification concept supports BIM approaches because it uses machine-readable identification coding rules.

Keywords: space identification, thermal zone identification, coding rules

C1. Introduction

C1.1 Background to study

Space layout planning is an important part of early-stage building design. Traditionally, building designers are entrusted with the responsibility of developing space layout plans (Dutta & Sarthak, 2011). In the early stage, space layout plans are developed based on user profiles, functional needs, client requirements, and regulations (Kim, 2013). However, to ensure sustainable, holistic space layout planning, building performance issues, such as building energy and indoor environmental quality, should be included. Therefore, early-stage space layout planning demands collaboration between the project participants involved, including building designers and energy/indoor environmental quality experts.

Space classification systems, which are organizational reference structures for describing space properties (U of L, 2014), can support this collaboration. By providing a common language for the identification of space type, space location, space number, and other elements, they facilitate communication between Architecture, Engineering, Construction, and Facility Management (AEC/FM) project participants. In addition, most space classification systems support a digital approach and Building Information Modeling (BIM) approaches, as they use standardized, machine-readable classification structures. As a result, space classification systems make it possible for AEC/FM project participants to exchange BIM-based space information generated by the classification structure (Jociene et al., 2013).

Space classification systems in current use include the American OmniClass (OCCS, 2012), the UK Uniclass (CPIc, 2014), the Swedish BSAB 96 (AB Svensk Byggtjänst, 1998), and the newly published Danish cuneco classification system (CCS) (cuneco, 2013).

The present study focuses primarily on the *identification* part of space classification, particularly, identification of space location and space number.

C1.2 Study goals

This study has two goals. The first is to present selected CCS space identification concepts. The second is to combine these concepts with specific building performance issues.

The study goals are addressed by: (1) a specification of relevant coding symbols to support the development of identification concepts, and (2) a specification of space and thermal zone identification concepts to support the communication of space layout plans.

C2. Methodology

2.1 Specification of coding symbols

Coding symbols, which are defined by simple, conventional prefixes, characters, and numbers, have been specified to facilitate a common human/machine-readable language for space and thermal zone identification. It is important to note that coding symbols have been developed as part of a larger classification and identification development project, namely the Danish CCS project. Based on a *triple helix* of university-industry-government interactions (Etzkowitz, 2003), an interdisciplinary project team of clients, project managers, contractors, architects, and engineers contributed to the development of classification structures and identification concepts for building facilities, building elements, building spaces, building properties, and other related matters (Friborg et al., 2014). The corresponding author of this study, representing the university and engineering link, was involved in space classification and identification activities.

Note: The coding symbols have been developed as part of the official CCS project, not solely by the corresponding author of this study.

2.2 Specification of identification concepts

Using these coding symbols, space and thermal zone identification concepts have been specified. The concepts have been developed to support integrated early-stage space layout planning, and to enable identification and differentiation between spaces and thermal zones.

Note: The identification concepts have been developed as part of the official CCS project, not solely by the corresponding author of this study.

C3. Coding symbols

C3.1 Symbols and rules

As previously stated, CCS coding symbols are defined by simple prefixes, characters, and numbers. Table C-1 shows specified symbols. Note that, in CCS, spaces are defined by the character "R" (Room).

Table C-1. Overview of coding symbols.

Prefixes	
--	Combined Product ID
Characters	
C	Construction Entity
S	Section
F	Floor (floor, above ground level)
M	Mezzanine Floor (inserted floor, above ground level)
B	Basement (floor, below ground level)
U	Under Ground Floor (inserted floor, below ground level)
R	Room (space)
Z	Zone (thermal zone)
Numbers	
01	First
02	Second
03	Third

The "Combined Product ID", represented by the prefix "--" (line line), is the CCS term applied to the concept of combined coding, for example, combining construction entities, sections, floors, and so on. The combined product approach implements the following coding rule:

--ConstructionEntity.Section.Floor.Room.Zone

C4. Identification concepts

C4.1 Space and thermal zone identification

The above symbols and rules make it is possible to identify and communicate the precise location of building spaces and associated thermal zones. As an example, Construction Entity 16 – Section 8 – 4th Floor – Room 2 should be coded as follows:

--C16.S08.F04.R02

In practice, the coding should be read from right to left:

"Room 2 is located on the 4th Floor of Section 8, Construction Entity 16"

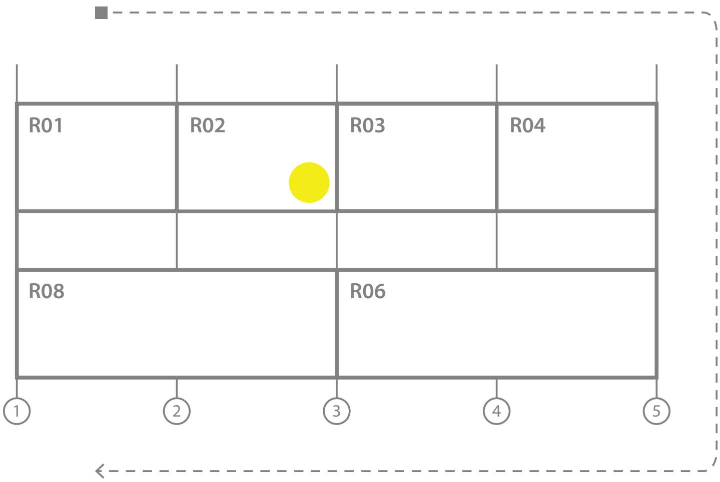

Figure C-1. Space/room identification.

Furthermore, the numbering of spaces/rooms should be calculated based on space plan grid lines, calculated clockwise. In Figure C-1, Room 2, highlighted with a yellow circle, is located between grid line "2" and "3".

Note that, in Figure C-1, spaces are defined by physical boundaries (walls). This definition represents the traditional building design space view, also referred to as the design view. However, the building design space view does not necessarily correspond to the building performance space view, also referred to as the thermal view (Bazjanac, 2004).

The thermal view often requires thermal zoning of spaces, and thermal zoning strategies can differ significantly by space type. In some cases, thermal zoning simply follows the existing space layout plan, each space constituting a thermal zone. In other cases, however, larger spaces, such as open-plan offices, may require a multi-zoning strategy due to differences in personal thermal comfort criteria. If possible, these large spaces should be divided into multiple thermal zones, to enable personal/local control over environmental conditions.

The multi-zoning strategy is shown in Figure C-2. Here, Room 6 is divided into two thermal zones, Zone 1 and Zone 2. Again, by using the coding symbols and rules, it is possible to identify the location of, for example, Zone 1, shown highlighted with a yellow circle. Accordingly, Construction Entity 16 – Section 8 – 4th Floor – Room 6 – Zone 1 should be coded as follows:

--C16.S08.F04.R06.Z01

And, if read from right to left:

"Zone 1 is located in Room 6, on the 4th floor of Section 8, Construction Entity 16"

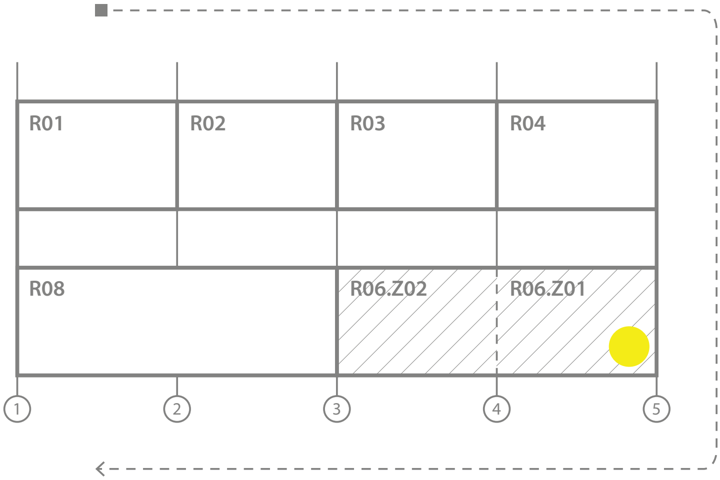

Figure C-2. Thermal zone identification (type #1).

In other cases, multiple smaller spaces, such as single-person offices, often have similar thermal profiles and conditioning requirements, and should therefore be aggregated into a single thermal zone. This thermal zone is typically served by a single HVAC system.

The aggregation strategy is shown in Figure C-3. Here, Room 1, Room 2, Room 3, and Room 4 are aggregated into a single thermal zone (Zone 3). Using the specified symbols and rules, it is possible to identify the location of, for example, Room 3, shown highlighted with a yellow circle. Therefore, Construction Entity 16 – Section 8 – 4th Floor – Zone 3 – Room 3 should be coded as follows:

--C16.S08.F04.Z03.R03

And, if read from right to left:

"Room 3 is located in Zone 3, on the 4th floor of Section 8, Construction Entity 16"

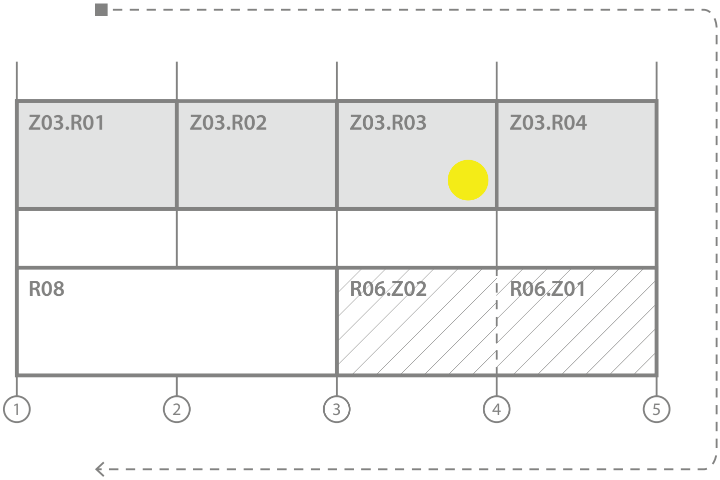

Figure C-3. Thermal zone identification (type #2).

Note that it is possible to rearrange the order of identification symbols, depending on the given thermal zoning strategy. However, the latter subject/symbol will always be located in the former subject/symbol.

C5. Conclusions

C5.1 Conclusions

In this study, the benefits of implementing a common space classification and identification system were emphasized. Benefits include improved communication of space layout plans, space location, and similar building design elements.

As previously stated, holistic space layout planning should embrace both design and thermal considerations. The CCS space identification system has been developed to meet this requirement and provides a flexible structure that enables coding and location of both spaces and multi-zoned/aggregated thermal zones. As a result, the proposed identification concepts enable redefinition of the space layout plan to sufficiently reflect specific thermal zoning strategies.

In early-stage building design, building performance is often determined based on the proposed space layout plan. Therefore, early identification of space/thermal zone location is particularly beneficial. However, for accurate early-stage building performance prediction, determination of space type and usage is also important, as this will make it possible to specify internal loads and schedules for people, lighting, and equipment.

It is essential that the proposed identification concepts and coding rules, which are both human and machine-readable, support a digital approach. It is recommended that a Building Information Modeling (BIM) tool is used to establish space and thermal zone identification, enabling automatic generation and linking of associated coding.

Currently, CCS space classification and identification procedures are being tested through selected AEC/FM pilot projects to prepare for future implementation. More information on cuneco/CCS is available at www.cuneco.dk.

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The author would like to thank all the people and organizations involved in this study. The work presented in this study was performed in the scope of the CCS project, initiated and funded by cuneco, Denmark.

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Scientific paper #2

Building Performance Simulation tools for planning of energy efficiency retrofits

STUDY INFO

Relevance to thesis: Focuses on BPS approaches to support building performance prediction, and identification and specification of BPS information exchange structures.
Primary contribution: BPS-based building design decision-making methodology.

Submission
Presented at the 10th Nordic Symposium on Building Physics
NSB Conference, 2014, Lund, Sweden

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Building Performance Simulation tools for planning of energy efficiency retrofits

Abstract

Designing energy efficiency retrofits for existing buildings will bring environmental, economic, social, and health benefits. However, selecting specific retrofit strategies is complex and requires careful planning. In this study, we describe a methodology for adopting Building Performance Simulation (BPS) tools as energy and environmentally conscious decision-making aids. The methodology has been developed to screen buildings for potential improvements and to support the development of retrofit strategies. We present a case study of a Danish renovation project, implementing BPS approaches to energy efficiency retrofits in social housing. To generate energy savings, we focus on optimizing the building envelope. We evaluate alternative building envelope actions using procedural solar radiation and daylight simulations. In addition, we identify the digital information flow and the information exchange structures for each simulation.

Keywords: Retrofit, energy efficiency, building performance simulation, information flow

C6. Introduction

C6.1 Background to study

The impetus to energy efficiency comes from a variety of sources. In the European Union (EU), the Commission has adopted an action plan aimed at achieving 20% reduction in primary energy consumption by 2020, the *20-20-20 goal*. This reduction will require major improvements in the energy efficiency of buildings, which represent around 40% of the EU's total consumption (European Union, 2009). Recently, the EU's drive to reduce consumption mainly focused on new buildings. However, considering that the average lifetime of a building is over 50 years, and a complete renewal of the existing European building stock would take more than 100 years (Kaderják et al., 2012), a substantial reduction in total consumption will not occur if no energy is saved through retrofitting existing buildings (Verbeeck & Hens, 2005).

Selecting specific retrofit strategies is a complex endeavor with many actions to be considered. A decision support approach is therefore needed (Kolokotsa et al., 2009). Here, Building Performance Simulation (BPS) tools have an important role to play (Peltormäki, 2009). With the evolution of Information Technology (IT), BPS tools have been developed to simulate the performance of a building (Doukas et al., 2009). Consequently, today's BPS tools allow any aspect of a building retrofit strategy to be simulated and assessed before it is implemented, helping project participants to understand the implications of their choices and to make informed decisions (Beaven, 2011).

C6.2 Study goals

Based on the above, this study has two goals. The first is to explore the current approaches to energy efficiency retrofits in the Architecture, Engineering, and Construction (AEC) industry. The second is to describe a methodology to facilitate BPS tools as energy and environmentally conscious decision-making aids.

Using an integrated and experience-based approach (Towns, 2001), the study goals are addressed by: (1) a review of trends in the field of energy efficiency retrofits to establish a knowledge base, and (2) a case study of a Danish renovation project to explore the effect of BPS tools to support building design decision-making.

C7. Methodology

C7.1 Review of current approaches

A review of current approaches to energy efficiency retrofits has been conducted and included articles and research conducted by academic institutes; industry work practice; and guidelines generated by government institutions. The review was carried out to understand and identify current trends in energy efficiency retrofits, and specifically focused on the uptake of integrating BPS tools as aids for building design decision-making.

C7.2 Qualitative case study research

A qualitative case study of energy efficiency retrofits in Danish social housing has been conducted. The case study approach facilitates "in-depth, multi-faceted explorations of complex issues in their real-life settings" (Crowe et al., 2011). In the present case study, multiple context-specific retrofit actions were compared to identify and evaluate trade-offs and post-retrofit benefits, which were defined as reduced energy consumption and improved indoor environmental quality. To achieve improvements, the case study retrofit actions focused on optimizing the building envelope.

A key feature of this case study was that BPS tools was used to predict the influence of the investigated retrofits. In particular, the researchers used a comprehensive suite of solar radiation and daylight simulations to show how building performance is affected by specific retrofit choices. Solar radiation simulations were performed using Autodesk

Ecotect Analysis [Ecotect](Autodesk, 2014a); daylight simulations were performed using IES Virtual Environment [IESVE] (IES, 2014). Both Ecotect and IESVE use data interpolation from the EPW weather file. As part of the simulation process, the case study identified the task/tool-specific information exchange structures for each simulation, in the present case study the required data input for each solar radiation and daylight simulation. Based on these simulations, knowledge was provided prior to the decision-making/retrofit planning, thereby facilitating a predictive, informative decision approach (Attia, 2012).

Notably, the primary purpose of this case study was to demonstrate the benefits of adopting BPS tools as aids to facilitate informative pre-retrofit investigations, not to present specific building performance figures.

Based on a *triple helix* of university-industry-government interactions, an interdisciplinary project team of clients, project managers, contractors, architects, engineers, and manufacturers collaborated in the case study (Etzkowitz, 2003). Here, representing the university and engineering link, the corresponding author of this paper was involved in simulation and design activities.

C8. Review

C8.1 Energy efficiency retrofits

Retrofitting is “the process of modifying something after it has been manufactured” (City of Melbourne, 2013). For buildings, energy efficiency retrofits are defined as actions that allow an upgrade of the building’s energy and environmental performance to a higher standard than was originally planned (Jaggs & Palmer., 1999). An overview of potential retrofit strategies, and retrofit actions which may improve performance figures, is shown in Figure C-4.

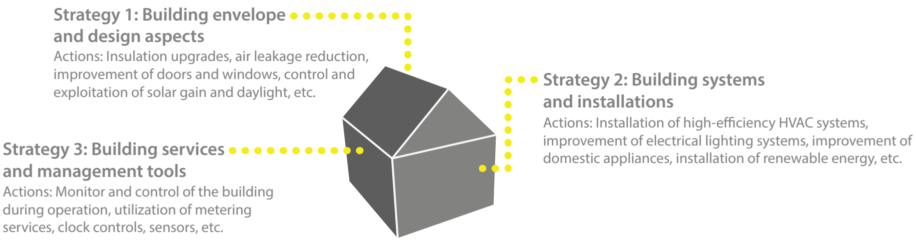

Figure C-4. Retrofit strategies/actions [Inspired by (Kolokotsa et al., 2009)].

An example of a retrofitting action is the upgrading of insulation levels. Here, re-insulation of the building envelope – external walls, roofs, and floors – will improve the energy consumption of the building by reducing thermal losses through the fabric.

Another example is the replacement of traditional single/double glazed windows with energy efficient triple glazed windows. As with the insulation upgrade, triple glazed windows will improve the building's thermal performance. Replacing or changing the position, size, and shape of the windows may also result in improved solar gains, and better daylight exploitation, thereby reducing heat consumption and electrical lighting consumption, respectively (Bokel, 2007).

Furthermore, a key feature of retrofit is the objective of improved indoor environmental quality, usually measured by occupant comfort. Indoor environmental quality is determined by several factors, including air quality, acoustics, temperature, and lighting conditions. Consequently, some retrofit strategies integrate natural ventilation for better air quality, thermo-active building systems for thermal stability, and natural lighting for a better quality of illumination (Osso et al., 1996) (Paul & Taylor, 2008).

The green agenda is generally a powerful instrument in a retrofit argument. However, retrofits also allow an upgrade of functionality, architectural quality, and aesthetic value of the building (Kalc, 2012).

C8.2 Retrofit performance criteria

The planning and evaluation of energy efficiency retrofits depend on well-defined project goals and carefully constructed criteria (Jaggs & Palmer, 1999). Accordingly, the main criteria for efficiency and sustainable performance in a retrofit include: (1) improvement of energy consumption, (2) limited impact on global environment, (3) improvement of indoor environmental quality, and (4) upgrading of functionality, architectural quality, and aesthetic value. Furthermore, the expected cost of a specific retrofit is key to its effective value. In this study, however, cost-effectiveness is not included as a criterion for retrofit evaluations.

Several of these criteria often appear to be in conflict, for example, energy consumption improvements versus architectural quality. Therefore, finding the optimum retrofit strategy is an optimization procedure. Here, the optimization involves iterative evaluations of proposed retrofit strategies/actions against selected criteria. Therefore, because optimization is complex, efforts for energy efficiency retrofits often focus on specific strategies/actions without the adoption of a holistic approach (Kolokotsa et al., 2009).

C8.3 BPS-based decision-making methodology

Generally, decisions taken during the early stages of the design process, where the impact of design decisions on building performance is more significant than decisions made in later design stages, can determine the success or failure of a retrofit. For this reason, ensuring informed decision-making in the early design stages of both new builds and retrofitting is important (Shaviv et al., 1996).

Here, BPS approaches can be supportive. In the BPS-based process, a virtual model is developed to identify the most beneficial retrofit strategies/actions through predictive performance simulations. More specifically, a BPS tool is used to simulate the performance of a virtual model representing a specific retrofit strategy/action. Then, simulation results are evaluated against predefined performance criteria. If the results are not satisfactory, the retrofit strategy/action is modified and the simulation process is repeated (Attia, 2012). This iterative procedure is shown in Figure C-5.

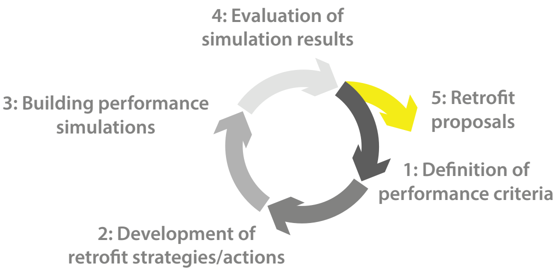

Figure C-5. Iterative decision methodology [Inspired by (Kolokotsa et al., 2009)].

C8.4 BPS-based retrofit design process

In contrast to design processes aimed at new-build, the retrofit design process is strongly influenced by the conditions of an existing building. The BPS-based retrofit design process is shown in Figure C-6, here integrating the above mentioned BPS-based decision methodology. As shown, the BPS-based retrofit design process consists of three stages: (1) analysis of existing conditions, (2) development of retrofit strategies/actions, including evaluation against performance criteria, and (3) implementation of proposed retrofit strategies/actions.

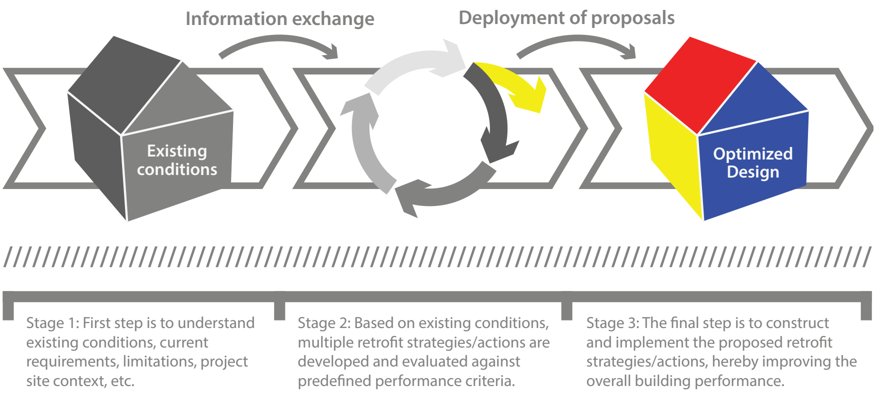

Figure C-6. BPS-based retrofit design process.

A key challenge to BPS-based retrofit design processes is the digital information flow between functional stages. In most cases, this information flow is defined by task/tool-specific information exchange structures, that is the required data input/output for specific BPS tasks/tools.

C9. Case study

C9.1 Analysis of existing conditions

The framework of this case study was directed toward the Gate 21 pilot project "Building Envelope Retrofits" (GATE 21, 2013). The aim of this project was to investigate the benefits of energy efficiency building envelope retrofits in Danish social housing, referring to "Strategy 1", implementing retrofit actions related to the building envelope and design aspects. In particular, Gate 21 was looking for creativity in developing multiple *exemplar* building envelope designs, with the aim of identifying successful actions that could be adopted into future building envelope retrofit projects. Another issue that was highlighted was that of developing building envelope designs optimized for solar radiation and daylight exploitation.

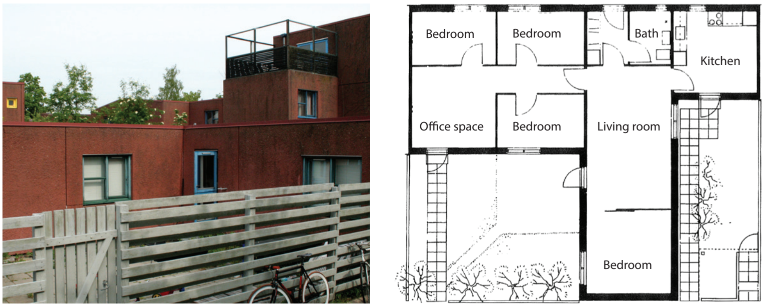

Figure C-7. Pre-retrofit conditions of case study house.

The dwelling used for the retrofit case study was a precast concrete construction, 1970s single storey house in Albertslund, Denmark (55.39°N 12.21°E). Pre-retrofit buildings typically have aging window units, poor insulation, air leakage, and mould growth due to surface condensation. These factors result in increased energy bills and poor indoor environmental quality. Figure C-7 shows the house exterior and plan.

C9.2 Development of building envelope retrofit actions

Based on review findings, the practice procedure for the development and evaluation of optimized building envelope retrofit actions followed five steps: (1) definition of performance criteria, (2) development of retrofit strategies/actions, (3) building performance simulations, (4) evaluation of simulation results, and (5) retrofit proposals.

C9.2.1 Definition of performance criteria

Case study performance criteria were defined to establish a basis for evaluation. Performance criteria were generated with two main purposes: (1) to improve energy consumption by optimizing the exploitation of solar radiation and (2) to improve indoor environmental quality by optimizing the exploitation of daylight. In many cases, such performance criteria will be some combination of potential improvements. For example, optimizing the exploitation of solar radiation may not only improve energy consumption figures, but also indoor environmental quality levels by supporting occupants' thermal comfort. Equally, optimizing the exploitation of daylight may not only improve indoor environmental quality levels, but also energy consumption figures.

C9.2.2 Development of retrofit strategies/actions

In collaboration with the case study project team, a list of retrofit actions was developed. Since the aim of this case study was to investigate the effects of multiple building envelope designs, basic retrofit actions included re-insulation of external walls and upgrading of existing windows. Specifically for this case study, the influence of selected building envelope design variables was investigated, particularly, that of alternative window positions, sizes, and shapes to investigate the resulting effects on solar gains and daylight conditions. The retrofit options consisted of nine building envelope designs/retrofit actions:

- Action 1: Energy efficient windows.
- Action 2: Energy efficient windows + increased window width.
- Action 3: Energy efficient windows + increased window height.
- Action 4: Energy efficient windows + extra window section at patio doors.
- Action 5: Energy efficient windows + double patio doors.
- Action 6: Energy efficient windows + small skylight in living room.
- Action 7: Energy efficient windows + large skylight in living room.
- Action 8: Energy efficient windows + extra window section in living room.
- Action 9: Energy efficient windows + extra window section in master bedroom.

C9.2.3 Building performance simulations

BPS tools were used to investigate the retrofit actions. Simulations were performed on two levels: (1) simulation of solar radiation striking exterior surfaces [Ecotect] and (2) simulation of interior solar gains and daylight distribution [IESVE]. Before simulating, specific information exchange/data input requirements for each simulation were identified:

- Site: Coordinates, weather data, elevation, 3D geometry, context [Ecotect + IESVE].
- Building: Coordinates, orientation, elevation, 3D geometry [Ecotect + IESVE].
- Spaces: Elevation, 3D geometry, space boundaries, [IESVE].
- External constructions: 3D geometry, U-values, [IESVE].
- Internal constructions: 3D geometry, U-values, surface reflectance values [IESVE].

- Windows: Orientation, 3D geometry, U-values, g-values, VT-values, shading information [IESVE].

In Figure C-8, selected solar radiation simulations are shown. Here, average hourly solar radiation is mapped over existing conditions, hours in question 06-18, all year, summer, and winter, contour range 0-200 Wh/m2. The Ecotect case study models were kept simple, representing outer volumes/exterior surfaces only. As shown, surrounding vegetation was not included.

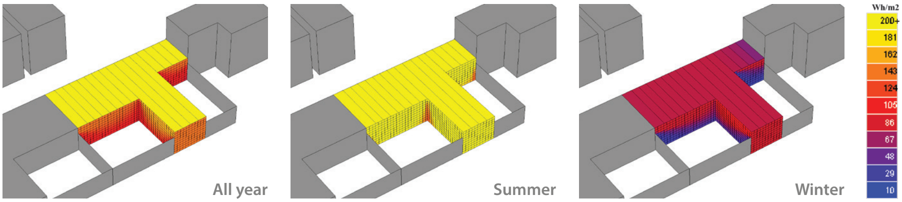

Figure C-8. Incident solar radiation on exterior surfaces (south view).

In Figure C-9, selected daylight simulations are shown. Here, average annual solar gains and daylight distribution are mapped over existing conditions, retrofit Action 1 with energy efficient windows, and retrofit Action 7 with energy efficient windows and a large skylight in the living room, contour range 40-760 LUX. The base-case model was created to understand the existing conditions of the case study building. This model was used as a reference to estimate improvements from retrofit actions 1 to 9.

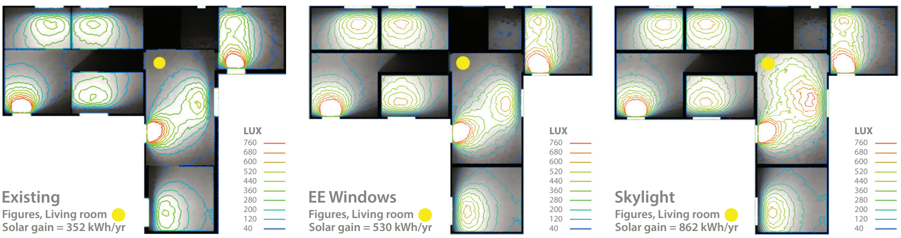

Figure C-9. Correlation of interior solar gains and daylight distribution (top view).

C9.2.4 Evaluation of simulation results

Based on the BPSs, several kinds of correlations were demonstrated. For example, Figure C-8 shows that an obstructed context greatly influences radiation values. As shown, the surrounding wooden fence causes overshadowing, particularly, during winter when the sun is low. Therefore, upper parts of the façades and freely exposed roofs should be prioritized when optimizing the exploitation of solar radiation.

Figure C-9 shows that the replacement of existing windows with energy efficient windows brings significant improvements. Energy efficient windows have smaller frames, allowing more sunlight and daylight to penetrate. In addition, the installation of the large skylight further improves the solar gains and daylight distribution and is particularly effective at bringing solar radiation and daylight into deep spaces/darker areas of the case study building.

C9.2.5 Retrofit proposals

The evaluation of simulation results forms a solution space for potential building envelope retrofit actions. This solution space does not define any specific optimum retrofit, rather a wide range of applicable retrofit actions. Nevertheless, installing large window openings will improve solar radiation and daylight exploitation. Note, however, that high intensity solar radiation is the commonest cause of overheating in buildings and should therefore be controlled, for example, with adjustable external solar shading.

C9.3 Implementation of retrofit strategies/actions

The final step is to implement specific building envelope retrofit actions into the case study building. For implementation, the case study project participants should select specific retrofit actions within the developed solution space. This selection process is currently being conducted.

C10. Conclusions

C10.1 Conclusions

In the decision-making process of selecting specific retrofit strategies, multiple actions are available. The decision maker has to take into consideration energy, environmental, functional, architectural, and financial aspects to develop a sustainable retrofit strategy. For this purpose, a decision support approach is needed.

In this study, the critical role of Building Performance Simulation (BPS) tools as energy and environmentally conscious decision-making aids was emphasized. In the case study, this was particularly shown by solar radiation and daylight simulations results. Based on this tendency, the BPS approach is generally evaluated as a useful methodology for planning of energy efficiency retrofits.

Acknowledgements

The authors would like to thank all the people and organizations involved in this study, particularly, the case study project participants. The work presented in the case study was performed in the scope of the pilot project “Building Envelope Retrofits”, initiated and funded by Gate 21.

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Scientific paper #3

Exploring Industry Foundation Classes interoperability between Building Information Modeling and Building Performance Simulation tools

STUDY INFO

Relevance to thesis: Focuses on IFC geometry exchange between BIM and BPS tools, and evaluation of geometry conversions and building modeling approaches.
Primary contribution: Insights into practical challenges of BIM-to-BPS IFC exchange.

Submission
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Exploring Industry Foundation Classes interoperability between Building Information Modeling and Building Performance Simulation tools

Abstract

The Industry Foundation Classes (IFC) data model standard has been identified as a potential means to facilitate interoperability between Building Information Modeling (BIM) and Building Performance Simulation (BPS) tools. At its best, IFC interoperability enables direct translation of BIM information (data) for use within BPS. However, many in the Architecture, Engineering, Construction, and Facility Management (AEC/FM) industry consider IFC procedures to be cumbersome and unreliable. Therefore, the industry-wide use of IFC-based information exchange is practically non-existent. In this paper, we explore and discuss issues related to IFC interoperability between BIM and BPS tools. We present a case study of a Danish-Norwegian IFC validation project, testing IFC interoperability between Autodesk Revit Architecture and IES Virtual Environment. In the testing, we focus on exchanging space boundary geometry. We evaluate the accuracy of tool-specific IFC export and import capabilities and geometry conversions, and compare building modeling approaches.

Keywords: IFC, BIM, BPS, interoperability, information exchange

C11. Introduction

C11.1 Background to study

Building Performance Simulation (BPS) tools are increasingly used to predict a building's performance. However, encouraging the use of BPS tools in early-stage building design, where the impact of design decisions on building performance is more significant than decisions made in later design stages, remains a challenge (O'Brien, 2002).

Complex information exchange structures and lack of interoperability between BIM and BPS tools are often cited as the reasons for the infrequent use of these tools (Venugopal et al., 2012). For example, getting accurate building geometry is an essential requirement for any BPS model, yet this is often a challenging process (Dimyadi et al., 2008) (Negendahl, 2014). For many years, geometric exchange between BIM and BPS tools has been possible only through custom-built translators, e.g. tool-specific middleware solutions, or manual translation (Venugopal et al., 2012).

Generally, BIM and BPS tools produce and exchange information in various formats. Due to their commercial nature, most of these formats are proprietary and have varying degrees of accessibility (Dimyadi et al., 2008). Therefore, to achieve better interoperability, BIM and BPS tools should refer to a common exchange reference model (Bazjanac, 2004). The Industry Foundation Classes (IFC) data model standard represents such a model (buildingSMART, 2014c).

However, many BIM and BPS users consider IFC information exchange to be insufficient and unreliable, creating problems such as information losses and geometric misrepresentations (Pazlar & Turk, 2008) (Venugopal et al., 2012). These problems may, of course, be due to deficiencies in IFC definitions. However, they could also be a result of tool-specific defects, poor IFC export and import functions, or human error, e.g. inappropriate geometric modeling procedures.

Therefore, to increase the reliability of IFC, the specification of IFC information exchange content needs to be improved. Furthermore, tool-specific IFC implementations and IFC interfaces need to reach a certain level of robustness and general usability, before they are accepted by BIM and BPS users (Kam et al., 2002).

C11.2 Study goals

Based on the above, this study has two goals. The first is to identify the challenges of IFC information exchange, in particular, IFC space boundary geometry exchange between BIM and BPS tools in early building design stages. The second is to explore the possibilities for improved efficiency of early-stage IFC information exchange.

Using an integrated and experience-based approach (Towns, 2001), the study goals are addressed by: (1) a review of current approaches to BIM-to-BPS information exchange and IFC interoperability to understand the background; and (2) a case study of a Danish-Norwegian IFC validation project to test and evaluate IFC interoperability between BIM and BPS tools.

C12. Methodology

C12.1 Review of current approaches

A review of current approaches to IFC information exchange between BIM and BPS tools has been conducted. The review included research conducted by academic institutes; technical reports from software vendors; and guidelines generated by the buildingSMART alliance. The review was carried out to understand and identify issues related to IFC interoperability, and specifically focused on the uptake of integrating IFC as a common exchange reference model for early-stage building geometry exchange.

C12.2 Qualitative case study research

A qualitative case study of IFC information exchange between an IFC-compatible BIM tool, Autodesk Revit Architecture V2014 [Revit] (Autodesk, 2014b), and an IFC-compatible BPS tool, IES Virtual Environment V2013 [IESVE] (IES, 2014), has been conducted. Here, multiple IFC exchange scenarios were compared to identify and evaluate some of the challenges of such exchanges.

Notably, IESVE only allows IFC imports of space boundary geometry. Therefore, the primary purpose of this case study was to validate IFC space boundary geometry exchange.

Since Revit was used to construct the case study building model, the corresponding IFC exchange file was obtained using the IFC export feature of Revit, more specifically the built-in “IFC2x3 GSA Concept Design BIM 2010” exporter (GSA et al., 2010). The GSA exporter was selected because of its ability to export space boundary geometry. It would also have been possible to test other export views, for example, the IFC Coordination View 2.0 and the space boundary add-on view (buildingSMART, 2014d).

After exporting from Revit, the IFC exchange file of the case study building model was imported into IESVE and then checked for compliance to the original case study building model to ensure all data had been correctly transferred. A supplementary compliance check was conducted using the FZK Viewer V4 [FZK] (KIT, 2013) and Solibri Model Checker V8 [Solibri] (Solibri, 2013). Figure C-10 shows the complete validation process.

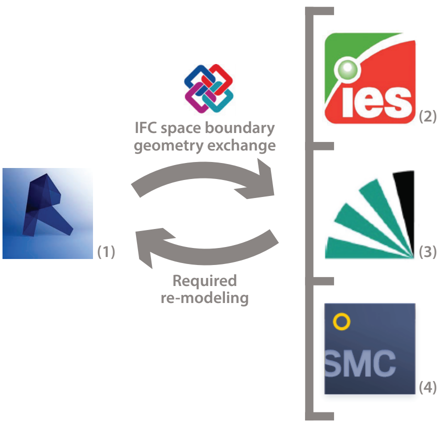

Figure C-10. IFC validation process via (1) Revit, (2) IESVE, (3) FZK, and (4) Solibri.

Based on a *triple helix* of university-industry-government interactions, an interdisciplinary project team of clients, architects, engineers, and software developers collaborated in the case study (Etzkowitz, 2003). Here, representing the university and engineering link, the corresponding author of this article was involved in geometric modeling/re-modeling and information exchange testing activities. The structure of the project team is shown in Table C-2.

Table C-2. Overview of project team.

Clients (Government)
* Statsbygg Norway, Oslo, Norway
Architects (Industry)
* Kleihues + Schuwerk Architects, Oslo, Norway
Engineers (Industry + University)
* Ramboll Denmark, Copenhagen, Denmark
* Ramboll Norway, Oslo, Norway
* Erichsen & Horgen, Oslo, Norway
* Technical University of Denmark, Kgs. Lyngby, Denmark
Software developers (Industry)
* Datacubist Oy, Tampere, Finland

C13. Review

C13.1 BIM-to-BPS interoperability

Building Information Modeling (BIM) and Building Performance Simulation (BPS) continues to play an important role for project participants in early-stage building performance prediction. However, despite their many benefits, a number of recent studies have shown that lack of interoperability between BIM and BPS tools, for example limitations in building geometry exchange, often brings challenges and frustration (Attia, 2012) (Mondrup et al., 2012).

As stated by Maile et al. (2007), the building geometry constitutes the critical input for BPS. Therefore, ensuring seamless building geometry exchange between BIM and BPS tools is important.

However, a clear distinction should be made between the geometry definitions underlying the modeling methods of BIM tools, and the modeling methods of BPS tools. BIM tools define building geometry in a design view; BPS tools define building geometry in a thermal view. Figure C-11 shows the relationship between these two kinds of views (Figure C-11(a) and Figure C-11(b)).

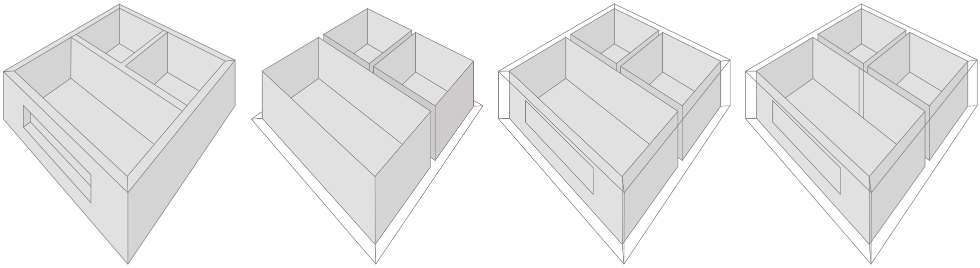

Figure C-11. Relationship between (a) design view, (b) thermal view, (c) 1st level space boundary view, and (d) 2nd level space boundary view [Inspired by (Ahn et al., 2014)].

The design view (Figure C-11(a)) defines spaces as systems of physical building elements, whereas the thermal view (Figure C-11(b)) defines spaces as systems of interior building surfaces (surfaces of walls, floors, ceilings, openings, etc.) (Hitchcock & Wong, 2011). Therefore, when exchanging building geometry between BIM and BPS tools, a conversion is required from the design view to the thermal view. Here, the space boundary view can be supportive.

The space boundary view (Figure C-11(c) and Figure C-11(d)) represents the link between the design view and the thermal view. More specifically, it defines boundaries for spaces (as defined in the thermal view), plus relationships between spaces and surrounding building elements (Ahn et al., 2014). Space boundaries can be broken down into first (1st) level space boundaries (Figure C-11(c)), which are defined as boundaries taking no account of any changes in surrounding building elements or adjacent spaces, and second (2nd) level space boundaries (Figure C-11(d)), which are defined as boundaries taking account of any changes in surrounding building elements or adjacent spaces. Furthermore, 2nd level space boundaries enable subdivision of walls/surfaces (Figure C-11(d)). This is particularly beneficial when defining spaces that are influenced by multiple adjacent spaces with different thermal conditions (Maile et al., 2007).

Notably, all views in Figure C-11 are without ceilings. This is, however, only for practical reasons, so that interior surfaces of spaces are visible. Generally, ceilings should be included in all views. In addition, in Figure C-11, space boundaries are calculated from internal surfaces, resulting in empty “construction spaces” between spaces/zones. These construction spaces are ignored in BPS. In cases where space boundaries are calculated from wall center lines, however, no such construction spaces occur.

Based on the above, space boundary geometry should be used for building geometry exchange between BIM and BPS tools. For detailed definitions, 2nd level space boundaries should be implemented.

C13.2 IFC interoperability

The Industry Foundation Classes (IFC), developed by the buildingSMART alliance, is an object-oriented data model standard that makes it possible to exchange information between BIM and BPS tools in a neutral file format (buildingSMART, 2014c). The IFC is recognized by the International Organization for Standardization as ISO 16739 (ISO, 2010b). The IFC provides a rich set of definitions related to building geometry/physical building components, including the space boundary data object "IfcRelSpaceBoundary", which enables exchange of IFC space boundary geometry (Hitchcock & Wong, 2011).

Successful IFC interoperability of space boundary geometry exchange relies on tool-specific IFC interfaces, because BIM and BPS tools in current use interpret IFC exchanges according to individual, internal IFC implementations. Therefore, to achieve IFC efficiency, and to ensure conformance of BIM and BPS tools, effective IFC software certification testing appears fundamental (Amor, 2008).

C14. Case study

C14.1 Case study framework

The case study framework was directed towards the Danish-Norwegian IFC validation project "Integration of BIM and BPS" (Statsbygg, 2013), which targeted optimization of IFC geometry exchange between BIM and BPS tools, specifically between Revit and IESVE.

C14.2 Case study building model

The building model used for the case study was a Revit model of a 3,746 m2, multi-story courthouse building in Molde, Norway (62.45°N 07.14°E). Figure C-12 shows the courthouse 3D geometry and plan (2nd floor plan).

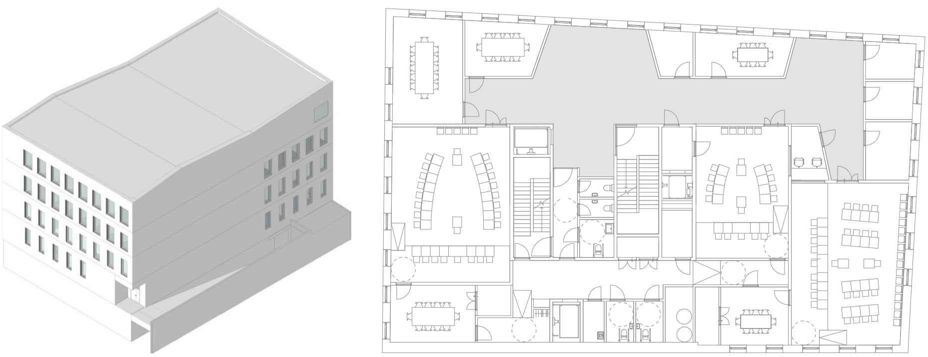

Figure C-12. Overview of case study building model [Revit model, courtesy of Statsbygg Norway (Statsbygg, 2014)].

The single space displayed in gray in Figure C-12 was selected for detailed IFC exchange investigations. As shown, this space connects multiple adjacent spaces, each with different functions and thermal conditions. Accordingly, to precisely simulate the performance of the selected space, 2nd level space boundaries should be included. Therefore, to investigate IFC space boundary geometry exchange, the exchange of 2nd level space boundary geometry was evaluated.

C14.3 Case study investigations

IFC space boundary geometry exchange investigations were carried out on two levels: (1) investigation of geometry conversions, and (2) investigation of modeling approaches.

C14.3.1 Geometry conversions

Figure C-13 shows the results of IFC space boundary geometry conversions, from Revit to IESVE, FZK, and Solibri. As shown, four conversion issues were identified: (i) missing 2nd level space boundaries, (ii) gaps in wall surfaces, (iii) a missing elevator door, and (iv) incomplete curtain wall elements.

[See Figure C-13 in next page] →

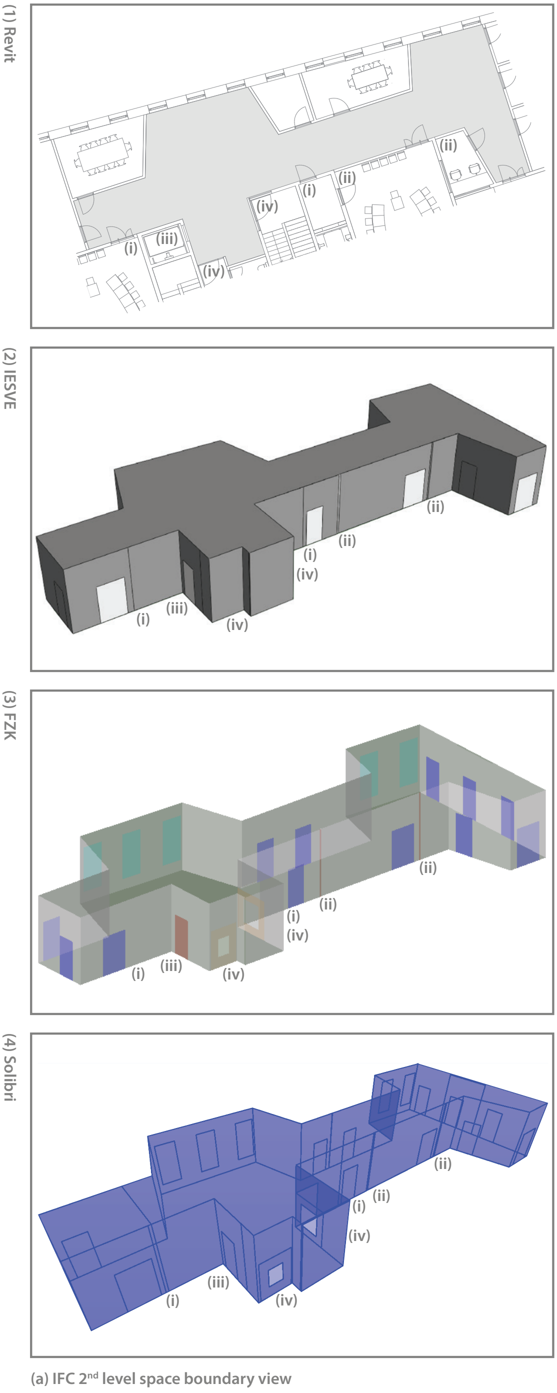

Figure C-13. Comparing (1) Revit, (2) IESVE, (3) FZK, and (4) Solibri.

Missing 2nd level space boundaries (i)

Based on IFC exchange/geometry conversion results, it is evident that 2nd level space boundary definitions are incorporated into the IFC2x3 GSA Concept Design BIM 2010 exporter. In IESVE and Solibri, wall surfaces that are influenced by multiple adjacent spaces are correctly subdivided into multiple surfaces; in FZK, however, they are completely ignored. Note that wall surface subdivisions are shown by simple dividing lines. This is because Revit uses wall location lines, in the present test case corresponding to wall center lines, to calculate space boundaries.

Gaps in wall surfaces (ii)

Gaps in wall surfaces may look similar to 2nd level space boundary subdivision procedures. However, this is not the case. In IESVE and FZK, surface gaps appear as holes in the wall; in Solibri, they appear as closed, unidentified surfaces. As shown, identified gaps appear in connection with specific wall junctions. The reason behind this may be that these wall junctions, or more specifically wall location lines, are out of alignment. If so, this will influence the calculation of space boundary geometry (Maile et al., 2013). This issue will be investigated further in section “C14.3.2 Modeling approaches”.

Missing elevator door (iii)

The missing elevator door may result from inappropriate modeling procedures. In IESVE and FZK, the missing elevator door appears as a hole in the wall; in Solibri, it appears as a closed, unidentified surface. The reason behind this may be that, in Revit, the elevator is constructed as a coherent object/family in which the elevator door is included. As a result, the wall opening in front of the elevator stands empty. This will evidently influence the calculation of space boundary geometry. For correct modeling, it is essential that elevator wall openings should be constructed with individual elevator doors on each floor.

Incomplete curtain wall elements (iv)

Incomplete curtain wall elements may result from misinterpreted Revit objects/IFC entities and associated conversion irregularities (Wong, 2011). In FZK and Solibri, incomplete curtain wall elements appear as partial holes in the wall; in IESVE, they are completely ignored. The Revit curtain wall elements, which are constructed as coherent objects/families, consist of a door part, a frame part, and a vision panel part. In the IFC schema, a similar structure is possible. Here, “IfcCurtainWall” (curtain wall element) can be defined as an aggregated entity, allowing it to be decomposed into “IfcDoor” (door part), “IfcMembers” (frame part), and “IfcPlate” (vision panel part) (J. Wong et al., 2009). If “IfcCurtainWall” is defined as such an aggregate, its geometric representation is the sum of the geometric representations of “IfcDoor”, “IfcMembers”, and “IfcPlate” (buildingSMART, 2014b). Bearing this in mind, IFC should, in principle, enable correct conversion/exchange of curtain wall elements. However, for this to happen, the aggregation relationship between “IfcCurtainWall” and “IfcPlate/IfcMembers/IfcDoor” needs to be appropriately incorporated into both the sending and receiving software tool (Wong et al., 2009).

In addition, the IFC space boundary geometry conversion modifies the geometric representation of curtain wall elements. Using Solibri IFC design view and Solibri IFC 2nd level space boundary geometry view, after Revit-to-Solibri IFC exchange, Figure C-14 compares in detail incomplete curtain wall elements. As shown, the geometric representation of the vision panel parts is modified in the space boundary geometry view, although the correct vision panel area is maintained. The reason behind this may be that the calculation of IFC space boundary geometry responds to embedded simplification rules. If so, these rules should be listed in official IFC implementation agreements (buildingSMART, 2014a).

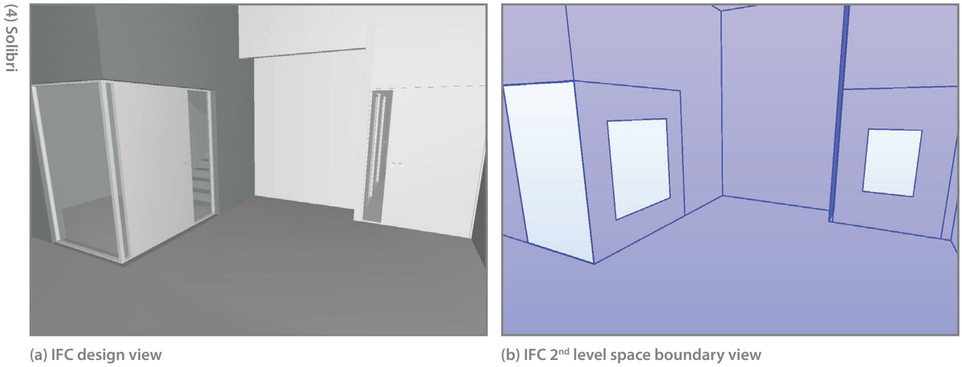

Figure C-14. Comparing (a) IFC design view and (b) IFC 2nd level space boundary view.

C14.3.2 Modeling approaches

Using the above problematic wall junctions as a test case, Figure C-15 shows selected Revit building modeling approaches and the resulting IFC space boundary geometry exchange. As shown, three modeling approaches were tested: (a) original building model, (b) merged wall elements, and (c) aligned wall location lines. Note that the space boundary is marked as a solid vertical line in top row Revit images.

As previously demonstrated, the original Revit modeling approach, which was used to construct the tested wall junction, resulted in gaps in IFC space boundary geometry wall surfaces (see left column of Figure C-15). However, by simply merging the wall elements, significant improvements are achieved (see middle column of Figure C-15). In addition, by aligning the wall location lines, which in the present test case correspond to wall center lines, surface gaps are successfully assembled into uniform space boundary geometry (see right column of Figure C-15).

Therefore, it is evident that different modeling approaches influence the calculation of space boundary geometry. Consequently, this presents challenges when exchanging space boundary geometry between discipline or tool-specific modeling views (Jones et al., 2013).

The primary reason, however, is that, in the present test case, Revit uses wall location lines/center lines for calculation of space boundaries. Therefore, if wall location lines/center lines are not properly connected, space boundary gaps occur.

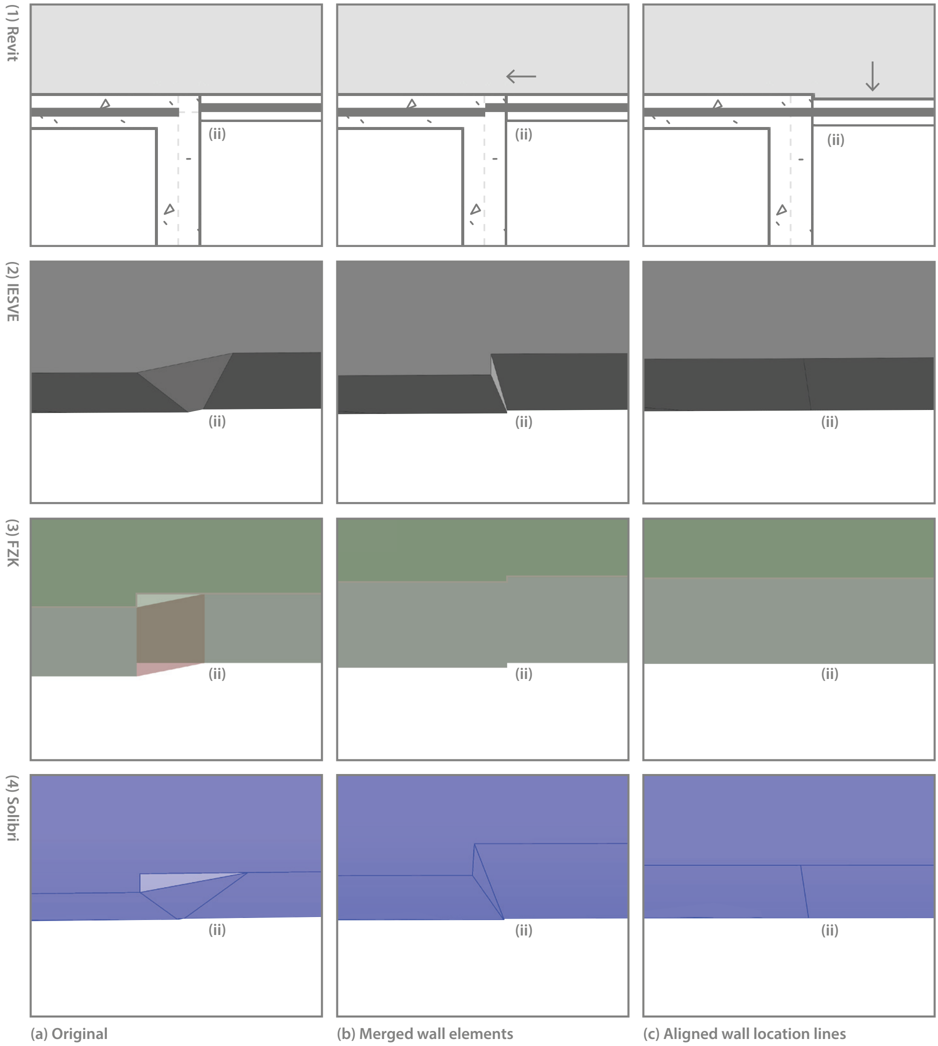

Figure C-15. Comparing (a) original building model, (b) merged wall elements, and (c) aligned wall location lines.

C15. Conclusions

C15.1 Conclusions

In early-stage building design, BIM-models serve as the most up-to-date representations of buildings. BPS experts need information from such models to accurately simulate building performance. However, information exchange between BIM and BPS tools often appears problematic, particularly when exchanging geometric information.

In this study, we emphasized the critical role of implementing IFC as a technical solution for space boundary geometry exchange. We tested multiple IFC space boundary geometry exchanges between Autodesk Revit Architecture V2014 and IES Virtual Environment V2013, FZK Viewer V4, and Solibri Model Checker V8, and found a number of important shortcomings. For example, differences were found in tool-specific IFC space boundary geometry conversions, in the present test case Revit-based conversions, indicating conversion irregularities. In particular, conversion of wall junctions and curtain wall elements presented difficulties. The conversion of such geometric information is necessary for BPS. Modeling approaches also played an important role. In particular, overlaps were found between wall location lines and space boundary geometry calculation lines, resulting in space boundary calculation errors.

To address these challenges, a common understanding is needed. It is essential that when preparing IFC space boundary geometry exchange between BIM and BPS tools, the sender and receiver, in this case the building designer and BPS expert should communicate before exchanging data. Such communication should, if possible, be supported by predefined exchange specifications and detailed BIM-to-BPS modeling guidelines. Furthermore, model checking and conformance testing, using an external model-checking tool, should be an integral part of any IFC space boundary geometry exchange process. Finally, and perhaps most importantly, effective IFC certification testing should be given a high priority to ensure well-functioning tool-specific IFC interfaces.

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Scientific paper #4

Introducing a new framework for using generic Information Delivery Manuals

STUDY INFO

Relevance to thesis: Focuses on AEC/FM communication and information flow management, and identification and specification of decomposed AEC/FM processes and associated information exchanges.
Primary contribution: IDM Framework for generic AEC/FM processes.

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Introducing a new framework for using generic Information Delivery Manuals

Abstract

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

Keywords: Information flow management, BIM, buildingSMART, IDM

C16. Introduction

C16.1 Background to study

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

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

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

To address these issues, the buildingSMART alliance has introduced the Information Delivery Manual (IDM), which provides a methodology to specify AEC/FM process flows and their information content (Wix et al., 2009).

However, despite the great potential of IDMs, and the fact that more than 100 IDMs are currently registered on the buildingSMART website (Karlshoej, 2013), the industry-wide use of IDMs is limited (Karlshoej, 2012).

C16.2 Study goals

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

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

C17. Methodology

C17.1 Review of current approaches

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

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

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

C17.2 Development of IDM Framework

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

C18. Review

C18.1 Industry Foundation Classes (IFC)

The Industry Foundation Classes (IFC), developed by buildingSMART, is a data model standard that has been proposed to describe, exchange, and share information in a neutral file format (See et al., 2012). Generally, IFC is the means of achieving software interoperability in AEC/FM projects. However, as stated in (Aram et al., 2010), the industry-wide use of IFC remains a challenge. To date, IFC-based information exchange mainly focuses on geometry exchange.

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

C18.2 Information Delivery Manual (IDM)

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

- IDM use case: Defines the activities, information exchanges, and project participants required for a specific AEC/FM process.
- IDM Process Map (PM): Formalizes the relationship between these activities, information exchanges, and project participants.
- IDM Exchange Requirements (ERs): Define the information units required for each use case-specific information exchange.

- IDM Exchange Requirements Models (ERMs): Organize the ERs into Exchange Concepts (ECs), that is reusable information exchange packages.

The core of an IDM is the AEC/FM process that is to be standardized. However, limited guidance is provided by buildingSMART on which parts of the AEC/FM project life cycle, and which specific processes, should be included in the individual use cases that form the basis of new IDM developments. Generally, buildingSMART recommends that AEC/FM industry experts and participants of specific IDM development groups be allowed to determine the areas of need (See et al., 2012). Of particular interest is that these experts and development groups often represent specific AEC/FM disciplines or organizations. As a result, currently available IDMs describe a diverse scope of the AEC/FM project life cycle, making them difficult to reuse and implement in unique AEC/FM projects. In addition, the researchers found that using the currently available IDMs to describe greater areas of the AEC/FM project life cycle may result in both significant process overlaps and critical gaps between sub-processes that are not yet included.

C18.3 Model View Definition (MVD)

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

- MVD Description: Defines the information exchanges required for specific IDMs.
- MVD Concepts. Address these information exchanges, by linking with the IDM-specific ERMs/ECs.
- MVD Diagrams: Identify and structure the IFC entities required for exchanging these Concepts.
- MVDXML: Generates a machine-interpretable representation of the information exchanges.

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

C18.4 Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS), developed by the United States Department of Defense, is a project management methodology that defines and organizes the processes of a project (Brotherton et al., 2008) (O'Donnell, 2012). The WBS methodology uses a hierarchical tree structure, and enables the processes of a project to be broken down into smaller, more manageable sub-processes. Figure C-16 shows an example of a WBS.

Work breakdown structure

1. Design
    - 1.1 Outline conceptual design
    - 1.2 Full conceptual design
        - 1.2.1 Architecture
        - 1.2.2 Engineering
            - 1.2.2.1 Structural engineering
            - 1.2.2.2 Mechanical engineering
                - 1.2.2.2.1 HVAC engineering
                    - 1.2.2.2.1.1 Facade performance engineering
            - 1.2.2.3 Electrical engineering
    - 1.3 Coordinated design

Figure C-16. WBS for building design.

Arguably, if processes described in IDMs are intended to be applicable and reusable across AEC/FM disciplines and organizations, it will require that these processes can be mapped against a generic WBS, representing all processes within the AEC/FM project life cycle.

C18.5 Increasing project complexity

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

Hjelseth (2011) recommended that BIM Guidelines (similar to IDMs) be decomposed into individual Information Modules (IMs), with each IM representing a specific use case and a set of associated information exchanges. Such IMs would provide the basis for BIM Guidelines to be implemented in a wide range of AEC/FM projects, as compared to traditional BIM Guidelines, which tend to focus on the authoring organization or project, and therefore make them less useful in other AEC/FM organizations or project types. Generally, BIM Guidelines are not sufficient to support AEC/FM information exchange. However, IDMs are. By defining IDMs in the above manner, improved approaches to standardizing information exchanges in unique AEC/FM projects can be realized.

C18.6 Review findings

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

- AEC/FM information flow management should be based on integrated approaches, common standards, and well-documented procedures.
- Unique AEC/FM projects require modular approaches and flexible methodologies if

standardized information exchanges are to be reusable throughout the entire AEC/FM project life cycle.
- IDM processes should be decomposed and identified in accordance with a commonly accepted AEC/FM WBS, such that the IDM can be reused and applied within any given AEC/FM project.

C19. IDM Framework

C19.1 IDM Framework structure

The proposed IDM Framework introduces a two-dimensional WBS-based methodology aimed at defining and organizing the information exchanges within AEC/FM projects.

The IDM Framework builds on a simple matrix structure of AEC/FM disciplines and project life cycle stages (Hall, 2012). This structure serves as an "umbrella", covering all main use cases of the AEC/FM project life cycle. Given that use cases are generally defined to establish a basis for IDM developments, each use case defined in the IDM Framework represents a specified IDM Package. Figure C-17 shows the WBS approach and the IDM Framework structure.

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

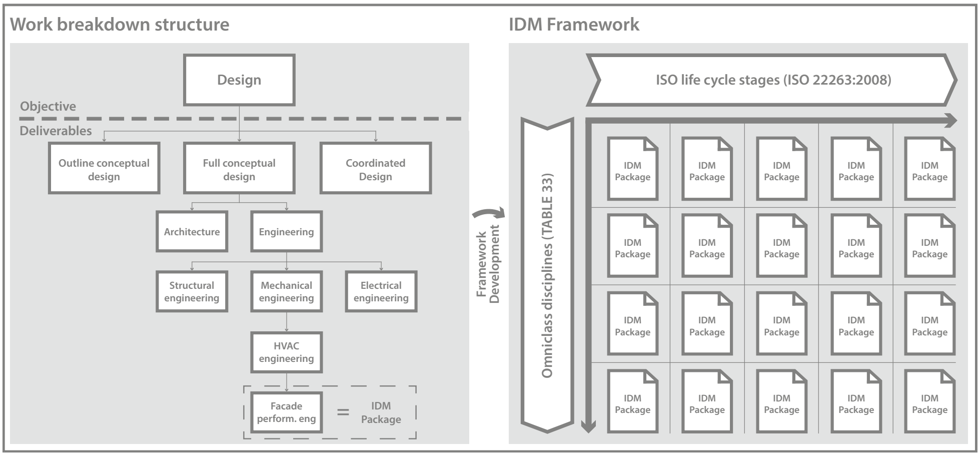

Figure C-17. WBS for building design and IDM Framework structure.

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

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

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

C19.2 Decomposing into IDM Packages

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

The IDM Packages cannot represent all use cases within every discipline of the AEC/FM industry, as local diversities and the need for customization of AEC/FM processes would require adjustments for specific purposes (Aram et al., 2010). Therefore, it could be argued that the purpose of the IDM Framework should be to identify the AEC/FM industry's best practices. Hence, the IDM Packages defined in the IDM Framework should describe generic use cases and best practices, allowing for adjustment to local needs.

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

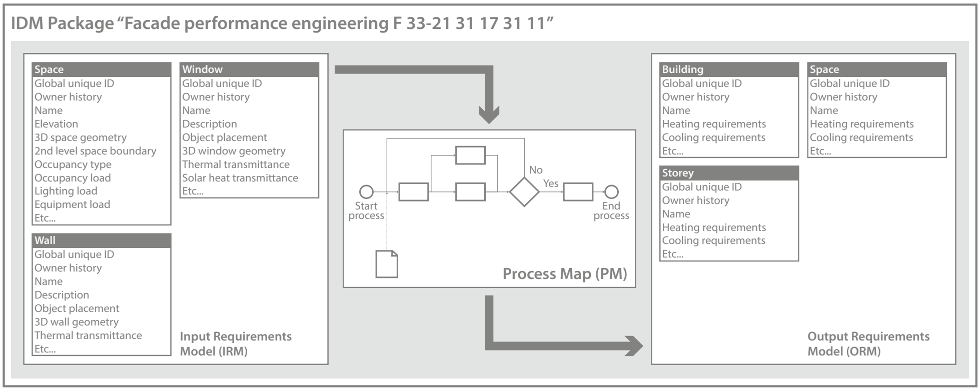

Figure C-18. IDM Package for façade performance engineering.

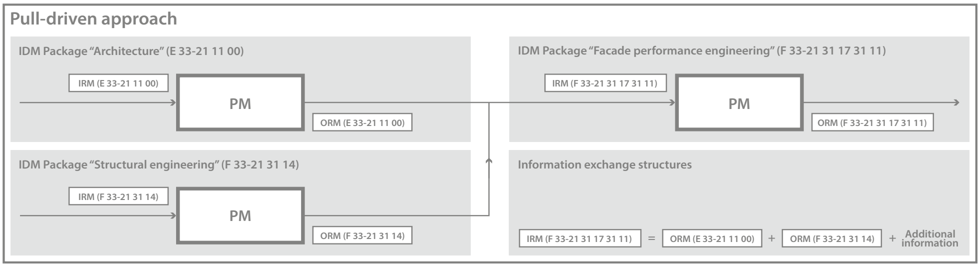

Figure C-19. Pull-driven approach.

As this study focuses on describing the overall concepts of the IDM Framework, we will not define the content of specific IDM Packages and associated IRMs and ORMs. However, Aram et al. (2010) recommended that AEC/FM industry experts be involved in the process of defining the IRMs and ORMs.

Figure C-18 shows an example of an IDM Package for façade performance engineering, and Figure C-19 shows an example of the "pull-driven" exchange approach and the relationship between IDM Packages and associated IRMs and ORMs. Note that the downstream IDM Package is affected by what is produced by the upstream IDM Packages.

C19.3 Defining IDM Project Plan

An important function of the IDM Framework is its ability to serve as a basis for defining an IDM Project Plan, in this way changing from generic use to project-specific use. Using this modular approach, the IDM Project Plan is created by selecting the specific IDM Packages required for the specific AEC/FM project. In addition, the IDM Project Plan provides an explicit description of the overall AEC/FM project scope, sequence flows, organizational interactions, and information exchanges.

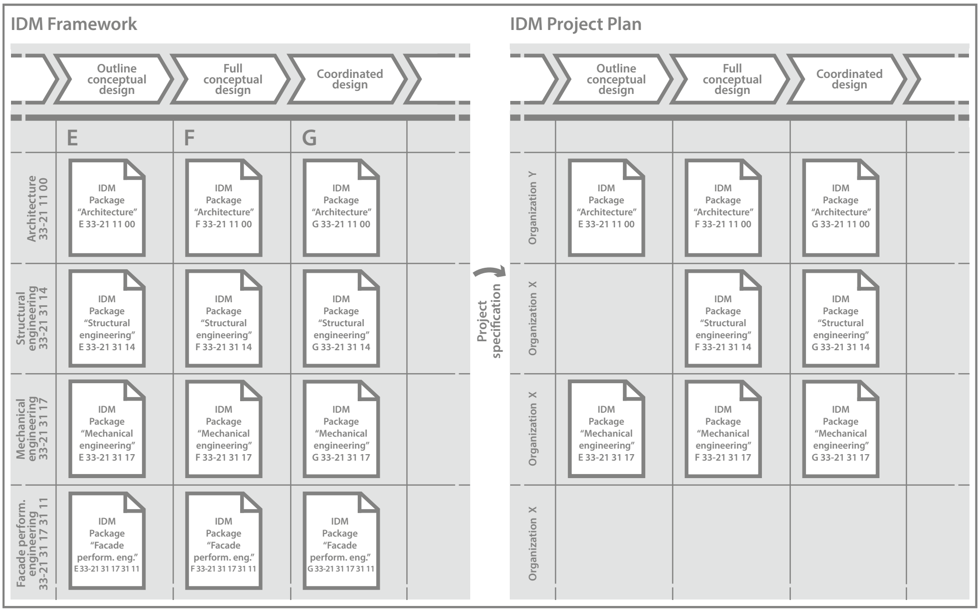

Figure C-20. IDM Framework and IDM Project Plan.

Furthermore, the graphical nature of the IDM Project Plan helps project managers to predict AEC/FM process flows and to communicate requests for deliverables throughout the given AEC/FM project. Figure C-20 shows an example of how selected IDM Packages can be placed in the IDM Project Plan.

C19.4 IDM Packages and MVDs

Traditionally, MVD developments are based on IDM-specific Exchange Requirements Models (ERMs) and associated Exchange Concepts (ECs). However, bearing in mind the concept of IRMs and ORMs, it is recommended to define MVDs based on the IRMs and ORMs of individual IDM Packages. Given that MVDs are generally defined to establish a basis for AEC/FM software integration, they can be used to describe the precise information that specific AEC/FM software tools should be able to import and export, as subject of specific IRMs and ORMs. This is particularly beneficial as it enables AEC/FM project participants to carefully select the most appropriate software tool for the specific process/use case in question.

Potentially, the IDM Framework will consist of hundreds of IDM Packages with an equal number of associated MVDs. Inevitably, this will challenge efficient and unified AEC/FM software adoption. Consequently, for the purpose of AEC/FM software certification, the combination of multiple IDM Packages into each MVD is recommended.

C19.5 Potential of IDM Framework
Generally, the IDM Framework provides a modular methodology to define and organize processes and information exchanges in unique AEC/FM projects. However, it also has the potential to provide a basis for many additional analyses and optimization tasks. For example, the selected IDM Packages in an IDM Project Plan could help to identify potential gaps in project-specific information exchanges, and, by observing senders and receivers of specific IRMs and ORMs, could also identify non-value propositions of specific AEC/FM processes.

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

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

C20. Conclusions

C20.1 Conclusions
In this study, we introduced an IDM Framework aimed at defining and organizing generic IDM Packages for all main use cases of the AEC/FM project life cycle. The IDM Framework was developed from the findings obtained from a review and supplementary expert discussions.

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

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

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

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

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Scientific paper #5

Information exchange structures for early-stage Building Performance Simulation

STUDY INFO

Relevance to thesis: Focuses on early-stage BPS adoption, and the identification, specification, and simplification of information exchange structures for early-stage façade performance engineering.
Primary contribution: IDM Package for early-stage façade performance engineering.

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Information exchange structures for early-stage Building Performance Simulation

Abstract

Decisions made in the early stages of building design have a lasting effect on the building's life cycle performance. It is critical, therefore, that these decisions are well informed, and here Building Performance Simulation (BPS) tools can support the process. BPS-based building design uses a virtual model to optimize design strategies. However, the process is not always practical, as the detailed information required is not always available in the early stages of a building project. In addition, the recurring lack of interoperability between Building Information Modeling (BIM) and BPS tools restricts BPS tools from delivering their full potential. To exploit this potential, a detailed, yet simplified specification of information exchange structures is required. The buildingSMART standard approach to this issue is based on the Information Delivery Manual (IDM). To illustrate the principles, we present an overview of a new IDM Package, developed to facilitate early-stage BPS adoption, and to support interoperability between BIM and BPS tools. In developing the IDM Package, we focus on the information needed by and resulting from early-stage BPS activities.

Keywords: Information flow management, BIM, buildingSMART, IDM

C21. Introduction

C21.1 Background to study

It is widely recognized that a significant part of a building's life cycle performance is determined by decisions taken in the early stages of building design (Bahar et al., 2013) (Basbagill et al., 2013) (Lin & Gerber, 2014). Therefore, a critical task in the early stages of building design, before important characteristics are frozen, is to create an overview of design alternatives and how they influence building performance (Ellis & Mathews, 2001) (Petersen & Svendsen, 2010). For this, a decision support approach is needed.

Building Performance Simulation (BPS) tools can help when evaluating building design alternatives (Kanters et al., 2014), as they can predict a building design's performance, helping building design participants to understand the design alternatives more completely and to make performance-based decisions. However, in common building design practices, the performance of a building is mostly simulated after the actual building design (Schlueter & Thesseling, 2009).

One of the most frequently cited reasons for this is that current BPS tools are not considered “designer-” or “architect-friendly”. Many building designers consider BPS tools to be complex and cumbersome (Attia et al., 2009). Therefore, BPS is mostly done by BPS experts, that is software experts or engineering consultants (Augenbroe, 2002). Integrating BPS into early-stage building design decision-making therefore requires building designers and BPS experts to work closely together (Ellis & Mathews, 2001). Here, the communication between the building designer and the BPS expert is key to the success of such integration.

Another important issue is that current BPS tools often require detailed data input that is not necessarily available during the early stages of building design (Ellis & Mathews, 2001) (Schlueter & Thesseling, 2009). In (Irving, 1988), the author states that “the probability of pure user-injected mistakes usually increases with the complexity of the input structure”. Consequently, many researchers and industry experts highlight the need to reduce complexity in BPS input data (Ellis & Mathews, 2001) (Petersen & Svendsen, 2010) (Kanters et al., 2014).

In addition, lack of interoperability between BIM and BPS tools is a common issue restricting BPS environments from attaining their full potential (Venugopal et al., 2012).

To resolve these issues, the buildingSMART alliance has introduced the Information Delivery Manual (IDM), which provides a collaborative methodology of specifying and displaying Architecture, Engineering, Construction, and Facility Management (AEC/FM) process flows and their information content (Wix et al., 2009). However, currently available IDMs mainly focus on standardizing significant areas and more general parts of the building design process. Consequently, these IDMs often appear too extensive and wide-ranging, involving multifaceted processes and complex information exchange structures (Mondrup et al., 2014).

For this reason, in real-life building design, the field of early-stage BPS, and the use of IDMs, are far from being mature. Therefore, more research needs to be conducted, and clearly articulated guidelines, well-coordinated workflows, and simple, yet detailed, information exchange structures should be developed.

C21.2 Study goals

This study has two goals. The first is to explore and identify current approaches to early-stage BPS. The second is to introduce a new IDM Package for early-stage BPS.

The study goals are addressed by: (1) a review of trends in the field of early-stage BPS to establish a knowledge base, (2) a qualitative survey of industry BPS experts to gain an understanding of their knowledge and experiences from integration of early-stage BPS, and (3) the development of an IDM Package for early-stage BPS.

C22. Methodology

C22.1 Review of current approaches

A review of current approaches to early-stage BPS has been conducted and included articles and research conducted by academic institutes; industry work practice; and guidelines generated by BPS expert groups. The review was carried out to explore trends in early-stage BPS, and focused on the challenges related to identifying information exchange structures for such simulation. In addition, the review examined selected buildingSMART standard approaches, namely the Industry Foundation Classes (IFC), the Information Delivery Manual (IDM), and the Model View Definition (MVD).

C22.2 Survey of industry BPS experts

A series of semi-structured interviews of industry BPS experts has been conducted to gain industry input on early-stage BPS. In particular, the interviews were carried out to identify BPS use cases or tasks performed in real-life early-stage building design processes, and also to identify the information needed by and resulting from these BPS use cases.

Survey participants were chosen using *purpose sampling* (Denscombe, 2007), a sampling method where the researcher consciously selects survey participants with particular expertise pertinent to the study. In this study, the participant selection was based around the participant's knowledge/use of early-stage BPS in a Danish-UK context. All participants had several years of practical experience in early-stage BPS. The sample consisted of seven BPS experts, all engineers. Table C-3 shows the structure of the survey sample.

Table C-3. Overview of survey sample.

Henning Larsen Architects, Copenhagen, Denmark * Two consulting engineers (Department of Sustainable Building Design)
Grontmij, Glostrup, Denmark * Three consulting engineers (Department of Building Energy)
ARUP, Manchester, UK * Two consulting engineers (Department of BIM + Department of Building Physics)

The interviews were structured around a thematic interview guide with, however, sufficient flexibility to allow questions to be modified depending on the situation. The interview questions guide was split into four stages: (1) stage one questions established the profile of the participants' organizations, (2) stage two questions identified specific early-stage BPS use cases performed by the participants, (3) stage three questions identified information exchange structures associated with identified BPS use cases, and (4) stage four questions investigated current practices of information exchange between BIM and BPS tools. The questions are shown in Table C-4.

Table C-4. Interview questions guide.

Stage one questions
"What type of business does your organization represent?"
"Which markets is your organization a part of?"
Stage two questions
"What type(s) of early-stage Building Performance Simulation (BPS) do you perform?"
"Which BPS tool(s) do you use to perform these simulations?"
Stage three questions
"What are the required input and output data for these simulations?"
"Is it possible to simplify the input and output data structures?"
Stage four questions
"How would you describe the information exchange between BIM and BPS tools?"
"Do you use standards to support such information exchange?"

It is interesting to note that the survey results represented a common frame of reference for industry best practice for early-stage BPS. They also served as key input in developing the IDM for early-stage BPS, particularly the identification of specific BPS use cases and associated information exchange structures.

C22.3 Development of IDM Package

Based on review findings and survey results, a structure for the development of an IDM for early-stage BPS has been planned. Generally, the IDM has been developed to address challenges highlighted in the review, specifically those related to early-stage BPS adoption. To achieve adoption improvements, the IDM aims to provide a detailed, but simplified, specification of information exchange structures for early-stage BPS. Ideally, the adoption of such IDM will lead to a better framework for the evaluation of BPS environments and for exchange of BPS information (Irving, 1988).

The developed IDM builds on the IDM Framework methodology presented in (Mondrup et al., 2014), in which IDMs are broken down into smaller, generic IDM Packages. Each IDM Package represents a specific use case and an associated set of information exchanges. The developed IDM represents such an IDM Package.

C23. Review

C23.1 Building Performance Simulation (BPS)

Generally, the aim of early-stage BPS is to provide guidance and performance-related knowledge prior to any actual building design decision (Attia, 2012). Despite some progress, the rate of adoption of early-stage BPS, however, has been relatively slow. Key reasons include: (1) complexity in Human-Computer Interaction (HCI), (2) complexity in information exchange structures, and (3) dysfunctional interoperable environments. Several authors agree with this (Augenbroe, 2002) (Wilde & Voorden, 2004) (Oxman, 2008) (Schlueter & Thesseling, 2009) (Attia et al., 2009) (Petersen & Svendsen, 2010) (Lin & Gerber, 2014).

As a result, common building design workflows rely on approximate methods and rules of thumb, leaving the detailed BPS to the final building design stage (Banke, 2013) (Kanters et al., 2014) (Negendahl, 2014). Therefore, more research is needed in this area to better understand and overcome the many challenges encountered in current early-stage BPS environments. For example, Ellis & Mathews (2001) warn against integration of BPS into the early stages of building design just for the sake of integration, suggesting that it will not be adopted if it significantly alters the process.

C23.1.1 Human-Computer Interaction (HCI)

A number of recent studies have shown that multiple challenges with early-stage BPS integration are caused by poor accessibility and usability of BPS tools. Therefore, many building designers consider BPS tools to be complex and difficult-to-use. These challenges are often referred to as Human-Computer Interaction (HCI) issues (Mahdavi, 2011) (Alsaadani & Souza, 2012). As a result, the need for simplified, “designer-friendly” BPS tools has recently received a lot of attention (Attia et al., 2009).

However, as stated in (Augenbroe, 2002), early-stage BPS tasks should not necessarily be executed by a non-expert, in this case the building designer. Rather, the execution of early-stage BPS should involve an integrated collaboration between building designers and BPS experts. Here, the BPS experts “are expected to use the best tools of the trade and infuse their irreplaceable expertise in the communication of analysis results with other design team members” (Augenbroe, 2002).

C23.1.2 Information exchange structures

Another frequent challenge is managing early-stage BPS information exchange. Information exchange structures are defined differently among researchers and professionals. In the context of this study, we define information exchange structures as related to information needed by and resulting from early-stage BPS, specifically the input and output data for early-stage BPS.

As previously stated, most BPS tools require a detailed description of the building. However, in the early stage, the building is only defined in a very coarse manner (Ellis & Mathews, 2001). As a result, early-stage BPS often relies on default values or certain assumptions that are built-in to the BPS tool or made by the person executing the simulation. If such assumptions can be replaced by more accurate information, or validated through a predefined information exchange specification, such as an IDM, the accuracy of early-stage BPS can be significantly improved (Bazjanac, 2004).

It is essential that when the accuracy of BPS is judged, the effect of BPS input data and calculation method should be evaluated separately. However, as stated by Kosonen & Shemeikka (1997), the input data generally affects more than the calculation method. Figure C-21 shows the importance of accurate BPS input data.

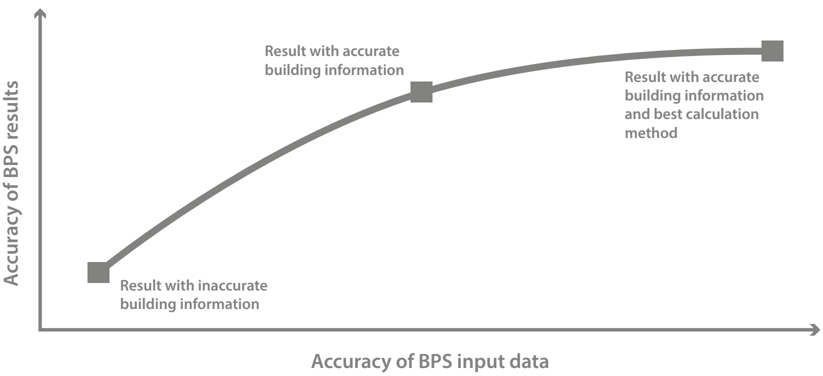

Figure C-21. Importance of BPS input data [inspired by (Kosonen & Shemeikka, 1997)].

To better specify the information exchange structures for early-stage BPS, multiple researchers and industry experts have suggested simplifying BPS input requirements (Petersen & Svendsen, 2010) (Kanters et al., 2014). As stated by Ellis et al. (2001), this can be achieved by using default values. In this approach, the BPS input data structure is a combination of a few critical parameters and a number of default values for the specific building type.

Another trend in information exchange simplification is towards automatic generation of complex building information (Bazjanac, 2004) (Negendahl, 2014). Here, a middleware is applied to auto-generate complex building information using, again, only a few critical input parameters. An example of such middleware is the Space Boundary Tool (SBT-1), developed by the Lawrence Berkeley National Laboratory. The SBT-1 provides a semi-automatic conversion of the building geometry defined in BIM tools, such as Autodesk Revit Architecture (Autodesk, 2014b) or Graphisoft ArchiCAD (Graphisoft, 2014), for import and use by the BPS tool EnergyPlus (DOE, 2013). This conversion applies predefined data transformation rules to simplify the imported space boundary geometry definitions requirements of EnergyPlus (LBNL, 2014).

However, neither of these simplification approaches necessarily reduces the BPS input structure complexity. Nevertheless, an added advantage could be that BPS experts need only acquire critical input parameters from the building designer, or the BIM-model, defining the remaining parameters themselves, for example, via default values or energy target values.

C23.1.3 Interoperable environments

A key challenge in successful early-stage BPS is the ability to seamlessly exchange information between BIM and BPS tools. For many years, this information exchange has been possible only through custom-built translators /dedicated middleware or manual translation (Venugopal et al., 2012).

To achieve full interoperability, BIM and BPS tools should refer to a common exchange reference model (Bazjanac, 2004). The IFC data model standard represents such a model (buildingSMART, 2014c).

C23.2 buildingSMART standard approaches

The buildingSMART alliance provides open standard, consensus-based methodologies to facilitate AEC/FM information exchange including: (1) Industry Foundation Classes (IFC), (2) Information Delivery Manual (IDM), and (3) Model View Definition (See et al., 2012).

C23.2.1 Industry Foundation Classes (IFC)

The Industry Foundation Classes (IFC) is the buildingSMART data model standard for describing, exchanging, and sharing building information in a neutral computer language (See et al., 2012). The IFC, which is recognized by the International Organization for Standardization as ISO 16739 (ISO, 2010b), offers opportunities to minimize data re-entry, increase accuracy of information exchange, and reduce design time during the early stage (Kam et al., 2002).

As stated by Bazjanac (2004), the IFC is increasingly gaining acceptance as the common data exchange format for interoperability within the AEC/FM industry. Nevertheless, a number of studies have shown that the industry-wide use of IFC remains a challenge (Plume & Mitchell, 2007) (Pazlar & Turk, 2008). Key reasons include: (1) a lack of initiative and guidance from software vendors, which results in poor IFC interfaces and unpredictable IFC export and import functions, (2) the fact that many judge the IFC schema as unnecessarily comprehensive with high levels of reduncancy allowing users to define IFC objects, attributes, and relations differently, which thereby creates confusion, and (3) differences in discipline-specific/user-specific procedures, for example, alternative geometric modeling procedures, which leads to misunderstandings when communicating IFC geometric representations (Olofsson et al., 2008) (Eastman et al., 2010) (Venugopal et al., 2012).

To extend the benefits of IFC interoperability, it is recommended that researchers, professionals, and software developers focus on improving information exchange specifications and robustness of tool-specific IFC implementations (Kam et al., 2002). The buildingSMART standard approach to these issues is based on the Information Delivery Manual (IDM) and Model View Definition (MVD) (See et al., 2012).

C23.2.2 Information Delivery Manual (IDM)

The Information Delivery Manual (IDM) is the buildingSMART process standard for identifying discrete AEC/FM processes and the information required for and resulting from executing these processes. The IDM, which is recognized by the International Organization for Standardization as ISO 29481-1 (ISO, 2010a), consists of four deliverables (See et al., 2012):

- IDM use case: The use case defines the activities, information exchanges, and project participants required for a specific AEC/FM process.
- IDM Process Map (PM): The PM formalizes the relationship between these activities, information exchanges, and project participants.
- IDM Exchange Requirements (ERs): The ERs define the information units required for each use case-specific information exchange.
- IDM Exchange Requirements Models (ERMs): The ERMs organize the ERs into Exchange Concepts (ECs), that is reusable information exchange packages.

IDM PMs are formalized using the Business Process Model Notation (BPMN), a standard, graphical modeling representation for specifying AEC/FM processes (White, 2008) developed by the Object Management Group (OMG, 2014). Basic BPMN modeling elements include: (a) events, (b) activities, (c) data objects, (d) sequence flows, (e) data flows, and (f) gateways (see Figure C-22) (Park et al., 2011).

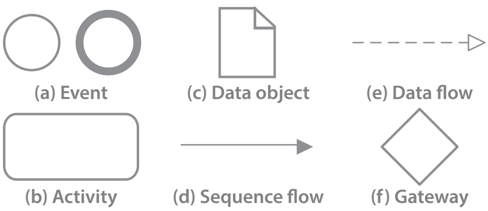

Figure C-22. Basic BPMN modeling elements.

The IDMs in current use mainly capture multifaceted and wide-ranging processes, and therefore often involve multiple use cases (Mondrup et al., 2014). Naturally, these IDMs involve comprehensive and complex information exchange structures, and are therefore often difficult to manage, and complicated to implement in real-life AEC/FM projects., It is recommended therefore that the IDMs are sub-divided into smaller, more manageable IDM Packages, with each IDM Package representing a specific use case and an associated set of information exchanges, executed at a specified stage of the AEC/FM project's life cycle (Mondrup et al., 2014). By breaking down the IDMs into smaller IDM Packages, the use case-specific information exchange structures can be simplified.

Arguably, IDM Packages should be broken down into appropriate detail, where the Exchange Requirements (ERs) of each IDM Package are stable and independent of any specific AEC/FM project or organization. As a result, the need to define "optional ERs" should be eliminated. If that is not possible, the specific IDM Package is either not broken down sufficiently, or the information exchange is not absolutely necessary and, therefore, should not be required.

An IDM Framework methodology to define and organize sub-divided IDM Packages has been proposed (Mondrup et al., 2014). The IDM Framework builds on a simple matrix structure of AEC/FM disciplines (vertical axis) and project life cycle stages (horizontal axis) (Hall, 2012). This structure serves as an "umbrella", covering all main use cases of the AEC/FM project life cycle. Figure C-23 shows the IDM Framework structure.

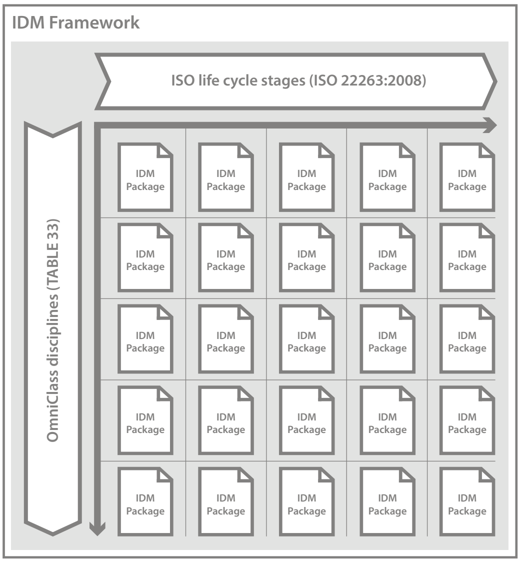

Figure C-23. IDM Framework structure.

Given that use cases generally are defined to establish a basis for IDM developments, each use case defined in the IDM Framework represents a specified IDM Package. Ideally, the IDM Framework should consist of an appropriate number of IDM Packages to efficiently support all main use cases of the AEC/FM project life cycle.

As shown, the IDM Framework disciplines build on the "OmniClass Construction Classification System Table 33 – Disciplines" (OCCS, 2012); project life cycle stages build on the "ISO 22263:2008 Organization of Information about Construction Works – Framework for Management of Project Information" (ISO, 2008). It is worth noting that ISO and OmniClass are not necessarily perfectly suited to the task; their purpose is to demonstrate one possible structure for the IDM Framework.

It is essential that the IDM Packages defined in the IDM Framework are generic and represent the AEC/FM industry's best practices, allowing for customization and adjustment to project-specific needs.

An important function of the IDM Framework is its ability to serve as a basis for defining an IDM Project Plan, in this way changing from from generic use to project-specific use. The IDM Project Plan, which is shown in Figure C-24, is created by selecting the specific generic IDM Packages required for the specific AEC/FM project. Ideally, this selection should be carried out, for example, via a customized, online IDM Project Plan generator.

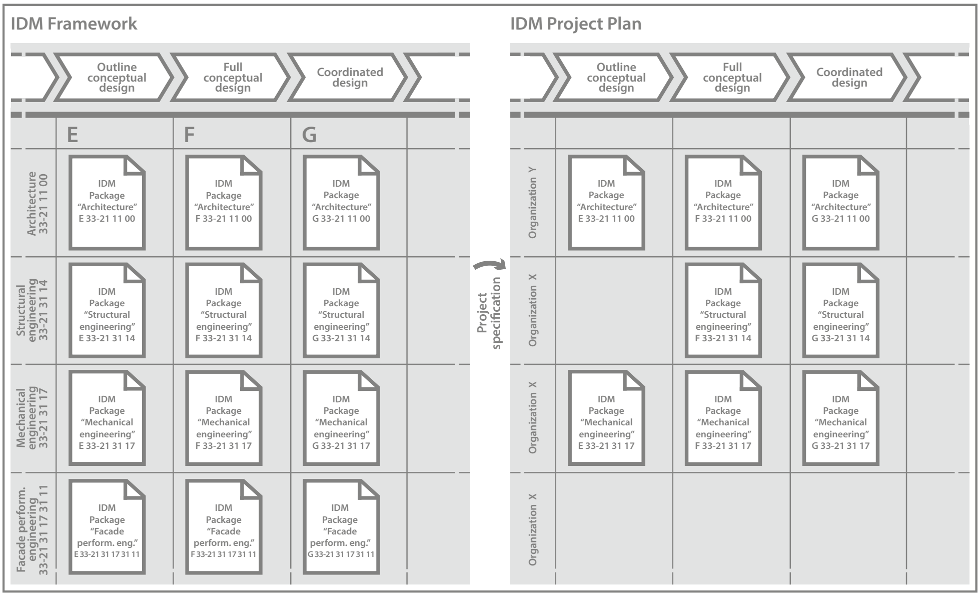

Figure C-24. IDM Framework and IDM Project Plan.

The IDM Project Plan provides an overview of the AEC/FM project scope, use cases to be carried out, and required information exchanges. In addition, the IDM Project Plan replaces OmniClass disciplines with project-specific organizations, thereby formalizing organizational interactions. Another advantage of the IDM Project Plan is its graphical form, which provides project managers with an overall view and helps them understand the interactions of the multiple use cases within the AEC/FM project.

Generally, the IDM Framework is constructed as a stable system, in which the Level of Development (LOD) of each IDM Package is defined according to the framework's AEC/FM project life cycle stages. This means that IDM Packages placed in, for example, the "Outline conceptual design" stage represents a lower LOD than IDM Packages placed in, for example, the "Coordinated design" stage.

In most AEC/FM projects, however, there is no strict correspondence between LODs and life cycle stages (Reinhardt & Bedrick, 2013). Building systems are developed at different rates and at different LODs. For example, design of façade systems is often well ahead of the design of HVAC systems. This calls for a flexible system, and the IDM Project Plan concept addresses this issue by allowing project managers to place IDM Packages separately and independently of their stage-specific origin in the project-specific IDM Project Plan. This means that, if necessary, IDM Packages taken from, for example,the "Coordinated design" stage of the IDM Framework can seamlessly be placed in, for example,. the "Outline conceptual design" stage of the IDM Project Plan.

When defining and organizing the multiple IDM Packages, focus should be on the full range of downstream and upstream impacts of stage-specific IDM Packages. Downstream IDM Packages are directly affected by what is produced by upstream IDM Packages (Anumba et al., 2010). For this reason, the subdivision of the ERs of each IDM Package into Input Requirements (IRs) and Output Requirements (ORs), and the ERMs into Input Requirements Models (IRMs) and Output Requirements Models (ORMs) is recommended. It could also be argued that IDM Packages should include IRMs and ORMs only, in this way supporting a digital approach.

C23.2.3 Model View Definition (MVD)

The Model View Definition (MVD) is the buildingSMART technical standard for documenting the information exchanges described in one or more IDMs. The MVD consists of four deliverables (See et al., 2012):

- MVD Description: The Description defines the information exchanges required for specific IDMs.
- MVD Concepts: The Concepts address these information exchanges, by linking with the IDM-specific ERMs/ECs.

- MVD Diagrams: The Diagrams identify and structure the IFC entities required for exchanging these Concepts.
- MVDXML: The MVDXML generates a machine-interpretable representation of the information exchanges.

Generally, MVDs are designed to enable IFC information exchange (See et al., 2012) and this is achieved by linking IDM-specific Exchange Requirements Models (ERMs) and Exchange Concepts (ECs) with the IFC data model standard. However, bearing in mind the concept of subdividing the ERMs into Input Requirements Models (IRMs) and Output Requirements Models (ORMs), the MVD should be developed based on IRMs and ORMs of specific IDM-packages.

Furthermore, MVDs are used for IFC software certification testing (Chipman et al., 2012). By combining the concept of IDM Packages and IRMs/ORMs with MVD-based IFC software certification testing, MVDs can be used to describe the precise information that a specific software tool should be able to import and export, as defined by any use case-specific IDM Package. As a result, software users can understand the capabilities and limitations of software tools in IFC-based information exchanges, including IFC-compatible BIM and BPS tools. Finally, the proposed IDM Framework will potentially consist of hundreds of IDM Packages with an equal number of associated MVDs. Consequently, for the purpose of software certification, the combination of multiple IDM Packages into each MVD is recommended.

C24. Survey

C24.1 Interview analysis

As stated by Aram et al. (2010), the involvement of industry experts is necessary in defining use case-specific Input Requirements Model (IRMs) and Output Requirements Model (ORMs). Therefore, interviews of relevant industry BPS experts have been conducted. These were used to satisfy the objective of identifying specific early-stage BPS use cases, and to specify the associated IRMs and ORMs. Interviews were analyzed using the predefined interviews questions guide as a basis. Only the key survey results are reported here due to restrictions on space.

C24.1.1 Stage one questions

Responses to stage one questions are summarized as follows:

- All surveyed BPS experts were engineers experienced in Building Information Modeling (BIM) and Building Performance Simulation (BPS).
- BPS experts represented large-scale international engineering or architectural consulting organizations.

C24.1.2 Stage two questions

Responses to stage two questions are summarized as follows:

- All surveyed BPS experts, irrespective of professional background, highlighted the importance of adopting BPS during the early stages of building design. The following quote indicates this: “It is very important that we are able to precisely evaluate the performance of different building designs…before important building characteristics are frozen.”
- Commonly performed early-stage BPS use cases included:
    - o How to orient the building?
        - Simulation: Exterior solar radiation, interior solar gains, and daylight distributions.
    - o Depth of space plan?
        - Simulation: Interior solar gains and daylight distributions.
    - o Window-to-wall ratio?
        - Simulation: Interior solar gains, daylight distributions, heat losses, glare, or overheating.
    - o Need for external solar shading?
        - Simulation: Interior solar gains, overheating, or cooling requirements.
- There are several software tools that can perform early-stage BPS. Based on survey responses, commonly used BPS tools in Denmark include Be10 (SBi, 2012), Ecotect (Autodesk, 2014a), DIVA-for-Rhino (Solemma, 2014), and IESVE (IES, 2014), and in the UK, Tas Engineering (EDSL, 2012) and IESVE.

C24.1.3 Stage three questions

Responses to stage three questions are summarized as follows:

- Generally, surveyed BPS experts found it difficult to precisely define the required input and output data for specific early-stage BPS use cases. Usually, they defined input and output requirements based on individual experience and/or the specific BPS tool: *“In our experience, when using BPS tools, such as IESVE, all parameters should, in principle, be inputted…to achieve satisfactory results. During the early stage, however, little information is available…therefore, we often use tool-specific presets or default values.”*
- Another issue was that of simplifying the information exchange structures for early-stage BPS; in particular, the BPS input data structure. Here, BPS experts highlighted the concept of defining critical BPS input parameters: *“Often, we only require a few critical parameters from the building designer…defining the remaining ourselves. Usually, this leads to a faster, more effective exchange process.”* Based on survey results, the critical BPS input parameters were defined according to the specific use case in question.

C24.1.4 Stage four questions

Responses to stage four questions are summarized as follows:

- Although BPS experts were generally interested in implementing the BIM-model as a data source for early-stage BPS, digital collaboration presented a number of technical challenges, for example, getting BIM and BPS tools to communicate properly. Therefore, early-stage information exchange often relies on non-technical, human-to-human communication.
- All BPS experts highlighted the potential of using standardized exchange formats such as the IFC data model standard. However, according to BPS experts, IFC information exchange appeared problematic: *"IFC geometry exchanges often bring geometric inequalities…resulting in simulation errors. Of course, these inequalities may be due to deficiencies in the IFC definitions...however, they could also be a result of defects in the given software tool or errors in the export/import…or perhaps inappropriate geometric modeling procedures?"*
- Surveyed BPS experts highlighted the issue of implementing common standards, such as the IDM, to support information exchange between BIM and BPS tools, particularly, when collaborating across AEC/FM disciplines. However, none of them used such standards in their day-to-day practices.

C24.2 Interview summary

Although many of the issues discussed echo the key points from the review, the survey gave greater insight into the practicalities of adopting early-stage BPS. Here, the respondents pointed out the potential of implementing BPS during the early stage, helping building design participants to understand the implications of their choices.

Several types of early-stage BPS use cases exist. However, based on survey responses, early-stage BPS use cases often focus on optimizing window (glazing) and façade systems, which generally have very large impacts on all aspects of building performance. Furthermore, façade designs, or building envelope designs, can significantly influence architectural building design values.

Information exchange between BIM and BPS tools – between building designers and BPS experts – appeared problematic. Therefore, there is a need for common standards that clearly identify and structure use case-specific information exchanges.

C25. IDM Package

C25.1 IDM Package deliverables

Based on the review findings and the results of the survey, and to demonstrate the general principles of the proposed methodology, an IDM package targeting façade performance engineering has been developed. This is a generic IDM Package, taken from the IDM Framework. To follow the specified OmniClass/ISO-based IDM Framework structure, the developed IDM Package is referred to as “Façade Performance Engineering F 33-21 31 17 31 11”. The number “33-21 31 17 31 11” represents the OmniClass discipline “Façade Performance Engineering”; the character “F” represents the ISO life cycle stage “Full Conceptual Design”. The “Façade Performance Engineering 33-21 31 17 31 11” discipline was coined for the present study, as a discipline under “33-21 31 17 31 HVAC Engineering”.

The façade performance engineering IDM Package consists of three main deliverables: (1) a description of the use case in question, (2) a formalization of the Process Map (PM), (3) a specification of the Input Requirements Models (IRMs) and Output Requirements Models (ORMs).

C25.1.1 Use case

The use case addresses early-stage façade performance engineering, which is used to provide building design participants with BPS-based predictions of the performance of building façade configurations, primarily to optimize the window-to-wall ratio. Optimizing the window-to-wall ratio for specific building designs plays an important role in improving a building’s energy and indoor environmental quality performance. BPS tools are used in the process to simulate alternative lighting/daylighting and thermal conditions.

Early-stage façade performance engineering involves a number of activities. In the present use case, these activities are clustered into two iterative blocks (activities 2.1-2.6; activities 4.1-4.3). The first block deals with preparation of the BPS model; the second block deals with simulation of the window-to-wall ratio. In this way, the use case facilitates iterative optimization and evaluation procedures.

As previously referenced, the generic IDM Package does not define the relationship between any specific project participants. Rather, it defines the relationship between a discipline, activities, and information exchanges.

C25.1.2 Process Map (PM)

Figure C-25 shows the PM for “Façade Performance Engineering F 33-21 31 17 31 11”, including the activities (numbered) and associated information exchanges. Activity ID numbers reference the descriptions in the following section.

Note that the IRMs/ORMs are supplemented with additional information/default values (ADDs). It is in keeping with the approach of simplifying information exchange structures, and the fact that only limited accurate information is available when performing early-stage façade performance engineering.

It is essential that IRM 2.1 and IRM 2.2 represent the results, the ORMs, of an upstream "3D site + building layout" IDM Package and a "3D space layout" IDM Package, respectively.

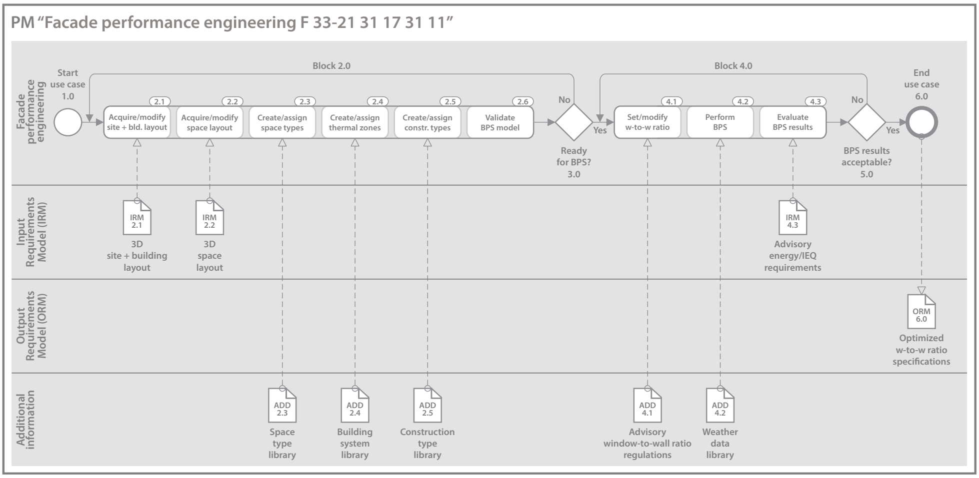

Figure C-25. PM for façade performance engineering (See Appendix A for larger scale PM).

C25.1.3 Input Requirements Models (IRMs) and Output Requirements Models (ORMs)
Table 2 describes the specific events, blocks, activities, gateways, and associated IRMs, ORMs, and ADDs included in the "Façade Performance Engineering F 33-21 31 17 31 11" IDM Package.

[See Table C-5 in next page] →

Table C-5. IRMs and ORMs.

ID	Description	Input Requirements Model (IRM)	Output Requirements Model (ORM)
1.0	**Event: Start use case** Start facade performance use case. Facade performance engineering is used to provide building design participants with predictions about the impact of various facade configurations on building performance.	**IRM 1.0** - Project identification - Project name	**ORM 1.0** -
2.0	**Block: Prepare BPS model** Prepare the BPS model for facade performance engineering in relevant BPS tool.	**IRM 2.0** -	**ORM 2.0** -
2.1	**Activity: Acquire/modify site and building layout** Acquire site and building layout from IRM 2.1 and modify it to comply with relevant BPS tool. Site 3D geometry should be represented by simplified surfaces, adjacent buildings 3D geometry should be represented by simplified outer volumes/exterior surfaces, and building 3D geometry should be prepresented by building elements/objects.	**IRM 2.1** - Site identification - Site location (global coordinates) - Site elevation (relative to sea level) - Site 3D geometry - Adjacent buildings geometry - Building identification - Building type - Building location (global coordinates) - Building elevation (relative to sea level) - Building orientation (true north) - Building elements identification - Building elements type - Building elements placement - Building elements 3D geometry	**ORM 2.1** -
2.2	**Activity: Acquire/modify space layout** Acquire space layout from IRM 2.2 and modify it to comply with relevant BPS tool. Space 3D geometry should include 2nd level space boundaries. At this point, the space layout (space types and their location) is defined for the complete building. The space layout/space identification should reference specific classification systems, such as OmniClass, CCS, etc.	**IRM 2.2** - Space identification - Space type - Space location - Space elevation (relative to sea level) - Space 3D geometry - Space boundaries (2nd level)	**ORM 2.2** -
2.3	**Activity: Create/assign space types** Create space types based on the modified space layout and assign additional information/default values from predefined space type library (ADD 2.3). The predefined space types drive assumptions for specific space performance characteristics (conditioning requirements, internal loads, operating schedules, etc). The predefined space type library may come from a viarity of sources, such as BPS tool-specific presets/templates or specific open access industry space type libraries.	**ADD 2.3** - Space conditioning requirements - Space occupant/equipment/lighting load - Space occupant/equipment/lighting schedule - Space thermal comfort criteria - Space ventilation criteria - Space ventilation design	**ORM 2.3** -
2.4	**Activity: Create/assign thermal zones** Create thermal zones based on space types and assign additional information/default values from predefined building system library (ADD 2.4). Thermal zoning strategies can differ significantly by space type. A thermal zone may be a single space, a multi-zoned space (space is divided into multiple thermal zones with different thermal profiles and conditioning requirements), or a group of spaces (group of spaces with similar thermal profiles and conditioning requirements are aggregated into a single thermal zone).	**ADD 2.4** - Thermal zone identification -Thermal zone type - Thermal zone conditioning requirements - Thermal zone HVAC type - Thermal zone HVAC schedule - Thermal zone thermal comfort criteria - Thermal zone infiltration rate	**ORM 2.4** -
2.5	**Activity: Create/assign construction types** Create construction types and assign additional information/default values from predefined construction type library (ADD 2.5). Allocate construction types to 3D building elements. The predefined construction types drive assumptions for specific construction performance characteristics (U-value, g-value, surface reflectance value, etc.). The predefined construction type library may come from a viarity of sources, such as BPS tool-specific presets/templates or specific open access industry construction type libraries.	**ADD 2.5** - Construction type - Material layer identification - Material layer type - Material layer U-value - Material layer composite U-value - Solar factor g-value - Visible transmittance value - Surface reflectance value - Shading value	**ORM 2.5** -
2.6	**Activity: Validate BPS model** Validate the modified BPS model. The validation should include model checking and conformance testing. This is preferably done by exporting an IFC file of the BPS model and using a relevant external model checking tool.	**ADD 2.6** -	**ORM 2.6** -

Table C-5. IRMs and ORMs (Continued).

ID	Description	Input Requirements Model (IRM)	Output Requirements Model (ORM)
3.0	**Gateway: Ready for BPS?** Is the BPS model ready for simulation? If the BPS model is not satisfactory, the BPS model preparation loop (Block 1.0) is repeated. If the BPS model is satisfactory, the BPS model is passed on.	**IRM 3.0** -	**ORM 3.0** -
4.0	**Block: Simulation window-to-wall ratio** Simulate the window-to-wall ratio in relevant BPS tool. Computational window-to-wall ratio optimization includes energy consumption and indoor environmental quality simulations (investigating a single space or multiple spaces/a complete building).	**IRM 4.0** -	**ORM 4.0** -
4.1	**Activity: Set/modify window-to-wall ratio** Set the window-to-wall ratio and, as a starting point, modify it to comply with advisory regulations (ADD 4.1). Window-to wall ratio optimization greatly depends on the simulation context (climatic conditions, adjacent buildings, building type, space type, etc.). Accordingly, window-to-wall ratio optimization requires iterative optimization/simulation loops.	**IRM 4.1** - Advisory window-to-wall ratio regulations	**ORM 4.1** -
4.2	**Activity: Perform BPS** Perform the window-to-wall ratio simulation, testing the selected window-to-wall ratio. For window-to-wall ratio simulations in BPS tools a simulation weather file is required. Weather data may come from a viarity of sources, such as Typical Meteorological Year (TMY3) or International Weather for Energy Calculations (IWEC). Window-to-wall ratio simulations predict energy consumption figures and indoor environmental quality levels (as influenced by the selected window-to-wall ratio).	**IRM 4.2** - Weather data	**ORM 4.2** -
4.3	**Activity: Evaluate BPS results** Evaluate the BPS results against predefined advisory energy consumption and indoor environmental quality requirements. Determine if the BPS results are accurate and reliable.	**IRM 4.3** - Advisory energy consumption/IEQ requirements	**ORM 4.3** -
5.0	**Gateway: BPS result acceptable?** Are the BPS results acceptable? If the BPS results are not satisfactory, the window-to-wall ratio is modified, and the BPS simulation loop (Block 4.0) is repeated. If the BPS results are satisfactory, and the energy consumption and indoor environmental quality requirements are accepted, the use case is ended.	**IRM 5.0** -	**ORM 5.0** -
6.0	**Gateway: End use case** End facade performance engineering use case. Optimized window-to-wall ratio specifications are passed on.	**IRM 6.0** -	**ORM 6.0** - Window-to-wall ratio specifications

C26. MVD Package

C26.1 MVD deliverables

In this study, we focus on the development of an IDM Package for early-stage façade performance engineering. Although out of the scope of this study, the next step should be to define an associated MVD consisting of four deliverables: (1) a description of the identified IRMs, ORMs, and ADDs, (2) a specification of the associated Concepts, (3) a specification of the IFC-binding Diagrams, and (4) a conversion into MVDXML format. Figure C-26 shows an example MVD Diagram for the IRM 2.1 (site layout only). Here, selected IRMs, ORMs, and ADDs are linked with subsets of the IFC data model standard. The structure of the MVD Diagram is similar to that proposed in (See, 2011).

Finally, the “Façade Performance Engineering 33-21 31 17 31 11” IRMs, ORMs, and ADDs may already be included in existing MVDs, for example, in the “IFC Coordination View Version 2.0” MVD (buildingSMART, 2011).

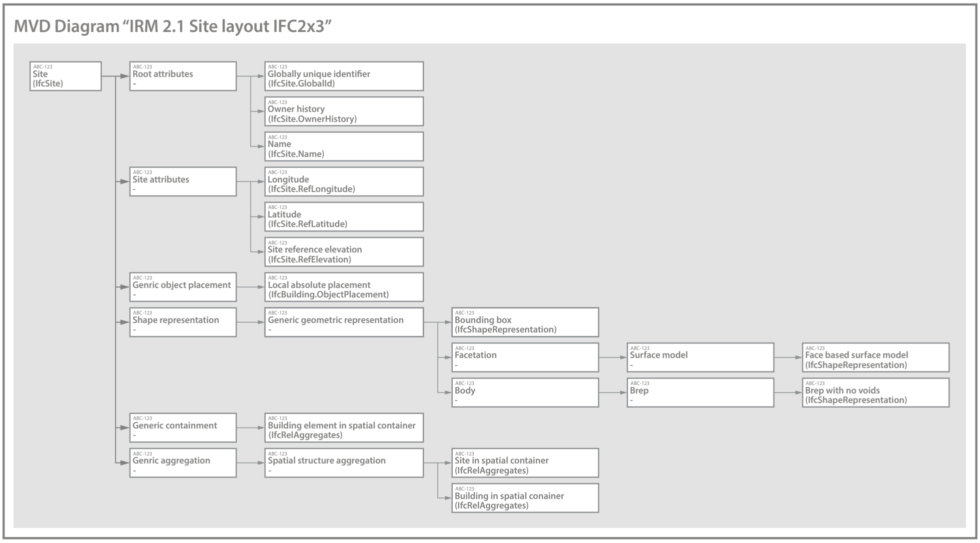

Figure C-26. MVD Diagram for IRM 2.1 (See Appendix B for larger scale MVD Diagram).

C27. Conclusions

C27.1 Conclusions

It is widely acknowledged that BPS offers most benefits if implemented in the early stages of building design. However, the process of early-stage BPS is not always practical as most BPS tools require detailed information, which is not necessarily available in the early stage, and information exchange between BIM and BPS tools often appears problematic. Therefore, to maximize the potential of early-stage BPS, a detailed specification of use case-specific activities and associated information exchanges is required.

In this study, we emphasized the critical role of implementing IDMs as a basis for specifying such activities and exchanges. To show the benefits of this approach, we presented an overview of a newly developed IDM Package for early-stage façade performance engineering. The façade performance engineering IDM Package has three merits: (1) it provides a basis for improved communication between building designers and BPS experts, because they will gain a common and more complete understanding of the specific façade performance engineering activities and associated information exchange structures, (2) it provides a basis for improved, and consistent information exchange between BIM and BPS tools, because the information needed by and resulting from façade performance engineering is detailed and defined, and (3) it provides a basis for façade performance engineering MVD development, enabling MVD-based software certification testing of relevant BIM and BPS tools.

Using the example of façade performance engineering to illustrate the general concept, generic IDM Packages are generally evaluated as a useful methodology for identifying and specifying use case-specific activities and associated information exchange structures.

Acknowledgements

The authors would like to thank all the people and organizations involved in this study, particularly the interview participants who gave their opinions and insights. The work presented in this study was performed in the scope of the corresponding author's PhD study at the Technical University of Denmark (DTU), Denmark.

[See Appendix A and Appendix B in next page] →

Appendix A

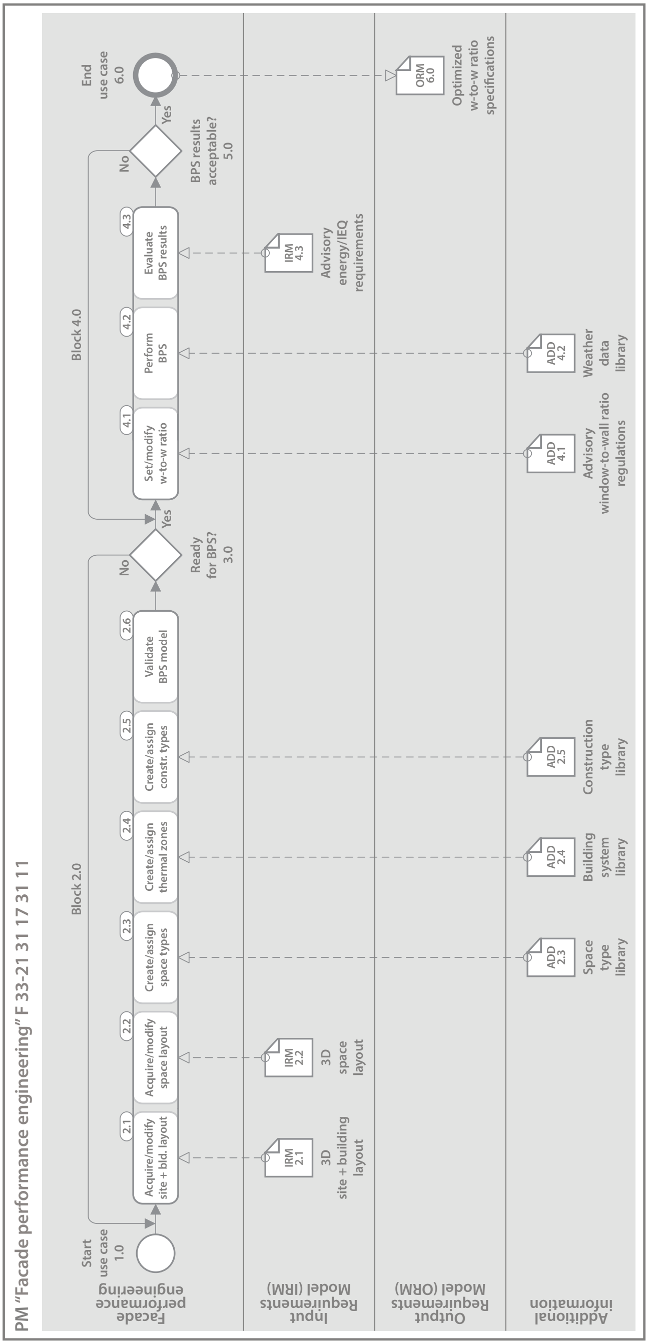

Figure C-A. PM for façade performance engineering.

Appendix B

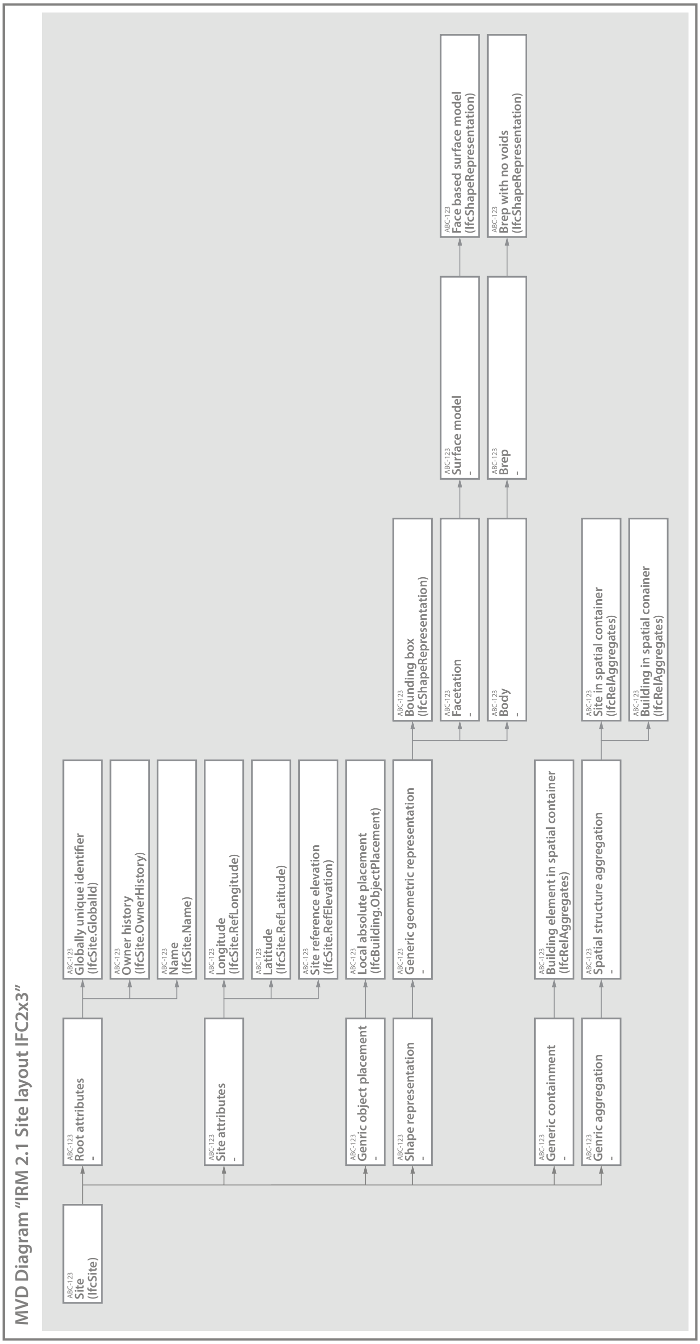

Figure C-B. MVD Diagram for IRM 2.1.

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Part D

Conclusions

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D1. Conclusions

D1.1 Summary

This thesis dealt with issues of Architecture, Engineering, Construction, and Facility Management (AEC/FM) communication and Building Information Modeling (BIM) and Building Performance Simulation (BPS) adoption. Two thematic studies and five scientific papers formed the basis for: (1) a series of high-level studies (thesis Part B), and (2) a series of detailed studies (thesis Part C).

D1.1.1 High-level studies

Cross-border AEC/FM communication and collaboration, and BIM adoption were the key issues of the high-level studies. Here, it was demonstrated that:

- International differences in design and construction traditions, organizational roles and responsibilities, work environments, and regulations hamper cross-border AEC/FM communication, lead to misunderstandings, and limit the potential for information sharing and knowledge transfer. Therefore, international cross-border AEC/FM communication and collaboration require extraordinary focus on harmonization efforts and support instruments [Thematic study #1].
- Cross-border harmonization efforts may include development of common AEC/FM communication and collaboration standards. To develop these standards, it is recommended that International AEC/FM standards are used as a foundation [Thematic study #1].
- Using the example of international cross-border AEC/FM collaboration, communication support instruments, such as the developed www.bygbygg.org website, are generally evaluated as useful methodologies for cross-organizational and/or cross-discipline AEC/FM communication and collaboration enhancement [Thematic study #1].
- Integrated BIM approaches have the potential to improve AEC/FM communication and collaboration. BIM is by its nature multidisciplinary and therefore brings AEC/FM project participants together, creating constant communication. Furthermore, BIM is a socio-technical system, combining technical structures and social practices [Scientific Paper #1].
- BIM adoption leads to a number of technical challenges, for example, getting BIM-compatible tools to communicate properly. Therefore, there is a need for common

IT regulations and standardized information exchange formats, for example, the Industry Foundation Classes (IFC) data model standard. In addition, BIM adoption leads to organizational change, for example, changes in work practices and interpersonal dynamics. Therefore, there is a need for extensive preparation and training of AEC/FM project participants [Scientific paper #1].

- Efficient and effective BIM adoption requires common BIM standards and execution guidelines that: (1) cover all audience levels and communicate with all AEC/FM disciplines, (2) provide guidance on technical issues and social behaviors, (3) consist of concrete, adaptable examples, (4) are simple and clearly articulated, and (5) available online. Notably, the potential benefits do not lie in simply setting common BIM standards. Rather, the benefits lie in the implementation and continuous development of the standards by AEC/FM project participants [Scientific paper #1].

D1.1.2 Detailed studies

AEC/FM information exchange specification and early-stage BPS adoption were the key issues of the detailed studies. Here it was demonstrated that:

- The presented space and thermal zone identification concept can assist in communicating space layout plans and thermal zoning strategies between AEC/FM project participants. In addition, the space and thermal zone identification concept supports integrated BIM approaches, by means of machine-readable identification coding rules [Thematic study #2].
- Integrated BPS approaches have the potential to improve building performance prediction. BPS is a useful methodology for simulation-based, energy and indoor environmental quality conscious building design decision-making. In addition, BPS can assist in communicating and presenting building performance information. Efficient and effective BPS adoption, however, requires special attention to identification and specification of information exchange structures; in particular, BPS input data structures [Scientific paper #2].
- Information exchange between BIM and BPS tools often appears problematic. BIM and BPS tools produce and exchange information in various formats, which, due to their commercial nature, are proprietary and have varying degrees of accessibility. Therefore, to achieve optimal interoperability, BIM and BPS tools should refer to a common exchange reference model, for example, the IFC data model standard [Scientific paper #3].
- IFC space boundary geometry exchange between BIM and BPS tools leads to a number of challenges, for example, irregularities in tool-specific geometry conversions and modeling approaches. Therefore, there is a need for standardized IFC information exchange specifications and detailed BIM-to-BPS modeling guidelines. In addition, it is recommended that model checking and IFC certification testing are given a high priority [Scientific paper #3].

- Information Delivery Manuals (IDMs) provide a common methodology to specify and communicate AEC/FM processes and associated information exchanges. However, IDMs in current use mainly capture multifaceted and wide-ranging processes, and therefore involve complex information exchange structures. As a result, current IDMs are difficult to manage and complicated to implement in real-world AEC/FM projects. Therefore, it is recommended that IDMs are broken down into smaller, more manageable IDM Packages [Scientific paper #4].
- The developed IDM Framework facilitates a common methodology to define and organize generic IDM Packages. The IDM Framework builds on a simple matrix structure of AEC/FM disciplines and project life cycle stages. Ideally, the IDM Framework should consist of an appropriate number of IDM Packages to efficiently support all main processes of the AEC/FM project life cycle. An important function of the IDM Framework is its ability to serve as a basis for developing an IDM Project Plan. The IDM Project Plan is created by selecting the specific IDM Packages required for the specific AEC/FM project. In this approach, the IDM Project Plan can assist in communicating the overall scope of the AEC/FM project, processes to be carried out, organizational interactions, and required information exchanges. [Scientific paper #4].
- Model View Definitions (MVDs) provide a common methodology to technically document required information exchanges defined in one or more IDMs. In addition, MVDs are designed to support IFC software certification testing. By combining the concept of IDM Packages with MVD-based IFC software certification testing, MVDs can be used to describe the precise IFC information that a specific AEC/FM software tool should be able to import and export, as required by use case-specific IRMs and ORMs [Scientific paper #4].
- The developed façade performance engineering IDM Package facilitates a common methodology to define and specify the precise activities and information exchanges required for early-stage, BPS-based window-to-wall ratio optimization. The IDM Package is particular effective at simplifying information exchange structures, thereby supporting early-stage BPS adoption. In addition, the IDM Package provides a basis for developing a façade performance engineering MVD. Ultimately, the IDM Package should advance all façade performance engineering communication and collaboration channels: human-to-human, human-to-computer, and computer-to-computer [Scientific paper #5].

D1.2 Contributions

This thesis contributed to original knowledge by firstly providing insight, in-depth understanding, and complex reflection on AEC/FM communication and BIM and BPS adoption. Secondly, it presented multiple instrument and methodology developments, including the AEC/FM communicative website, the space and thermal zone identification concept, the BPS-based retrofit design methodology, the modular IDM Framework, and the façade performance engineering IDM Package. It is important to note that the instrument and methodology developments propose adjustments to already well-established AEC/FM procedures and practices. However, implementation of the developed IDM Framework, including multiple specified IDM Packages, will help to reduce possible information gaps and losses between BIM and BPS-based AEC/FM processes (see Figure D-1), and thereby leads to improved BIM and BPS adoption, and eventually improved AEC/FM communication and building performance prediction.

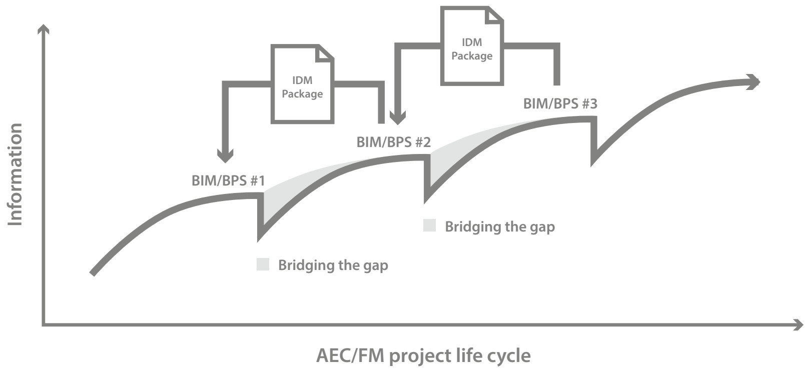

Figure D-1. Bridging BIM and BPS-based AEC/FM information gaps.

D1.3 Future studies

This thesis offers several possibilities for future studies. For example, “Buildings and BIM” and “Energy and indoor environmental quality” mappings should be extended with mappings to equivalent International conditions, in this way supporting Danish-Swedish-International AEC/FM communication and collaboration [Thematic study #1, Scientific paper #1].

Future areas of focus should also include testing of the space and thermal zone identification concept. Testing should be carried out through real-life AEC/FM projects, so that the identification system is systematically validated and fine-tuned for actual implementation [Thematic study #2].

In addition, future studies should focus on further refinement of the IDM Framework, and development of additional IDM Packages. This requires detailed studies of activities and information exchange structures for selected, decomposed AEC/FM processes. Finally, the IDM Framework and IDM Packages should be tested through real-life AEC/FM projects, in order to prove validity of the methodology [Scientific paper #4, Scientific paper #5].

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