Aalto University
School of Science
Degree Programme in Industrial Engineering and Management

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Transferring best practices enabled by Building information modeling (BIM) in Architecture, Engineering and Construction (AEC) to shipbuilding industry: An explorative study

Espoo, 12/5/2015

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AALTO UNIVERSITY SCHOOL OF SCIENCE Degree Programme in Industrial Engineering and Management	ABSTRACT OF THE MASTER´S THESIS

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<tr><td>Number of pages:
88</td><td>Date:</td><td>Library location:
TU</td></tr>
<tr><td colspan="2">Professorship:
Computer Integrated Construction</td><td>Code of professorship:</td></tr>
<tr><td colspan="3">Supervisor:
Professor Vishal Singh</td></tr>
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M.A. Markus Ahola, Professor Jan Holmström</td></tr>
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This thesis was carried out as a part of Triad 2014 - the joint master's thesis project of Cruise and Ferry Experience program, Aalto University. Meridiem funded and actively supported Triad 2014. This research explored the best practices enabled by Building information modeling in Finnish AEC industry and the current state of 3D CAD tools in Finnish shipbuilding industry. Furthermore, discussions were carried out on whether these best BIM-enabled practices can be transferred to the shipbuilding industry.

Data were collected by in-depth interviews with seven BIM experts and seven shipbuilding professionals in Finland. The top four BEPs mentioned by BIM experts were clash detection, visualization, quantity takeoff and scheduling. Through interviews with shipbuilding professionals it was found that the same CAD tool is used by different design disciplines in a shipbuilding project, i.e., the "one CAD" solution. In spite of benefits such as better design coordination and comprehensive collision detection, two major limitations of the solution, i.e., the lack of an open standard and the interior design is carried out with 2D CAD tools were identified.

Compared with BIM, 3D CAD in shipbuilding industry can carry out more comprehensive collision detection. Besides, shipbuilding industry also has a longer history of utilizing object-oriented 3D modeling. Both 3D CAD and BIM can generate high-quality quantity takeoffs. Scheduling in shipbuilding is conducted by specialized project management software other than 3D CAD. For future research aiming at increasing the productivity of shipbuilding industry, the identified limitations of current 3D CAD tools can be good starting points.

Keywords: BIM, 3D CAD, AEC, shipbuilding	Publishing language: English

Acknowledgements

The present thesis is carried out as a part of Triad 2014 - the joint master's thesis project of Cruise and Ferry Experience Program, Aalto University. I am extremely grateful for the thesis opportunity given by the program and the support from all the program memebrs. In addition, I am very thankful for the funding, networking and enjoyable working enviroment provided by Meridiem.

I would especially like to thank my supervisor, Professor Vishal Singh, who has inspired me and motivated me throughout the process. His advice and guidance has been extremely valuable. I would also like to express my gratitude to my instructor, Markus Ahola, for selecting me as Triad member and the generous support he has given. Besides, I would like to thank Pekka Puranen and Jarno Soinila from Meyer Turku for helping me finding the interviewees. I am also very grateful for the involvement of all the 14 interviewees. The thesis would not have been completed without their help.

My studies at Aalto have been nothing but wonderful. I would like to thank Professor Jan Holmström, who has helped to find such a great thesis project and supported me throughout my studies. I am also thankful for all the friends, colleagues and teachers I have met at Aalto, who have accompanied me in this wonderful and adventurous journey. I am more than lucky to know all of you.

Finally, I would like to express my deepest gratitude to all my family members for giving me their unconditional love and support.

Thank you.

Espoo, 06.06.2015

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Terms and abbreviations

BIM	Building Information Modeling
AEC	Architecture, Engineering and Construction – industry sector and activity
BEP	BIM-enabled practice
IFC	Industrial Foundation Class
CAD	Computer Aided Design

1 Introduction

1.1 Background of the study

Building information modeling (BIM) is one of the most promising recent developments in the architecture, engineering and construction (AEC) industry (Azhar, 2011). For the AEC industry that has been facing barriers and challenges to increase productivity, efficiency, quality and for sustainable development, BIM adoption is becoming an increasingly important matter (Arayici et al., 2011). Since its introduction in the last couple of decades, BIM has been considered essential in the AEC and the real-estate industries to manage, share and exchange information among project stakeholders, such as architects, engineers, contractors, owners and facility managers (Eastman, 1999).

Compared with traditional computer-aided design (CAD), BIM is neither simply a virtual representative of a real project nor a static encapsulation for project information. It transforms the paradigm of the AEC industry from 2D based drawing and information systems to 3D object based information systems (Mihindu & Arayici, 2008). Moreover, BIM provides dynamic decision-making information throughout the project lifecycle. The encapsulated information in BIM synchronizes with AEC practices ranging from design, execution, operation, maintenance, through to renovation (Lu & Li, 2011). In general, BIM is not only an advanced design tool, but also an efficient management tool that benefits all aspects of AEC projects.

Today, both in the academia and in the industry, BIM has attracted a lot of interest. People generally have very high expectation on BIM and see it as an advanced technology that is going to revolutionize the AEC industry. For instance, according to Vanlande et al. (2008), BIM has the potential to be the facilitator for integration, interoperability and collaboration in the future of the building industry. It is believed that BIM is changing the traditional AEC practices in a broader sense in terms of people, process, working culture, communication, business models, etc. Some even suggest the traditional AEC practices are facing a paradigm shift with the wider application of BIM

(Lu & Li, 2011). Nevertheless, for some BIM is simply a good tool that can help to make AEC processes more efficient, but the full potential are yet to be exploited in practice.

Although the goal of the single building information model has existed for at least 30 years and various standards have been published leading up to the 10-year development of the industry foundation classes (IFC) (Howard & Björk, 2008), it was not until recent years that there has been rapid expansion of BIM adoption in the AEC industry (Lu & Li, 2011). BIM development has also been emphasized by the government authorities and regulatory boards on a national level to improve software interoperability and cooperation among actors in the building industry. For instance, in Finland, there has been a major commitment by the public sector and large AEC process stakeholders to IFC usage (Howard & Björk, 2008). .

In general, the adoption of BIM in Finland is more advanced than the majority of the world. Companies in Finnish AEC industry are generally devoted to the usage of BIM in AEC projects. According to Finnish BIM survey 2013, 67 percent of the over 400 respondents were currently using BIM and 92 percent would use BIM in five years' time. BIM has been adopted in various projects in Finland, including new and renovation projects, as well as big and small-scale projects. For instance, Helsinki music center project (2004-2011) was the biggest BIM project in Finland. BIM was adopted throughout the whole project from design to construction phase, and the project has influenced all the BIM guidelines in Finland (Henttinen, 2012). The ongoing Helsinki Olympic Stadium renovation project has also adopted BIM. The stadium will be closed for renovation work from the end of 2015 and is estimated to reopen in 2018. The stadium will retain the 1930's architecture, but everything "under the skin" will be rebuilt.

Commercial ship design and production is constantly under the pressure to reduce time to market, reduce overall production costs, and improve the product quality across multiple performance criteria (Bronsart et al., 2005). In the first half of the twentieth century, European shipyards dominated global shipbuilding markets. However, overall, there was a major shift in global shipbuilding and general relocation of shipbuilding activity from Europe to East Asia in the latter half of the twentieth century (Poulsen et al., 2011). Due to the globalization and progress of technology, the European shipbuilding industry has undergone a fundamental shift from a mainly labor-intensive industry to a capital and know-how dominated high-tech industry, relying on the availability of highly-skilled workforce (Tholen & Ludwig, 2006). As a traditional member of the European shipbuilding industry, the Finnish shipbuilding industry has also undergone this fundamental shift.

In order to produce a ship design that satisfies the customer's requirements, a large number of software tools are used in each stage of the design process to evaluate a variety of characteristics and life phases (structural, operational performance, production scheduling, etc.) (Whitfield et al., 2003). Among these tools, CAD software has been an indispensable tool for designers to carry out design work successfully. In the shipbuilding industry, different CAD systems are used for different design domains, structure, and outfitting (Li et al., 2011). Since its introduction in the 1970s, these CAD tools have gradually evolved from 2D to 3D. Nowadays, there are various 3D CAD tools in the market that are specialized in ship design, such as Cadmatic, Tribon, Aveva, Napa, etc.

In spite of the demonstrated benefits of 3D CAD tools, in recent years, it has been widely acknowledged in shipbuilding industry that certain limitations of CAD tools have hindered the development of the design process. Both software vendors and researchers in shipbuilding industry are actively searching for better solutions. As AEC industry and shipbuilding industry share many similarities (e.g., involve complex engineering processes, require collaboration of numerous multidisciplinary team members, and take long time from delivery to completion), shipbuilding professionals are interested in learning from the AEC industry. Since BIM is currently the most topical theme in AEC industry, which is described as an efficient design and management tool, it is desirable to study whether BIM can be adopted in shipbuilding industry. In other words, it is important to study if, and how, BIM knowledge from AEC can be implemented in the shipbuilding industry.

This thesis is carried out as a part of Triad - the joint master's thesis project of Cruise and Ferry Experience program (CFE). The CFE program is a research program held by Aalto Unviersity Marine Technology research unit and is concerned with research and education between all six schools of Aalto University in passenger ship context. Companies and research institurions such as Meyer Turku (formerly known as STX Finland), Foreship, Royal Caribean, Meridiem, etc, have been actively supporting and involved in the CFE porgam. In year 2010, the program initiated Triad, a yearly organized project that connects students from different fields to work on their master's theses from a equivalent topic in passenger ship context. The common topic of Triad 2014, in which this thesis was begotten, is BIM and shipbuilding. Three students from differnet departments of Aalto participated in Triad 2014, including one doctoral candidate from Department of Strutural Engineering, one master's candidate from Department of Applied Mechanics and the author, master's candidate from Department of Industrial Engineering and Management. In general, the multidisciplinary research enviroment resulted in great synergy among Triad 2014.

1.2 Research objectives

The current research mainly aims at: (1) exploring the realized practical benefits of BIM in AEC industry and (2) studying whether BIM can be a potential solution to improve the productivity of shipbuilding projects.

Although BIM has been widely discussed in the academia and the AEC industry, benefits of BIM may be over exaggerated, due to commercial purpose (of software vendors), steep expectations on BIM (e.g., people believe that BIM is going to revolutionize the AEC industry, which is clearly an unrealistic expectation in incoming years), and the increasing popularity of BIM adoption that has been propelled by the inefficiency of AEC industry. Thus, in order to find out how BIM actually contributes to improving the productivity of AEC industry, i.e., how AEC projects benefit from the utilization of BIM, it is worthwhile to study not only the literature, but also obtain experts' views on BIM. In the context of this research, experts are practitioners who have been closely involved in the utilization of BIM, for instance, BIM consultant, BIM researcher, BIM software vendor, etc. Moreover, in order to achieve a high level of practicality, the research only focuses on practices enabled by BIM that have been put into use in AEC projects. These practices are named as best BIM-enabled practices (BEPs) in the context of this research.

Due to the lack of communication between AEC and shipbuilding industries, AEC professionals generally have limited knowledge of shipbuilding industry. Likewise, shipbuilding professionals' understanding of AEC industry is limited. Therefore, in order to achieve the second research objective, i.e., studying which BEPs can be a potential solution to improve the productivity of shipbuilding projects, the current state of 3D CAD tools in shipbuilding industry must be examined. Literature study on 3D CAD in shipbuilding industry should be performed first to form the background of the research. Besides, it is also important to look into the views of shipbuilding professionals. They have been working extensively with 3D CAD tools, and hence, they understand how these tools are utilized in shipbuilding projects. After building a comprehensive understanding of the current state of 3D CAD in shipbuilding industry, the next step is to study which BEPs have the potential to be transferred to shipbuilding industry and help improve the efficiency of shipbuilding process.

The formulation of the research objectives leads to four main research questions. The first research question discovers the benefits of BIM based on existing literature. This question is mainly addressed in the literature review chapter. The second research question aims at exploring the best BEPs based on BIM experts' views. It is built on the basis of research question 1 and is addressed in empirical study. The third research question studies the current state of 3D CAD software in shipbuilding industry and identifies the utilization of these software applications in shipbuilding projects. This question relates to both the existing literature and views of shipbuilding professionals. Therefore, it is addressed in both literature and empirical studies. The fourth research question concerns the transferability of identified BEPs to shipbuilding industry. It also summarizes the research results and discusses theoretical and practical implications. This question is addressed in the last two chapters.

RQ 1: What are the benefits of BIM in AEC industry?

RQ 2: What are the best BIM-enabled practices in AEC industry in Finland?

RQ 3: What is the current state of 3D CAD in shipbuilding industry? How are 3D CAD tools utilized in shipbuilding projects in in Finland?

RQ 4: Which best BIM-enabled practices can be transferred to shipbuilding industry?

1.3 Research scope and limitations

The research focuses on two industries, i.e., AEC industry and shipbuilding industry. Recruited interviewees and the companies they represent are either Finnish or based in Finland. Therefore, the results of the empirical study mainly represent the current status of BIM in Finnish AEC industry and the utilization of CAD software Finnish shipbuilding industry.

Due to the qualitative research method, geographical/cultural influence and the author’s understanding of AEC and shipbuilding industries, this research have following limitations:

- Although adoption of face-to-face interviews enabled the collection of more in-depth information on the topic studied, as well as a more comprehensive view, it also limited the number of participants compared to quantitative research methods such as questionnaire survey. Thus, findings from face-to-face interviews are possible to be influenced by the subjective views of the participants.
- In spite that interviewees recruited for this study are BIM experts and shipbuilding professionals and have been involved in projects of different scales and with international relevance (i.e., developing projects for both Finnish and

overseas markets and participating in the international cooperation), because the interviews were conducted within Finland and the participants were based in Finland, the findings therefore may be influenced by the specific perception and culture of practices in this region.

- Since the author is a master's candidate at the Department of Industrial Engineering and Management, her knowledge of AEC and shipbuilding industries is limited. Therefore, in spite that the interviews were carried out successfully, the contents of the interviews might not be in-depth enough. Besides, findings from the interviews are possible to be influenced by the author's ability to capture and comprehend the subtle or in-depth information delivered by the interviewees.

1.4 Structure of the thesis

The research objectives were addressed in two stages: 1. the literature study, 2. the empirical study. Based on the research objectives and research questions, the structure of this thesis is summarized in Figure 1.

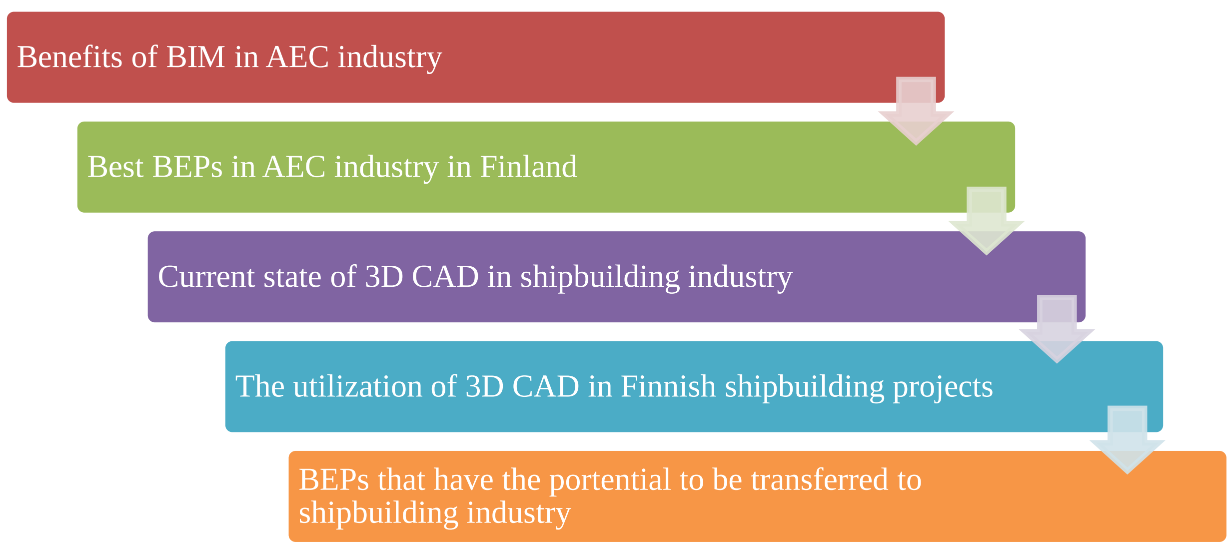


Figure 1 Structure of the thesis

In the following chapter, the literature study is divided in to two sections. In the first section (2.1) definitions of BIM are studied. Besides, a thorough literature review on benefits of the utilization of BIM in AEC industry is carried out. The second section (2.2) of the literature review focuses on the current state of 3D CAD in shipbuilding industry. Both benefits and limitations of current 3D CAD tools are discussed.

Chapter 3 presents the methodology of the thesis. It thoroughly explains the data collection method adopted and how were the interviews carried out.

Chapter 4 describes the results of the empirical study. It is divided into two sections. In the first section (4.1), based on the results of interviews with Finnish BIM experts, a list of BEPs is compiled and the top four frequently mentioned BEPs are further studied. In the second section (4.2), results of interviews with shipbuilding professionals are presented. The utilization of 3D CAD tools in Finnish shipbuilding industry is discussed. Areas that need further development are identified.

In the discussion and implications chapter (5), the transferability of BEPs is studied, i.e., which of the identified BEPs can be transferred to shipbuilding industry. It also includes the theoretical and practical implications for future research.

2 Literature review

The literature review of this study consists of two parts. This first part is a literature review on BIM in AEC industry, which built a theoretical basis for further empirical study on the utilization of BIM. In order to establish understanding of software development in shipbuilding industry, the second part focused on 3D CAD in shipbuilding industry. The sources of reviewed literature included academic publications, white papers and technical reports from software vendors, guidelines and reports generated by professional groups, government and other regulatory bodies. Besides, in order to build an up-to-date view, online articles related to latest development of BIM and shipbuilding software applications written by well respectable experts were also reviewed.

2.1 BIM in AEC industry

Building information modeling (BIM) is one of the most promising recent developments in the AEC industry (Azhar, 2011). Since it is introduced in the last few decades, BIM has been believed to be essential in AEC and the real-estate industries to manage, share and exchange information among project stakeholders, such as architects, engineers, contractors, owners and facility managers (Eastman, 1999).

2.1.1 Definitions of BIM

So far, there is no universal definition of BIM. One reason for this is that: there are various professionals involved in AEC project, such as contractors, architects and engineers. These professionals playing different roles at different stages of the AEC project, and thus they have different focuses on BIM. Therefore, their perceptions of BIM highly depend on their roles in the project life cycle. As Aranda-Mena et al. (2009) noted in their evaluation of the business sense of BIM, “For some, BIM is a software application; for others it is a process for designing and documenting building information; for others it is a whole new approach to practice and advancing the profession which requires the implementation of new policies, contracts and relationships amongst project stakeholders.”

Academics, professional groups and software vendors also have their own definitions of BIM. As Barlish and Sullivan (2012) noted in their study on how to measure the benefits of BIM that, “In fact, most publications attempt to define BIM in their own terms and, with over 1000 publications on this topic, BIM takes on a variety of definitions”. For instance, Succar (2009) has defined BIM as “a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle.” The McGraw Hill “The Business Value of BIM” Report (2009), a commonly referenced document by contractors, defines BIM as, “The process of creating and using digital models for design, AEC and/or operations of projects.” According to Autodesk (2015), “BIM is an intelligent model-based process that provides insight to help you plan, design, construct, and manage buildings and infrastructure."

One of the most widely accepted definition of BIM comes from the National Building Information Model Standard Project Committee (NBIMS-US, 2015):

> *Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*

2.1.2 Benefits of BIM

BIM has become an overwhelming topic in AEC industry in recent decades. Both theoretical and technological developments of BIM suggest that it will generate numerous benefits over the whole lifecycle of building; it is not only useful for geometric modelling of a building, but it can also assist in improving the building performance as well as the management of AEC projects (Bryde et al., 2014). Nowadays, BIM is increasingly being used in high profile large-scale AEC projects (e.g., London 2012 Olympic 6,000 seating Velodrome cycle track and the renovation of Sydney Opera House). Meanwhile, BIM is also used on individual components of projects of a smaller scale. For example, the modular stairs in the new bus station at Slough, UK, that was officially opened in June 2011 was designed and fitted using BIM (Buildoffsite, 2011). The advent and proliferation of BIM in AEC industry has produced a wealth of information related to its use and implementation. There are numerous studies on the benefits of BIM carried out in the industry and in academia (CRC, 2007; Azhar, 2011; Barlish & Sullivan, 2012; Becerik-Gerber & Rice, 2010).

As Cooperative Research Center (CRC) for AEC Innovation summarized in their publication on adoption BIM for facility management in 2007, the key benefit of BIM is its accurate geometrical representation of the parts of a building in an integrated data environment. Other related benefits are:

- *faster and more effective* processes — information is more easily shared, can be value-added and reused
- *better design* — building proposals can be rigorously analyzed, simulations can be performed quickly and performance benchmarked, enabling improved and innovative solutions
- *controlled whole-life costs and environmental data* — environmental performance is more predictable, lifecycle costs are understood
- *better production quality* — documentation output is flexible and exploits automation
- *automated assembly* — digital product data can be exploited in downstream processes and manufacturing
- *better client service* — proposals are understood through accurate visualization
- *lifecycle data* — requirements, design, AEC and operational information can be used in *integration of planning and implementation processes* — government, industry and manufacturers have a common data protocol

Barlish and Sullivan (2012) also conducted a study to analyze the benefits of BIM through an in-depth literature review. After analyzing over 600 sources of information, they identified 21 sources that were relevant to the benefits of BIM utilization. Based on the literature review, a key list was then compiled of the top mentioned benefits of BIM. See Table 1– Literature review – top mentioned benefits.

Table 1 Literature review – top mentioned benefits (adapted from Barlish and Sullivan, 2012)

Benefit	Frequency of being mentioned
Schedule	11
Sequencing coordination	7
Rework	5
Visualization	5
Productivity	5
Project cost	5
Communication	4
Design/engineering	4
Physical conflicts	4
Labor	3
RFIs	3
Safety	3
Change orders	2
Maintenance applications	2
Prefabrication	2
Quality	2
Simulation	2
As-builts	1
Pilot costs	1

In general, the benefits of BIM summarized by different groups and researchers correspond to and cover the lifecycle management of a building. For instance, although the work of Barlish and Sullivan was mainly built on the basis of academic publications (17 out of 21 sources were journal articles and conference proceedings), the 19 listed top mentioned benefits of BIM share great similarity with the benefits of BIM summarized by CRC AEC Innovation. Benefits such as visualization/accurate geometrical representation (design related), schedule/faster and more effective processes (project management related), life cycle data/ maintenance applications (operations related) were mentioned by both studies.

In spite of the general benefits of BIM summarized by academics and professional groups, in the AEC industry, there are mixed perspectives of and opinions on benefits of BIM. Even though the concept of BIM has been widely implemented, the overall and practical BIM effectiveness is difficult to justify at this stage (Lu & Li, 2011). As noted by Barlish and Sullivan (2012), although BIM as a technology is not new to the building industries, the specific software, programs and applications have evolved over the years, becoming manifested as different systems. In addition, as there are different stakeholders interacting in the utilization of BIM, their perspectives are different when establishing benefits of BIM. Moreover, the industry adoption rate of BIM varies, and knowledge on BIM also varies across different disciplines within the AEC industry (Gu & London, 2010). Therefore, the benefits of BIM still remain a mixed topic. More in-depth studies on benefits of BIM are needed to form a clear and comprehensive view.

A review of literature was performed in this study to analyze the current information available with regards to benefits derived from the utilization of BIM. Instead of summarizing the most frequently mentioned benefits in existing literature, this study took a closer look on these benefits by systematically categorizing them into three groups: technical benefits, project management benefits and economic benefits. Each group was then further studied.

2.1.2.1 Technical benefits

The adoption of Industrial Foundation Class (IFC) as a standard BIM file format specification has contributed to the following two key technical advantages of BIM: (1) the interoperability among AEC/FM software applications, and (2) object-oriented 3D models that contain lifecycle information of building elements.

IFC, developed and maintained by buildingSMART International (formerly known as International Alliance for Interoperability, IAI), is a neutral data format to describe, exchange and share information typically used within the AEC/FM industry. It is an object-oriented data schema based on class definitions representing the objects (such as building elements, spaces, properties, shapes, etc.) that are used by different software applications used in AEC or facility management project (buildingSMART International, 2015). More specifically, the IFC schema defines a standardized file format that can be used as a mechanism for sharing semantically rich building information between CAD systems and an ever-expanding range of design analysis tools. Furthermore, the IFC model schema can be loaded into a STEP model server, providing the opportunity to hold the building model as an object database on a central shared computer and accessible across the Internet as a resource to support collaborative design (Plume & Mitchell, 2007).

Interoperability

The notion that building design is a multi-disciplinary process involving contributions from an increasingly broad range of specialists is well understood and generally accepted (Plume & Mitchell, 2007). However, as in many other industrial sectors, a major difficulty that AEC companies are currently facing with ICT is the lack of interoperability of software applications to manage and progress in their business (Grilo & Jardim-Goncalves, 2010). For instance, computer programs for building design, analysis, and maintenance can usually not exchange data directly, even when the same team uses them. Buildings, therefore, take longer to be designed and built (Vanlande et al., 2008). Besides, the exchange of information and documents with new partners often cannot be executed automatically and in electronic format, which is principally due to problems of incompatibility with the reference models adopted by the software applications they are working with. Such problems arise not only during the project phase, but also across the whole life cycle, including operations and maintenance stages.

The Institute of Electrical and Electronics Engineers (IEEE, 1990) has defined interoperability as “The ability of two or more systems or components to exchange information and to use the information that has been exchanged." Interoperability is achieved by mapping parts of each participating application's internal data structure to a universal data model and vice versa. If the universal data model employed is open (i.e. not proprietary), any application can participate in the mapping process and thus become interoperable with any other application that also participated in the mapping. Interoperability eliminates the costly process of integrating every application with other applications (Grilo & Jardim-Goncalves, 2010).

As a standard for sharing data throughout the project lifecycle, globally, across disciplines and across technical applications in the AEC/FM industry (IAI, 1999), IFC facilitates interoperability by allowing software vendors to create interoperable applications via the IFC file format. More specifically, it allows information to be read and manipulated by any compliant software, reduces user "lock in" to proprietary solutions, and supports third-party software to be the "best of breed" to suit the process and scope at hand (CRC for AEC Innovation, 2007). In other words, IFC provides a foundation which enables software applications to share and exchange information directly and defines a shared building project model. Therefore, end-users in the AEC/FM area can effectively share the model data through IFC files.

In general, through facilitating interoperability in AEC/FM software applications, IFC not only provides comprehensive support for asset and facilities management functions, but also offers new management, collaboration and procurement relationships based on sharing of intelligent building data. New partners can join the AEC project technology-wise easily.

Object-oriented 3D models

Digital building descriptions using objects which belong to predefined classes have usually been called building product models (Björk, 1989), although some software vendors have recently coined the new term building information model for essentially the same thing. The research concerning such models was envisaged as early as in the late 1970’s (Eastman, 1979) but started to gain more momentum around 1985, when the ISO STEP standardization project started (Howard & Björk, 2008).

Based on the object specifications or classes defined by IFCs, generally, a building information model consists of two kinds of information—building elements and their attributes represented in building design terminology and the relationships between these building elements (Fu et al., 2006). For instance, an IFC door is not just a simple collection of lines and geometric primitives recognized as a door; it is an “intelligent” object door which has a door's attributes linked to a geometrical definition (Vanlande et al., 2008). Azhar (2011) gave a more comprehensive description of the information that a building information model contains: building information model characterizes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories and project schedule.

As an advanced approach to object-oriented CAD, BIM extends the capability of traditional CAD approach by defining and applying intelligent relationships between the elements in the building model (Singh et al., 2011). The principal difference between BIM and traditional CAD is that the latter describes a building by independent 2D views such as plans, sections and elevations. Editing one of these views requires that all other views must be checked and updated, an error-prone process that is one of the major causes of poor documentation (CRC AEC Innovation, 2007). The self-coordination of BIM ensures that when a change is made in the design, it will be implemented throughout the entire project and will, thus, provide a security concerning the quality of information coming from the design (Vanlande et al., 2008).

Another key difference between BIM and traditional CAD is that data in 2D drawings are graphical elements only, such as dots, line and polygons (CRC AEC Innovation, 2007). Instead of 2D drawings, BIM models consist of “intelligent objects” like walls, doors, windows, columns and so on, and include both geometric and non-geometric data such as object attributes and specifications. The built-in intelligence of BIM allows automated extraction of 2D drawings, documentation and other building information directly from the BIM model (Singh et al., 2010). In addition, BIM models are data rich and comprehensive as they cover all physical and functional features of a building. BIM models are also rich semantically as they store high amounts of semantic information on building elements (Vanlande et al., 2008). Therefore, BIM models can be used to demonstrate the entire building life cycle (Bazjanac, 2004).

The benefits that object-oriented models bring are not limited to design related technical advantages such as visualization, clash detection and etc. Besides utilizing BIM as a better design tool compared with traditional CAD, BIM experts are actively exploring wider application of BIM in AEC industry. As noted by Jung and Joo (2011) in their recent study on BIM framework for practical implementation, “though utilizing 3D BIM models solely for design practice is becoming highly beneficial, the advent of BIM concepts in recent years actively explores better utilization of 3D models.” They further categorized these areas into two types: Passive and active use of 3D models. Passive use of 3D models means BIM are simply used as input information or as visualization, for example, for engineering analyses in areas as structure, energy, disaster prevention in design phase, construction planning, scheduling, project control, safety in construction phase, and even interactive systems in the maintenance phase.

2.1.2.2 Project management benefit

AEC projects are generally very complex and require collaboration of numerous multidisciplinary and sometimes geographically separated team members. There is high interaction between these parties in terms of exchanging project information. Summarized by Zhang and Hu (2010), the AEC process is a very complex activity with the following characteristics: 1) Construction products are fixed, while the construction process is flowing, which constitutes the main conflict of spatial arrangement with time-series; 2) tasks are often co-completed by workers from different professions, using different construction machineries; 3) construction is a long-duration, comprehensive procedure with a great number of activities; and 4) the structural features during the construction period differ a lot from those during the service period, therefore it is possible that the most dangerous situation appears in the construction period.

In order to resolve conflicts, speed up solutions, and keep projects on time and on budget, continuous, accurate, and real-time information sharing among project participants is the key (Becerik-Gerber & Rice, 2010). BIM is seen as an enabler that may help AEC industry improve collaboration of project participants by facilitating information sharing among them. In general, BIM is understood as not only software that allows the geometrical modelling and the input of information but also tools and processes related to project management (Bryde et al., 2013). The holistic nature of BIM has been widely highlighted in AEC industry (Succar, 2009; Autodesk, 2014; NBIMS-US, 2015). It has a potential use for AEC project managers in improving collaboration between stakeholders, reducing the time needed for documentation of the project and, hence, producing beneficial project outcomes.

Allison (2010) described 10 reasons why project manager should champion 5D BIM. 5D BIM is traditionally understood as BIM that includes, besides the 3D model, scheduling information (the 4th D) and information for estimating the project from the model (the 5th D). More specifically, 5D BIM contains objects and assemblies in the BIM model that have a cost dimension added to them, either by incorporating cost data within the BIM model objects themselves, or which can be “live linked” to estimating software tools (Boon & Prigg, 2012). Table 2 compiles the advantages of BIM based on Allison’s work, i.e., the potential ways in which BIM can benefit Project Managers.

Table 2 Potential benefit of using BIM for project managers (after Allison, 2010; adapted from Bryde et al., 2013)

Potential benefit for PMs	Why?
Organize the project schedule and budget	An integrated 5D BIM model immediately updates both the schedule and budget when any design change occurs
Work well with the Design Team	By using the integrated 5D BIM model to visualize and explore the impact of changes, s/he can keep project scope in check and become a trustworthy liaison between the designers and Owner
Hiring and controlling the Subcontractors	Having a handle on clash detection and coordination plays a key role in keeping Sub-contractors' work predictable
Requests For Information (RFIs) and Change Orders	Utilizing Coordination Resolution in preAEC, these numbers can be brought to near zero.
Optimize the Owner's experience and satisfaction	Owner received a big injection of confidence in the GC when the PM showed him/her how design decisions impacted cost and schedule
Project closeout	PM to present a 6D BIM – a facilities resource with information on warranties, specifications, maintenance schedules, and other valuable information
Profit margin	By thoroughly understanding the project in 5D, the PM has more tools at his disposal to keep tight reins, and more reports to monitor progress
Progressive Owners are mandating BIM on their projects:	Becoming the BIM expert, in both preAEC and out in the field, makes the PM invaluable and a key player
PM Firm Growth	Project's success with 5D BIM means the opportunity to grow the firm's reputation and helps the corporate team win new business.

On the basis of Allison's work, Bryde et al. (2013) further explored the project benefits of BIM by studying secondary data from 35 AEC projects that utilized BIM. The data obtained from the case studies suggest that BIM is an effective tool in improving certain key aspects of the delivery of AEC projects. The most frequently reported benefit related to the cost reduction and control through the project life cycle. Significant time savings were also reported. The study of Bryde et al. (2013) shows that most of the a priori benefits of using BIM for Project Managers (Allison, 2010) shown in Table 1 are actually being reported in real-life case studies.

2.1.2.3 Economic benefits

Although a relevant and accepted calculation methodology and baseline to properly evaluate BIM's benefits have not been established (Barlish and Sullivan, 2012), there have been several studies that reported economic benefits from the utilization of BIM in AEC projects. For instance, Becerik-Gerber and Rice (2010) carried out an industry-wide online survey to understand the perceived value of BIM in the U.S. building industry. The survey had 424 complete respondents. Around 41 percent of the respondents realized an increase in overall profitability with the use of BIM; 55 percent of the respondents said BIM helped cut project costs; and 58 percent found that overall project duration was reduced by up to 50 percent. In 2013, Bryde et al. conducted a study on 35 AEC projects that utilized BIM reported from 2009 to 2010. The study results suggest that the most frequently reported benefit of BIM is related to cost reduction and control through the project life cycle.

2.2 3D CAD in shipbuilding industry

In recent years, global competition among companies and diversification of customer requirements has led to very short product life cycle (Kim et al., 2002). Companies are under the pressure to reduce lead time and overall production costs, as well as to improve product quality and meet multiple criteria at the same time. This is especially true for shipbuilding industry, as shipbuilding projects usually involve players working from all over the world and materials are manufactured and shipped from different places. The key to survive in the tough market is tightly connected with the ability to deliver ships of required quality at an acceptable price, and in the established delivery terms, ability which can be obtained by increasing the productivity and by cutting down the overheads (Milanović et al., 2005).

During the past decades, various software tools/systems have been developed and adopted throughout the shipbuilding process, aiming at automating conventional processes, promoting inter- and intra-organizational collaboration and as a result, increasing productivity and quality. Among these tools, 3D CAD software has been widely adopted in ship design process, which plays an important role in assisting ship designers to produce high-quality design drawings.

2.2.1 Overview of shipbuilding process

Shipbuilding, unlike other industries such as automobile or aircraft, has an individual nature. Mass production is rather seldom in this industry (Solesvik, 2007). Different from automobiles, airplanes, etc., which are made according to the concept of "multi-kinds, mass-production", driven by manufacturers, ships are made according to the concept of "multi-kinds, small-amount production", driven by customers called ship owners (Roh & Lee, 2007a). In other words, ships are often tailor-made and designed to meet the specific needs of ship owners (Solesvik, 2007). Customer, rather than the manufacturer, plays a key role in defining the "characteristics" of the ordered ship. Therefore, shipbuilding is a kind of "production to order", not "mass production", and as the customer's requirements often varies, the design and production details are almost different every time (Okumoto et al., 2009).

Building a ship is a very complex process, involves collaboration of various parties and usually takes years of time. Starting from order to delivery, the shipbuilding process mainly consists of two stages: design stage and manufacturing stage. With the increasing availability of information, the design stage can be divided into several sub-stages. According to Kim et al. (2002), these sub-stages include contract design performed for the negotiation with ship owner, basic design to meet the requirements of ship owner, and manufacturing design performed in functional aspect. On the other hand, the manufacturing process is composed of multiple stages, including pre-processing, processing, assembly, precedence outfitting, painting, precedence block erection, block erection, outfitting (Kim et al, 2002). Figure 2 shows the flow of each process composing the shipbuilding process.

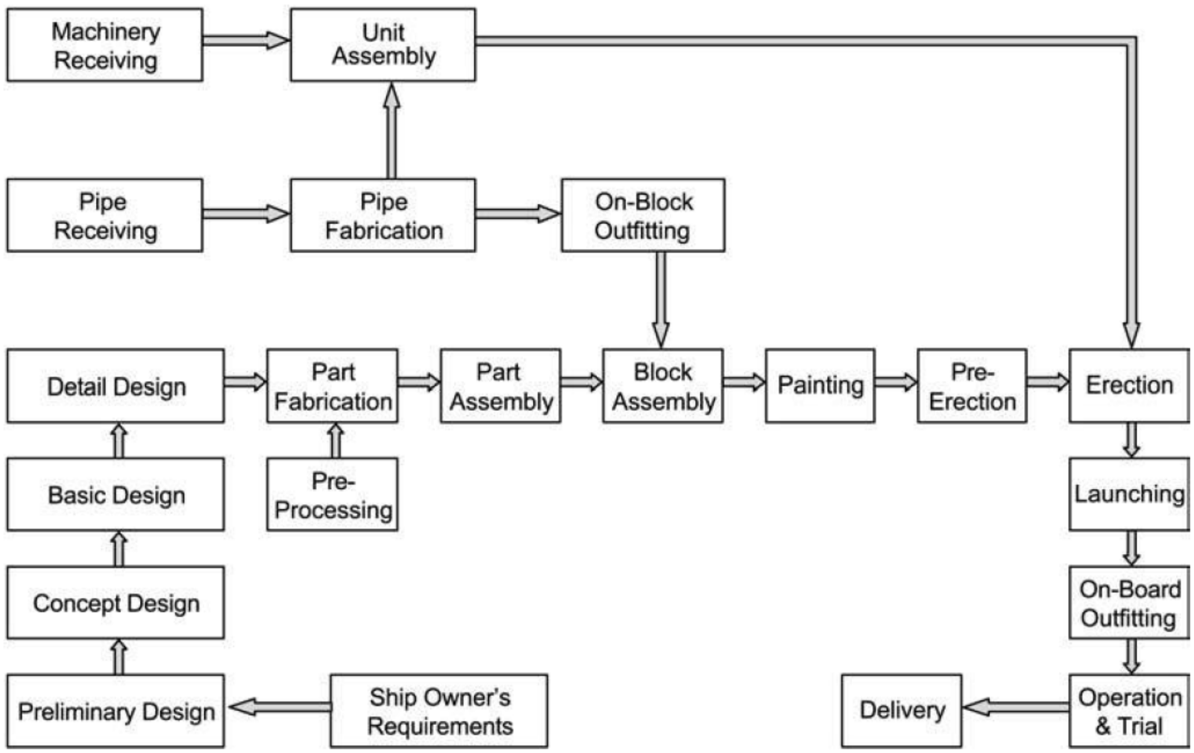


Figure 2 Flow of shipbuilding process (Adapted from Kim et al., 2002)

The process of ship design plays a key role in a shipbuilding project. It is a very complex process with a huge array of numerical computations, and it is not easy to extrapolate knowledge from past successes (Yeun & Yang, 1997). This is due to the individual nature of shipbuilding, i.e., in shipbuilding industry, usually one ship is very different from another. The differences depend on factors such as ship type, size, speed and main engine horsepower (Park & Storch, 2006), which are, to a large extend, determined by the requirements of the ship owner. On the contrary, in the case of automobiles and airplanes, the same product can be continuously made using the same production line after a product is well designed (Roh & Lee, 2007a). As a result, the ratio of design cost to total cost in shipbuilding industry is significantly higher, as ship designers rush into their work on the basis of a number of assumptions in the absence of any clear understanding of the design (Park & Storch, 2006).

The manufacturing processes of ship also differ greatly from that of other manufacturing industries. Unlike an automobile, a ship cannot be manufactured all at once (Roh & Lee, 2007b). The manufacturing processes of a ship occur in a very complex pattern over a long period of time (Kim et al., 2002), and ships are constructed using blocks. The ship is first divided into a number of blocks, which are the basic construction units in shipbuilding. Each block is designed and then assembled in the assembly shop near the lock. Large blocks (i.e., erection blocks) are made by joining several blocks together. Finally, large blocks are moved to the dock and welded together to form an entire ship (Kim et al., 2015). As noted by Roh and Lee (2007b) in their overview of shipbuilding process, "essentially, the manufacturing process of ship is similar to that of a large product by use of Lego blocks ".

2.2.2 Benefits and limitations of 3D CAD in shipbuilding

As noted in the former section, ship design processes consist of different sub-stages, in which different tasks are to be performed to produce production information for ship construction. A traditionally accepted ship design process includes the following phases (Tann & Shaw, 2007):

- Feasibility studies or designs that are low level of definition, based on the initial requirements from the ship owner,
- Concept design with a slightly higher level of definition (system definition, e.g., definition of the ship type, deadweight, type of propulsion, service speed),
- Preliminary design with additional system definition,
- Contract design with a level of definition sufficient to produce a bid package (integration of design with production and specific material, equipment, and outfit items specified),

- Detailed design with the highest level of definition (definition of joining, mountings, and foundations).

Ship design is a knowledge-intensive industry. Knowledge possessed by a firm's engineers is the main resource leading to a competitive advantage (Solesvik et al., 2012). In order to produce a ship design that satisfies the customer's requirements, a large number of software tools are used in each stage of the design process to evaluate a variety of characteristics and life phases (structural, operational performance, production scheduling, etc.) (Whitfield et al., 2003). Among these tools, CAD software has been an indispensable tool for designers to carry out design work successfully.

In general, CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing (Sarcar et al., 2008). Shipbuilding, as well as other industries such as automobile, aircraft, etc. has a long history of utilizing CAD in product design and development. Different CAD systems are used by different design stages and departments (Tann & Shaw, 2007). Since its introduction, CAD tools have evolved from 2D to 3D, and the functions of CAD have also been gradually improved to meet increasing needs from the industry. In their study on the role that 3D CAD plays in knowledge-based product development systems, Baba and Nobeoka (1998) summarized three stages in the evolution of CAD usage in product development (design and manufacture) since 1970s. Based on their work, Table 3 is formed to present the evolution of CAD usage in the design process.

Table 3 The evolution of shipbuilding CAD systems and their usage (after Baba & Nobeoka, 1998)

Stage	I. Introduction	II. Diffusion	III. Integration
CAD system	2D/3D mixture	2D/3D mixture	3D
Primary purpose	Efficiency in drawing	Diffusion and learning more efficiency	Real concurrent engineering
Relationship with traditional product design process	Support for efficiency in drawing	Support for efficiency in drawing	Fundamental change in process
Period (in the case of automobile)	1970–1985	1985–1995	1995–

The utilization of CAD in the industry dates back to 1970s, when it was first developed for defense-related purposes and was subsequently adopted for commercial use in the aircraft, automobile and shipbuilding industries (Aoshima et al., 1999). In the first stage (introduction stage), CAD tools were primarily used by designers to produce design drawings with significantly higher efficiency. The second stage is a learning and diffusion stage. At this stage, designers learned to use CAD tools more efficiently. Meanwhile, the benefits of CAD tools increased, which resulted in an increasing number of designers starting to adopt these tools. In the first two stages, 2D and 3D CAD tools were used in mixture, i.e., some components were designed in 2D and some were in 3D. However, it needs to be noted that at these two stages, CAD tools were simply used as efficient design tools, and no fundamental change in development process was caused by using them (Baba & Nobeoka, 1998).

At the third stage (integration stage), 3D CAD tools are used by designers to produce design drawings for all components. Same 3D data are shared by different disciplines involved in design and manufacture stages. Besides, all components are digitally pre-assembled (simulated) as a finished product at the early stage of the development project.

In addition, a communication capability is incorporated to the integrated CAD systems for sharing the latest digital data among individual computer terminals. This enables all of the engineers to monitor the latest design that is being worked on by their colleagues. (Baba & Nobeoka, 1998)

At around the same time when Baba and Nobeoka did their study, NSRP (National Shipbuilding Research Program [1]) published an Evaluation of Shipbuilding CAD/CAM/CIM Systems. Table 4 shows the evolution of shipbuilding CAD/CAM systems from 1972 to 1996, in terms of hardware, software and users. In general, both the work of Baba and Nobeoka and NSRP demonstrated that shipbuilding CAD tools experienced a significant growth of usage from 1980s. At the same time, the function of CAD software was greatly improved as well.

Table 4 The evolution of shipbuilding CAD/CAM (NSRP, 1997)

Periods	**1972–1978**	**1979–1986**	**1987–1996**
CAD system	2D/3D mixture	2D/3D mixture	3D
Hardware	Main frames	Midi/mini computers	PCs, LAN
Software	Independent applications	Integrated applications	Fully integrated applications
End users	Big shipyards	Big/medium shipyards	Big/medium/small shipyards

2.2.2.1 Benefits of 3D CAD in shipbuilding

3D CAD has been widely studied in industries such as shipbuilding, automobile and aircraft, as it plays a key role in increasing the productivity of design processes of these industries. These industries have benefited from the utilization of 3D CAD tools in a

[1] Owned by US Department of the Navy Carderock Division.

quite similar way. In general, 3D CAD contributes to more efficient ship design through (but not limited to) the following aspects:

3D visualization

With 3D CAD, all components are designed in 3D. This enables designers and engineers to access more relevant information during the drawing process by seeing and working on an entire form of the component, i.e., the component can be viewed from any perspective (Baba & Nobeoka, 1998). Also, with 3D models, designs can be made with a higher level of detail and accuracy. It is also easier to store and deliver design semantics in 3D designs. In contrast, 2D designs are often very complicated with too many lines, which can easily confuse even skilled designers (Lynch, 1988). Besides, it is difficult to reflect and deliver all design semantics by 2D drawings (Lee et al., 2004). Figure 3 is an example of a 2D drawing and the corresponding 3D CAD model, which clearly demonstrates the adavntages of 3D CAD model.

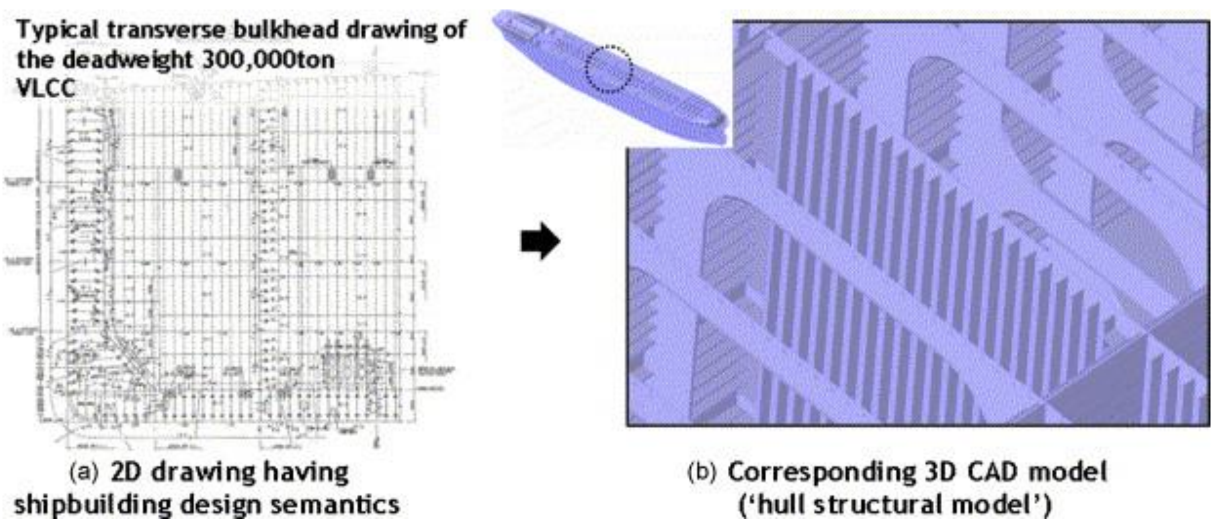


Figure 3 Example of the 2D drawing and the corresponding 3D CAD model of the 300k VLCC (A deadweight 300,000 tonne Very Large Crude oil Carrier). (Adapted from Roh & Lee, 2007b)

Design simulation and interference - checking

The 3D CAD system is indispensable in order to apply the production simulation for ship production (Okumoto, 2009). When only 2D CAD tools are available, simulation is rarely carried out during the design process and instead physical prototypes are made and tested. This is beacuase simulation requires designers and engineers to translate 2D designs into three dimensions which is time consuming and costly (Baba & Nobeoka, 1998). With 3D CAD, it is much easier to perform simulation analysis of such problem as thermal, mechanical stress and vibration with 3D design than with 2D design (Baba & Nobeoka, 1998).

Interference-checking (i.e., collison detection) can be carried out more efficiently with simulation enabled by 3D CAD tools as well (Okumoto, 2009). As ships generally have very limited area, it is very often that there are interferences between euiqpement, installations, humans, etc. Therefore, it is important for designers to optimize the use of space while ensuring there's no interference. Using simulation by 3D CAD, interferences can be observed at the design stage and thus avodied by design changes. Figure 4 and Figure 5 show two typical examples of using simaltion by 3D CAD for interference checking (carriage of equipment and "Walk through" in Engine room).

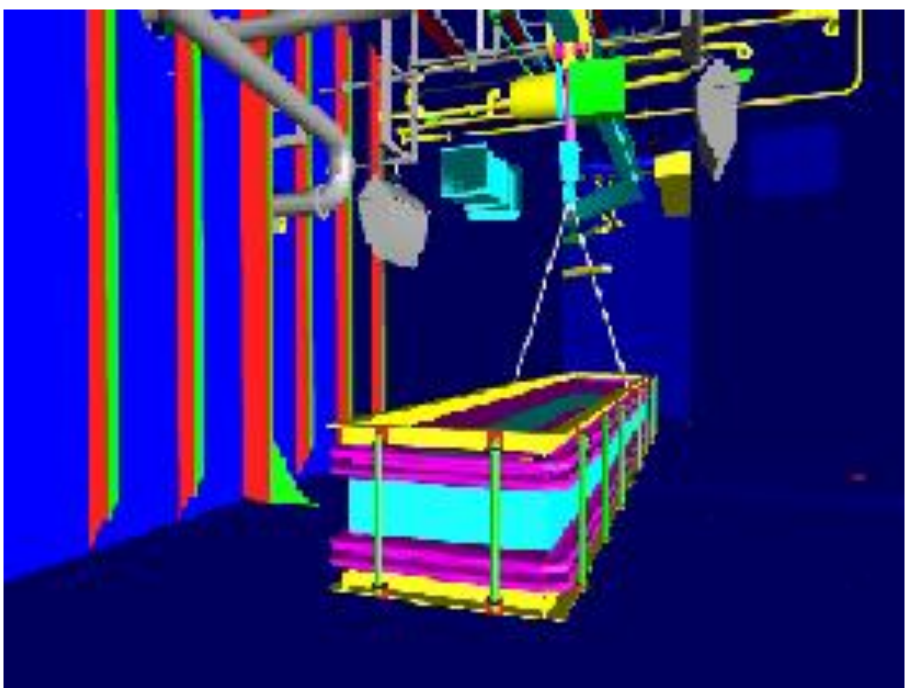


Figure 4 Carriage of equipment (Adapted from Okumoto, 2009)

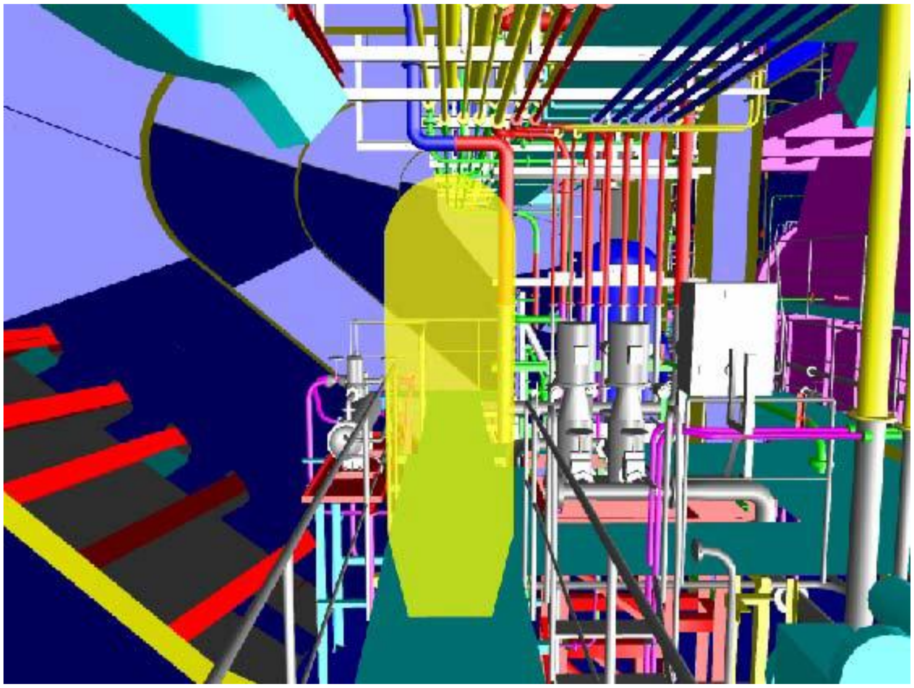


Figure 5 "Walk through" in engine room (Adapted from Okumoto, 2009)

Communication and coordination

Ship design has been collaborative in nature (Solesvik, 2007). At the design stage, there are at least two agencies cooperating– the ship owner and the designer. Communication amd coordination take place all the time. For instance, there is not only internal communication whitin the design/engineer team, but also external communication between designers/engineers and other players (e.g., ship owner, classification societies, suppliers, etc.). Communication and coordination play a central role in determining the effectiveness of concurrent engineering (Baba & Nobeoka, 1998). In order to implement concurrent engineering successfully and to construct a ship efficiently and safely, it is necessary for all related workers to have a common acknowledge and to work in cooperation (Okumoto et al., 2009).

With traditional 2D CAD, although computer aided drafting environment is available to support designers, other designers or engineers must undertake the arduous task of translating the product model information defined on the 2D drawings (Lee et al., 2004). The translation often leads to misunderstanding and takes long time. The 3D CAD systems can visulize deisgn information in an intuitive and understandable form (Aoshima et al, 199). Therefore, different functional groups are able to share common knowledge and language through 3D models of components and prototypes assembled digitally (Baba & Nobeoka, 1998). In addition, 3D data can be used directly by manufacturing engineers as well. In this way, 3D CAD significantly improves coordination and communication effectiveness among designers and engineers.

2.2.2.2 Limitations of 3D CAD in shipbuilding

In spite of the demonstrated benefits of 3D CAD tools, some argue that CAD technology has reached maturiy after having drvien productivity at a high rate of growth from the 1980s to the middle of 1990s (Park & Storch). In recent years, it has been widely realized and discussed in shipbuilding industry that certain limitations of CAD tools have hindered the development of design process. Among these limitations, the lack of interoperatbility of different CAD systems and the inability of CAD tools to support initial design are the most frequently discussed.

The lack of interoperability among different CAD systems

One of the most difficult tasks in collaborative design is to construct the interoperability commitments enabling to communicate and coordinate the distributed design support systems (Tann & Shaw, 2007). This is especially true for shipbuilding industry, in which CAD systems are used for different design domains, structure, and outfitting (Li et al., 2011). In order to deliver a shipbuilding project successfully, many designers from various disciplines, working at different stages and cooperating in complex design circumstance. Each designer(s) have their own design objective (Tann & Shaw, 2007). Therefore, different CAD systems are used by different design stages and departments in order to best suit their needs. These systems are, for instance, Cadmatic, Tribon, Aveva, Napa, etc. Information exchange among different CAD systems is necessary to complete the whole design process. Figure 6 shows the flow of design information among different CAD and CAE systems, which are used for ship structural design at one Korean shipyard.

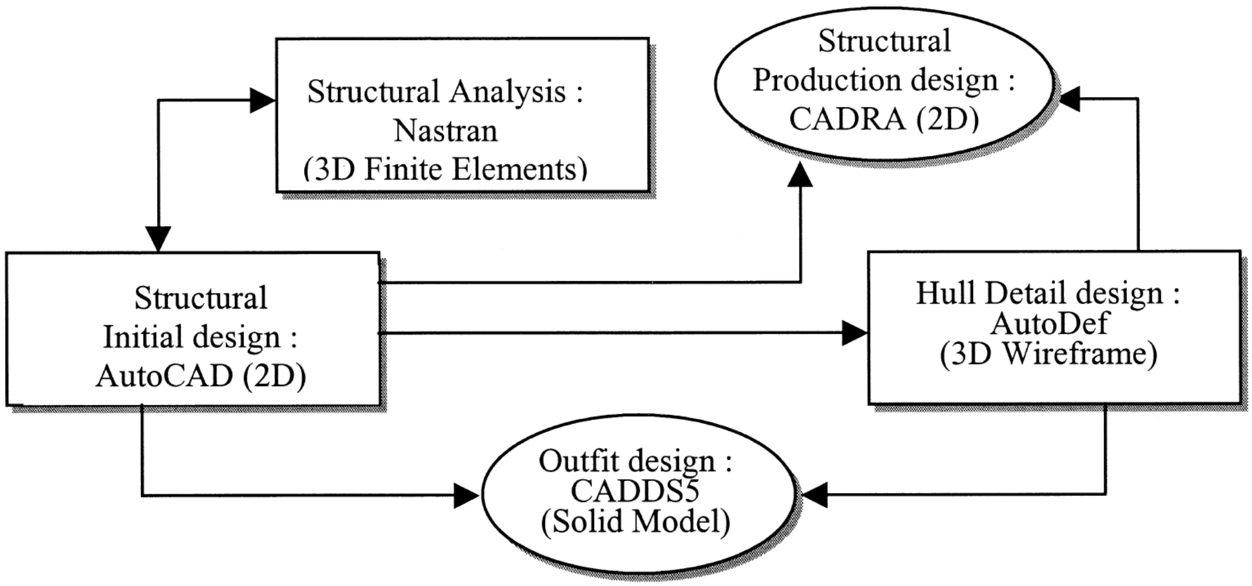


Figure 6 Flow of design information of ship hull (Adapted from Shin et al., 2000)

Information exchange between different CAD systems is an important issue in shipbuilding industry. Unfortunately, many CAD systems do not work well together because of incompatible data formats and conflicting execution environments (Scallan, 1992). Bronsart et al., (2005) studied the integration of software tools used in ship design and production. In their study they noted that exchange of data between different CAD/CAE tools is in many cases still based on a bilateral agreement on proprietary formats. This is because that there exists no general/ consistent data representation of the product which could be accessed and used consistently in different CAE/CAD systems by all partners in a shipbuilding network. The main reason for this situation is that software vendors have always been very reluctant to open up their systems for the integration of other tools which are based on open standards (Bronsart et al., 2005). In other words, they are reluctant to create compatible software to competitors' products (Tann & Shaw, 2007).

Currently, there are two approaches to data exchange in shipbuilding industry: 1. direct translation performed by translators, 2. indirect translation based on a neutral data format (Li et al., 2011). One major disadvantage of the first approach (indirect translation) is that as the number of CAD systems increases, the number of translators needed increases exponentially. As for indirect data exchange, various data formats (international standards) have been studied and discussed in the industry, whereas currently there is still no open standard widely shared by major CAD vendors. To avoid troubles caused by the lack of interoperability among different CAD tools, it is much better to develop the whole project in the same CAD, or at least to have the necessary tools to integrate the information in a viewer compatible to all of them, which sometimes it is a very difficult task (Fernández & Alonso, 2015).

The inability of CAD tools to support initial design

At the initial design stage of a shipbuilding project, basic design is carried out to meet the requirements of ship owner. This stage is a function-oriented definition process of a product, focusing on functions such as the arrangement, rough definition of the shape, and determination of the dimension of hull structural parts (Roh & Lee, 2007b). Compared with the following design stages, the initial design stage plays a more important role in determining the success of the shipbuilding project, as most of the critical decisions are taken at this stage, which will greatly decide the cost of the ship (Alsonso et al., 2013).

However, in spite of the common use of a 3D model of the ship at the detailed design stage, the early design stage is still based on 2D drawings in many companies, though those drawings may be produced by a sophisticated drafting software application (Alsonso et al., 2013). For instance, at the initial design stage of a hull structure, all design information is being first defined on 2D drawings not 3D CAD model and then transferred to following design stages through the 2D drawings (Roh & Lee, 2007b). Designers represent geometry, arrangement, and dimension of hull structures with 2D geometric primitives such as points, lines, arcs, and drawing symbols (Lee et al., 2004). As shown in Figure 3a – a typical 2D transverse bulkhead drawing of a ship, design results are implicitly represented by lines, arc, and drawing symbols.

The use of 2D drawings at the initial design stage may result in long design periods, repetition of relevant parts of the work in subsequent stages and a potential gap for multiple design inconsistencies, which can lead to a major increase in costs and a low production performance (Alsonso et al., 2013). For instance, in order to use product information defined on the 2D drawings that are produced at the initial design stage, designers must translate the information intelligently in the following design stages. As a result, the design results are repetitively inputted at each design stage, and a gap in transferring the design results between the design stages exist (Roh & Lee, 2007a). Problems such as loss of design semantics and delay of design processes that follow could be triggered because of errors by mistranslating the information (Lee et al., 2004). In addition, it is difficult to keep coordination between the different 2D drawings, ensuring that any change that made to one drawing will also appear in all the relevant drawings (Alsonso et al., 2013).

In spite of the fact that many researchers and shipbuilding companies have been focusing on 3D CAD modeling of the hull structure of the ship at the initial design stage, currently, there is not yet a CAD system with which to support the initial design stage, in which design changes arise very frequently (Roh & Lee, 2007b). In addition, designers are reluctant to produce 3D models at the early design phase, as it takes longer than simply generating the plain set of drawings, even though 3D models produced at the early design phase is greatly beneficial in the long run of the project (Alsonso et al., 2013).

3 Methodology

After a thorough review of the literature, it became evident that BIM makes the AEC processes more efficient and effective (CRC AEC, 2007; Allison, 2010; Bryde et al., 2013). Meanwhile, the current state of 3D CAD implies that shipbuilding industry is actively seeking for better software solutions (Bronsart et al., 2005; Roh & Lee, 2007a; Roh & Lee, 2007b; Alsonso et al., 2013). However, in order to identify the benefits of BIM by practice (i.e., BIM-enabled practices that have been put into use and proven to be beneficial) and investigate whether these practices can be transferred to shipbuilding industry, data collected from existing publications and studies were inadequate. More in-depth first-hand data on the benefits of BIM in AEC industry and the current state of 3D CAD in shipbuilding industry needed to be collected. Therefore, it was decided to carry out a qualitative study based upon the views of a number of experts from these two industries. In-depth individual interview was applied as the main research method for data collection.

3.1 Research method

Seven BIM experts from AEC industry and seven shipbuilding professionals were invited to interviews. Professional backgrounds of the interviewees are diverse. For instance, there were software vendors, contractors, engineers and IT specialists, etc. Most interviewees have more than one role in the industry (e.g., engineer and software vendor, BIM consultant and architect, etc.,) and have been constantly involved in international projects.

The interviews were carried out in two phases. In the first phase, individual face-to-face interviews with seven BIM experts were conducted to study BEPs in Finland. Based on the results of interviews with BIM experts, in the second phase, seven shipbuilding professionals were interviewed individually to study the utilization of 3D CAD software in Finnish shipbuilding industry. In total, 14 individual interviews were conducted. These interviewees were mainly chosen by recommendations from two shipbuilding professionals who are most interested in the research topic. The recommended BIM experts are generally top level BIM experts in Finland with international presence (Table 5); the recommended shipbuilding professionals work closely with CAD tools (Table 6). Notes were taken during all the interviews, as well as recordings. Each interview was transcribed and emailed to the interviewees for proofread before analyses started.

Generally, in the development of the empirical study, the following four steps were taken:

1 Seven Interviews with BIM experts from AEC industry were carried out to identify practical benefits of BIM in AEC industry in Finland.

2. A list of best BEPs was compiled based on a thorough analysis of results of interviews with BIM experts, and top four BEPs were further studied.
3. Seven interviews with shipbuilding professionals were carried out to (1) explore the current state of 3D CAD in shipbuilding industry in Finland, and (2) identify particular areas that need further development.
4. Based on the results of the first three steps, discussion was carried out on which BEPs could be potentially transferred to shipbuilding industry to improve the productivity of identified areas that need further development.

3.2 Interviews with seven BIM experts

In order to identify the best BIM-enabled practices in AEC industry, six BIM experts from five BIM-related companies (including one BIM consultant company, one BIM software distributor, one BIM software provider, one construction company and one energy consultancy company that utilize BIM software in projects) and one professor specialized in BIM were invited to interview. In total, there were seven face-to-face interviews carried out. The interviews lasted from 40 to 100 minutes.

The interviewees are generally top level BIM experts in Finland with international presence. For instance, several interviewees participated in writing Finnish BIM guidelines, and the majority of them are members of buildingSMART Finland. Several interviewees are actively promoting the use of BIM all over and world and thus travel abroad frequently. Backgrounds of the seven interviewees distribute well between different disciplines in AEC industry, such as architecture, engineering and software development, etc. Besides, the companies they represent are active practitioners of BIM and are closely involved in the application of BIM at different stages of the building lifecycle (e.g., design, construction and operation). See Table 5 for the backgrounds of the interviewees and the companies they represent.

Table 5 Backgrounds of seven BIM experts and companies they represent

Interviewee	Title	Company	Stage
1	General Manager	A: a consultant and IT developer for building industry, specialized in BIM consulting services and solutions	Design
2	Founder of Company A & Chair of buildingSMART Finland		
3	ArchiCAD Specialist	B: distributor of AchiCAD (BIM software developed by Graphisoft) in Finland	Design
4	Professor in AEC Management and Economics (expertise: BIM on building life cycle, BIM based processes)	C: Finland's second-largest university in engineering sciences	Design & Construction
5	Senior Vice President	D: software engineering corporation develops BIM software that can cover the entire construction workflow	Design & Construction
6	Vice President, R&D	E: one of the world's leading project development and construction groups; has implemented BIM on many types of projects	Construction
7	Director, Innovation and Development	F: specializes in design, consultancy and software services; actively participates in national and international development projects on the utilization of BIM models	Operation

The interviews were carried out semi-structured. Same seven open-ended questions were asked to all the interviewees to capture their understanding of BEPs. The first question addressed the interviewee's personal background, such as educational background, working experience and their perception of BIM. The next two questions (2 and 3) focused on the company's background and its role in BIM industry. Question 4 to 6 required the respondents to thoroughly explain the key benefits of BIM that they acquired or witnessed, and how were these benefits put into practice. In order to maintain the practicability of the study, only benefits that have been realized were discussed during the interviews. The last question of the interview (7) explored interviewees' personal opinion towards the transferability of the identified BEPs to shipbuilding industry. In spite that their understanding level of shipbuilding industry varies, not all the interviewees were able to give their opinions, and the validity of answers needs to be further examined, it was interesting to see how these BIM experts thought about the adoption of BIM in shipbuilding industry.

The 7 interview questions are listed below:

1. What is your background?
2. What is your company's basic information?
3. What is your company's role in BIM industry?
4. What are the most important benefits of BIM that you have seen in practice?
5. What are the benefits of BIM that you have seen divided by each stage of a typical AEC project (e.g., design, construction and operation)?
6. How do the successful companies realize these benefits through practices?
7. Which practices can be transferred to shipbuilding?

3.3 Interviews with seven shipbuilding professionals

The second group of interviews were carried out in a similar manner as the first group. Seven shipbuilding professionals were invited to individual face-to-face interviews to further study the current state of 3D CAD in shipbuilding industry, i.e., the utilization of 3D CAD tools in Finnish shipbuilding projects. Among the seven interviewees, four work at a shipyard in Finland, two works at a consulting and engineering company with clients from shipbuilding industry, one works for a developer and supplier of 3D software for the plant- and shipbuilding industries. More than half of the 7 interviewees have international working experience or have worked with international colleagues. Besides, although some of them nowadays work in sales, business development or on a management level, they all have relevant shipbuilding education and previous working experience in design or engineering roles in the industry. See Table 6 for the backgrounds of the interviewees and the companies they represent. The specialized areas of interviewees in shipbuilding industry are also listed.

Table 6 Backgrounds of seven shipbuilding professionals and companies they represent

Interviewee	Title	Specialized area	Company
8	CAD and PLM Development Manager	HVAC engineering, design development	G: shipyard in Finland, specialized in building cruise ships, car-passenger ferries, technically demanding special vessels and offshore projects.
9	Designer, Electrical Design	Electrical design, cable routing, 3D administration & 3D modeling with Cadmatic	
10	CAD Administrator, HVAC and Catering design	3D modeling with Cadmatic	
11	Head of Main Department, Design & Engineering	Naval architecture, project management, operations management	
12	Chief software administrator	Shipbuilding design software administration and training	H: leading European consulting and engineering company, offers design, engineering, project management and other services to clients in the marine industry.
13	Senior VP, business development	Naval architecture, project management, project engineering	
14	Senior Sales Manager	Ship & Plant 3D Design, Project and Information management solutions.	I: developer and supplier of 3D software for the plant- and ship building industries.

Seven open-ended interview questions were formed, aiming at finding out whether these identified BEPs could be transferred or not. The first question addressed the interviewee's personal background, such as educational background, working experience and current job. Question (2 and 3) related to the company's background and its role in shipbuilding industry. In order to find out whether there is any existing integrated solution of different design models (i.e., software solution that plays a similar role in shipbuilding industry as BIM software does in AEC industry), Question 4 was asked. Question 5 focused on the current state of object-oriented model in shipbuilding industry, which is widely understood as one of the key technical advantages of BIM. Question 6 asked about the benefits or practices enabled by the integrated solution (if any) or object-oriented 3D model (if any). The last question (7) worked as a reminder for the interviewee, as in the context of this research, the focus is on realized benefits or practices.

The 7 interview questions are listed below:

1. What is your background?
2. What is your company's basic information?
3. What is your company's role in shipbuilding industry?
4. Is there any integrated solution of different design models?
5. Is object-oriented 3D model used in shipbuilding?
6. What are the benefits or practices enabled by the integrated solution or object-oriented 3D model?
7. Which of these listed practices have been applied in shipbuilding already?

4 Results

4.1 BIM-enabled practices in Finland

4.1.1 Perceptions of BIM

As noted in the literature chapter, there are various definitions of BIM from the industry and the academia. Naturally, the seven interviewed BIM experts have diverse perceptions of BIM because of their different background and roles in the industry. Therefore, before starting analyses of BEPs, it is worthwhile to learn these experts' understanding of BIM and how their opinions accord, differ, or oppose.

For interviewee 2, chair of buildingSMART Finland and CEO of a BIM consultant company, "BIM means IFC – open shared data". He emphasizes that IFC is the premise for BIM, i.e., only software applications adopt IFC as a standard specification are qualified BIM applications. In addition, from his point of view, BIM has evolved from simply a technology to a process. In order to benefit the most from BIM, the processes need to be changed as well. His opinion well explains why he started a BIM consulting company specialized in BIM coordination for AEC projects.

Interviewee 4, professor with expertise in BIM on building life cycle & BIM based processes, holds the opinion that "BIM essentially means Building Information Management", and "it is a supporting element which enables lean construction". In other words, the core of BIM lies in the management of information. This is because traditional AEC projects usually start from scratch, whereas in lean construction, there are product libraries that the construction team can use.

For interviewee 5, senior vice president at a leading BIM software company, BIM is "a communication technology that conveys information in the processes". The essence of BIM is the communication it enables. However, he thinks BIM software still needs development before it can fulfill all the received anticipations.

Although some advocate that the traditional AEC practices are facing a paradigm shift with the wider application of BIM (Lu & Li, 2011), interviewee 6 views BIM simply as "a tool to help and make the processes more reliable and efficient." He believes that BIM has not changed the AEC processes or tasks, but it has made some of them better. As interviewee 6 works for a construction group, his perception of BIM, driven from the utilization of BIM in different AEC projects, is very practical. See Table 7 for the quotes from interviewees on their perceptions of BIM.

Table 7 Perceptions of BIM

Interviewee	Perceptions of BIM
1	"To make a system working, there are technology, process and people. People in Finland and in BIM generally concentrate on technology and are technology-oriented. However, Process is where we have the biggest problem."
2	"BIM means IFC – open shared data." "At the beginning, BIM is only technology. Then it became process-related. Every time you are talking about BIM, you are also talking about processes." "In order to change the construction business, they (i.e. construction professionals) need to change the processes."
3	None
4	"In my opinion, BIM is an enabler for lean construction. If you are not using BIM, you cannot really do lean construction. It's a supporting element." "For me, BIM is building info management."
5	'BIM is technology' "There software is nowhere ready yet." "BIM is conveying info in the processes." "BIM is communication."

6	"BIM is not doing anything itself. It's like a tool to help and make the processes more reliable and efficient. So basically, it hasn't changed the processes and tasks, but it has made some of them faster, easier, more efficient and more reliable. In that way we perform better than earlier."
7	"BIM is not only for new building."

4.1.2 Identified BIM-enabled practices

After carefully analyzing the opinions of the seven BIM experts, 11 best BEPs were identified. Based on the frequency of how often these topics were raise, the practices are summarized in Table 8, ranking from the most to the least frequently mentioned.

Table 8 Best BIM-enabled practices

No.	BIM-enabled Practices	Frequency of being mentioned (number)
1	Clash detection	7
2	Visualization	6
3	Quantity takeoff	5
4	Scheduling	4
5	Energy simulation	2
6	Reporting and checking	2
7	Mobile apps	2
8	Continuous performance measurement	1
9	Safety planning	1
10	Alternatives testing	1

11	Identify function system	1

As can be seen from Table 8, the top four most frequently mentioned BEPs are: 1. Collision/Clash detection, 2. Visualization, 3. Quantity take-off, 4. Scheduling. These practices were commonly accepted and widely recognized by the seven interviewees as the best and thus were further studied in the following part of this chapter.

During the seven interviews, practices in design and construction phases were more frequently mentioned by the experts than practices in operation phase. This is mainly because: 1. the majority of interviewees work at design and construction phases in AEC projects; 2. Currently in AEC industry in Finland, BIM is more commonly applied in design and construction phases than in operation phase. Therefore, in order to keep the focus of the research on the most frequently mentioned BEPs, these less frequently mentioned BEPs were excluded from further study, despite that they were considered as the best by one or two of the interviewees.

4.1.3 Clash detection

Not surprisingly, clash detection was unexceptionally emphasized by the seven interviewees as the best BEP. It has been widely understood as the main reason for companies in AEC industry to start using BIM from the beginning. It is also one of the most extensively used features of BIM. As stated by interviewee 1: “Typically, where you get most out of this combined BIM model is clash detection. This is the answer you are going to get from everywhere”.

In BIM modeling, there are several models created and then integrated into a composite model. Based on the architect’s original model, each discipline such as structural engineering, MEP engineering, environmental engineering, etc., creates a model, independently of all the others. After these models are finished, clash detection is then carried out, which is the process of finding where the models clash, e.g., objects from different models occupying the same space, or with parameters that are incompatible.

In order to get a comprehensive view on clash detection, it is important to differentiate the following two terms: clash detection and collision detection. Although clash detection is more frequently used in BIM-related discussion, it has been noted that during the interviews and often in reality, people in AEC industry use collision detection and clash detection interchangeably, holding the opinion that these two terms are basically the same. However, there is a subtle but important difference between these two concepts: collision detection is the process of identifying incongruous objects in different models that are found to occupying the same space in the master (Stowe, 2013), whereas clash detection can also refer to clashes in scheduling of activities, for example, order of assembly (Singh, 2014). Similarly, clashes in rules can also be identified. In general, there are three types of clashes in a typical AEC project, i.e., hard clash, soft clash/clearance clash and 4D/workflow clash (Table 9). Therefore, collision detection only refers to the detection of hard clash (Figure 7 shows an example of hard clash). In this context of this research, the term clash detection is used to cover all three types of clashes.

Table 9 Three types of clash (after Patel, 2014)

Type of clash	Explanation
Hard clash	It occurs with two objects are taking up the same space, for instance, a beam which is going through a plumbing run is designed.
Soft clash/Clearance clash	It indicates that the object needs more positive spatial/geometric tolerances, spaces and buffers within their buffer zone for better accessibility, insulation, maintenance and safety.
4D/Workflow clash	With 4D/Workflow clash detection method, you can determine scheduling clashes for the crews, equipment/materials fabrication & delivery clashes. Moreover, other project timeline issues can be examined and perceived using a BIM modeling project.

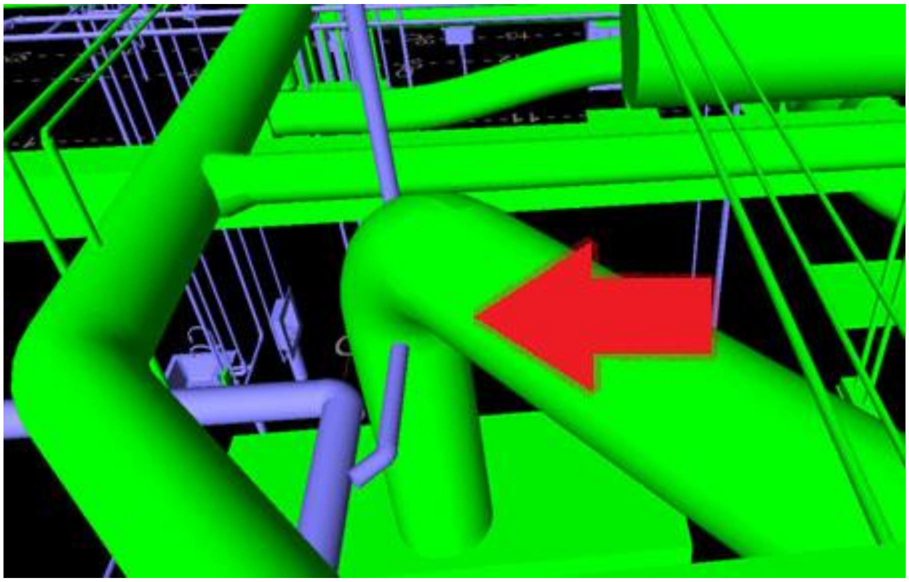


Figure 7 An example of hard clash: two pipes occupying the same space (adapted from George, 2012)

Based on the interviews, it can be concluded that clash detection contributes to more efficient AEC processes by:

1. Enabling clashes to be detected at early design phase

Clash detection, a critical step to ensure the quality and speed of the construction project, is not new. It is just that in traditional construction projects, clash detection takes place on the construction site. A common instance can be that: only after constructing a beam designed by the structure engineer, the construction workers notice that at the same location, the MEP engineer located the path of air conditioning units. At this point, it is apparently very money and time-consuming to fix this “detected clash”. Moreover, the whole project is likely to be impacted. Such problem is very common in traditional construction projects. Besides hard clash, which is explained in the instance, soft clash and workflow clash are also very likely to impact the project if not detected late.

With BIM-enabled clash detection, clashes can be detected at early design phase, before the actual construction work starts (i.e. pre-construction). Compared with traditional clash detection (i.e., prior to computerization, clash detection was a manual process of overlaying drawings on a light table to visually see clashes), in BIM modeling, clash detection can be conducted with higher speed and accuracy. This is mainly due to 3D visualization, which is thoroughly discussed in the next section. In addition, since clash detection is carried out at early design phase, when no actual construction work has started, it means that clashes can be detected and fixed virtually as many time as possible (within budget and time limits). As noted by interviewee 2: "Through BIM, buildings can be built virtually and then check. If it's wrong, then you can change the design". More importantly, as the design phase of lifecycle has a critical influence on building's performance and has the largest impact on lifecycle costs when compared to other phases (Figure 8), by enabling clashes to be detected and fixed at early design phase, the project can save vast sums of money and time, reduce risks at construction phase, and thus, produce a better building.

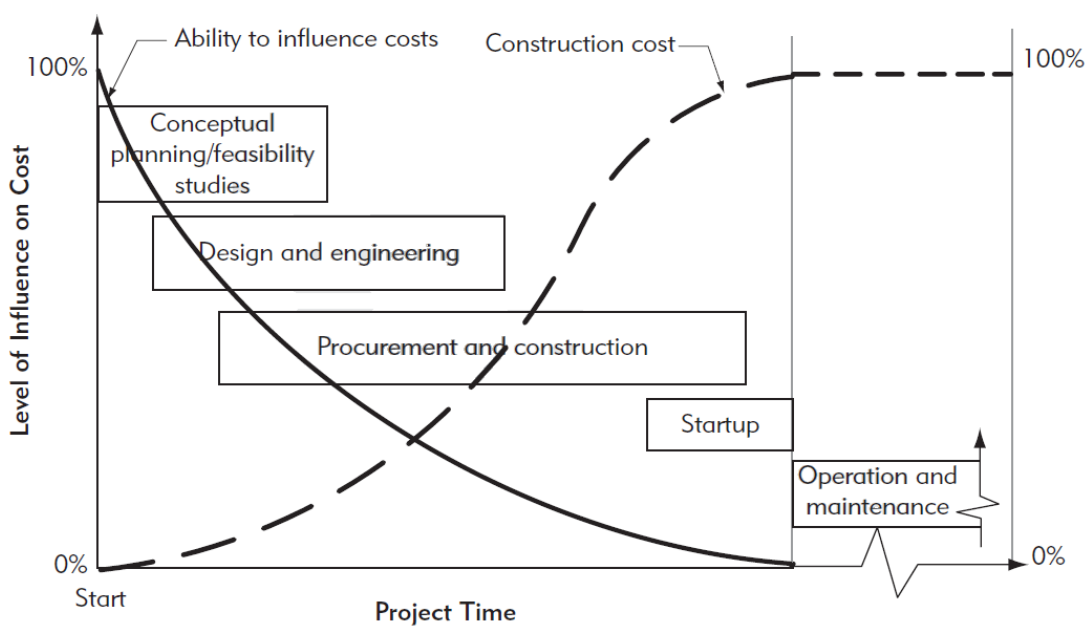


Figure 8 Influence of overall project cost over the project lifecycle. Adapted from Eastman et al., 2011: 164

2. Enabling better design coordination

Another major benefit of clash detection is its positive role in the coordination of different design disciplines, i.e., it enables better design coordination. For instance, in large construction projects, there are always external designers involved, with whom design coordination often remains a challenging task. With BIM software, it is easy to detect clashes among models from different disciplines, including those from these external designers. As mentioned by interviewee 6, who works for a construction group, "clash detection has really helped them to combine models, find out clashes and coordinate design."

Clash detection also requires the designers and engineers from different disciplines to collaborate from the early design phase of the project. Although BIM enables clashes to be detected automatically by the software, the results is semi-finished. It is because there might be thousands of clashes detected in one project. These detected clashes then need to be prioritized, as some of them are critical for the project and are likely to have huge impact if not handled in time and correctly, whereas there are also clashes that are ok all the time (Interviewee 7, 2014). Thus, it is the designer's/ engineer's call to decide and prioritize which of these clashes are more critical than the others. Therefore, there are two critical steps in a complete clash detection process: 1. software clash detection and 2. prioritization of detected clashes by designers and engineers. This requires the designers and engineers from different disciplines to work together and communicate with each other from the early design phase of the project.

By involving different disciplines from the early design phase of the project, information from the client can be better delivered. As explained by interviewee 3, traditionally, a construction project starts with architects, i.e., the owner first communicates with architects about his or her requirements. At some point, the construction company makes the decision to build, and only after this, other consultants (e.g., engineers) start to join the project. As information delivered from the client is first filtered by the architect, it is likely that some information never reaches the engineers, i.e., there is information loss (Figure 9). Now that BIM-enabled clash detection requires different disciplines to collaborate from the early design phase of the project, information from the client can be delivered to them at the same point. In this way, information loss can be avoided to a large extent, which then contributes to better design coordination, and furthermore, a better construction project. The project management method of involving all members from the beginning of the project is called integrated project delivery (IPD).

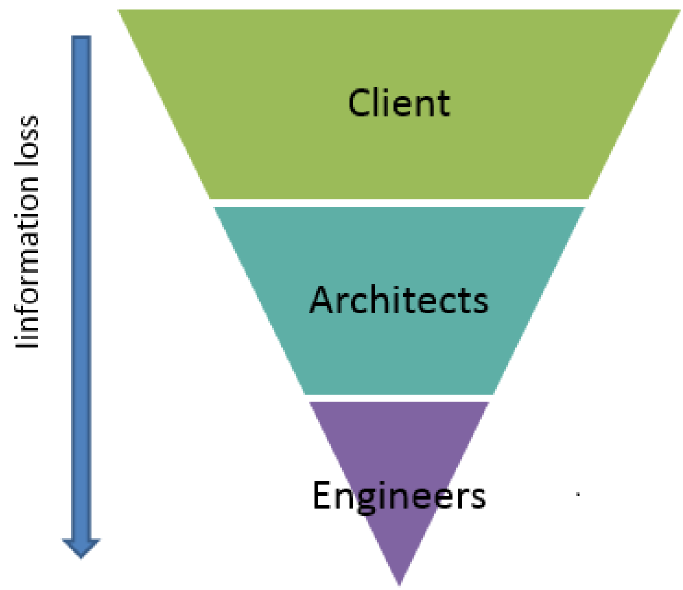


Figure 9 Information delivery process in traditional construction projects

4.1.4 Visualization

BIM-enabled 3D visualization is the second frequently mentioned BEP during the interviews, which is widely understood in the AEC industry as a key benefit of BIM. It is also a key feature that differentiates BIM from conventional design tools. As mentioned by one of the interviewee, "it's one of the typical outcomes of BIM" (Interviewee 1, 2014).

Traditionally, visualizing an architectural design often relies on envisioning the building based on orthogonal drawings or a small-scale physical model or an artist's sketch or watercolor (Autodesk, 2008). The process of reading and interpreting complex and sometimes ambiguous 2D drawings is very time-consuming. It calls for excellent spatial thinking skill to understand the relationship of the drawings, which usually ends up in errors and misunderstanding among different disciplines. The situation becomes even worse when a designer is required to understand a design from outside of his own discipline. For instance, the structure engineer is asked to talk with a MEP engineer about their conflicted designs. Also, when comes to physical models, the cost of producing them has a big impact on the quality of visualizations.

Different types of design visualizations can be produced by BIM. For instance, with BIM tools, 3D renderings can be easily generated in house with little additional effort (Azhar, 2011), as well as animated walkthroughs, 3D architectural models, 3D structural models, etc. (Figure 10). Compared with traditional visualizations, these computer-based visualizations enables design information to be communicated in a much more effective way. Besides design visualizations, since BIM produces accurate and detailed building models, these models can also be used for advanced visualizations, such as creating images for in process-design reviews (e.g., a rendering of an urban building project with the existing structures surrounding it), lighting simulations (e.g., a lighting study that shows precisely how a new shelf design will impact indoor lighting at all times of the day and throughout the seasons) and highly polished marketing materials (Autodesk, 2008).

Figure 10 Examples of different 3D BIM models (Adapted from Skanska, 2015)

In general, 3D visualization benefits different roles involved in an AEC project throughout its entire lifecycle, such as the design team, the client, the construction team, etc. It offers different teams an opportunity to communicate directly and avoids misunderstanding.

For designers from different disciplines, accurate design visualizations produced by BIM tools contributes to open communication within the design team. In other words, the team members build better shared understanding of designs. As explained by interviewee 2, “the real benefits through BIM have been already realized - visualization-enabled open communication. Architects and engineers are working together. Everyone understands the model.” Already in the early 1990s, 3D BIM tools immediately showed great potential in their ability to communicate views of designers through visualization in the development of the project details (Richard, 2002). 3D design models help different disciplines, such as architects, structural engineers and MEP engineers, to get rid of redundant 2D drawings, providing a more intuitive and comprehensible way to share information, communicate design intentions and form mutual understanding. In addition, 3D models facilitate the study of alternative approaches to design solutions (Grilo & Jardim-Goncalves, 2010), which owes to the improved ability to visualize the design proposals in the early project and make the assessment of the spaces and aesthetic finishes of the building and structure.

Besides better internal communication within the design team, 3D visualization contributes to more efficient external communication (i.e., communication with the client), which was frequently mentioned by interviewees. According to interviewee 4, "discussion with the client is one very good benefit of using BIM, otherwise the client has no idea what it will look like or how it will operate". Similar opinion was expressed by interviewee 3, who put great emphasis on helping client to understand the design. With accurate visualizations, the "communication gap" between the client and the design team can be greatly narrowed. As the designs can be vividly represented in the format of detailed 3D models, the client is relieved from the process of interpreting complicated architectural drawings. For instance, through 3D architectural models or model walk-throughs, the client can experience different design proposals in a visual way, and thus can better understand designs and communicates his requirements. In other words, the communication between the design team and the client can be improved, especially at early stages of design process. Besides, as design proposals can be visualized in the early project, the client and design team members can more easily and accurately embrace the details and adjustments that should be made until the design meets the desired goals (Grilo & Jardim-Goncalves, 2010).

3D visualization also helps to ensure the quality of the project by enabling the client to participate in the project in a much more active manner than in conventional construction projects. Traditionally, the client is present only at the beginning of the project to deliver his requirements and then during the commissioning phase to take over the building. The isolation of client from the design and construction processes causes lower client satisfaction, as the end product, i.e., the building, could be different from client's expectation. Also, issues such as cost overrun and project delay are usually out of the client's control. With 3D BIM models, the client can not only better understand the designs, but also the construction process, and thus constantly monitor the project by referring to up-to-date models. For instance, during the construction phase, with 3D BIM models at hand, the client can understand what is happening on site.

During the construction process, 3D visualization benefits both site supervisor and construction worker by help them: 1. get familiar with the project, 2. plan work beforehand, 3. monitor ongoing construction work. With the help of 3D models, site supervisors can easily get familiar with the project, as different information can be accessed from the model, such as the size of objects, quantities, etc. (Interviewee 6, 2014). For construction workers, 3D visualization makes it much easier to understand the project and plan their work beforehand. For instance, if a MEP worker needs to install a pipe above the roof, he can check from the 3D model what has been or will be in the same or near place in advance. The model can be used during relevant meetings as well (Interviewee 6, 2014). In addition, mobile applications that contain 3D BIM models have been developed by BIM software companies such as Tekla to support the construction work on site. For instance, in Finland, there are more than 150 Ipads used on site by site supervisors from company E[2] (Interviewee 6, 2014). Whenever there is something unclear, the supervisor can get relevant information from the application and then follow the instruction. It is also much easier for the supervisor to monitor ongoing construction work, as he can use the 3D models as the benchmark to check whether the work is done as planned, i.e., whether the work matches the 3D model. At the commissioning phase, 3D visualizations can be used to check the quality of the construction work, i.e., whether the building was built as designed.

Another major benefit of BIM-enabled 3D visualization its important role in marketing. For companies in AEC industry, 3D BIM models can be used as excellent web marketing materials. Companies decorate their website by highly polished pictures of 3D BIM models, as well as videos containing 3D animations of the modelling process

[2] Company E: one of the world's leading project development and construction groups; has implemented BIM on many types of projects

done by BIM tools (See Figure 11). In addition, BIM mobile applications supporting 3D visualizations have been developed for marketing purpose, among which Skanska Kodit is a typical example. Clients can download Skanska Kodit for free from the internet, take a tour of the apartment and make adjustments (e.g., where to put the sofa or what kind of surface material to use) before they make the purchase. 3D BIM models are also widely used during meetings with potential client, as they offer a more direct way to communicate and understand the project.

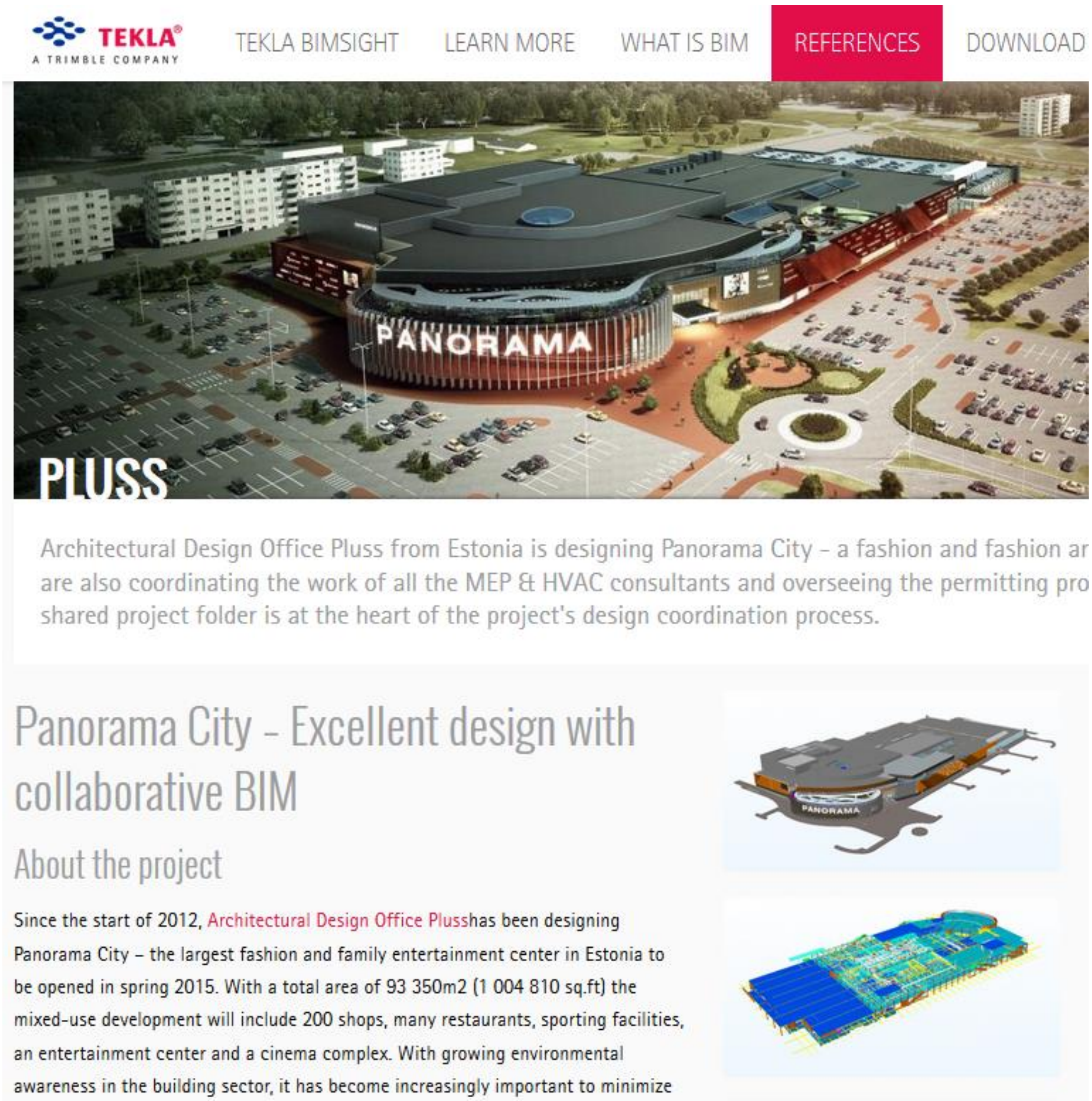


Figure 11 Panorama City – Excellent Design with Collaborative BIM: an example of webpage marketed by BIM visualizations (Tekla, 2015)

4.1.5 Quantity takeoff

Quantity takeoff (QTO) has been mentioned by five out of the eight interviewees as a best BEP. It directly influences the accuracy of cost estimation. Through the utilization of BIM, it is possible to make quantity takeoff considerably more effective, and to increase the utilization of quantity data in different decision-making situations (CoBIM, 2012). As stated by interviewee 4, "so absolutely it is the biggest advantage."

Quantity takeoff is an activity performed by general contractors, subcontractors, cost consultants, and quantity surveyors as part of the construction process. It involves counting the number of items associated with a particular construction project, determining the associated materials and labor costs, and formulating a bid (or estimate) as part of the bidding process. Quantity takeoff is also applied to the pricing process. This process allows the project team to see the cost effects of their changes, during all phases of the project, which can help curb excessive budget overruns due to project modifications. (N.p., 2006)

As a key component in the production of accurate estimate and cost information for clients, quantity takeoff is of key importance for the decision making of AEC projects. In AEC industry, contractors must guarantee a price to the client to participate in the bid on the AEC project, before knowing how much the actual price will be. The estimated price has considerable influence on the bidding result, because traditionally, contractor with the lowest bid is awarded the project. Moreover, cost estimation (i.e., the estimated price) in AEC projects is an important factor for decision making in not only the early phase, but also the detailed design phase (Choi et al., 2014). This arises out of the fact that 70–80% of construction costs are determined by designers′ decisions in the early design stage (Bhimani & Mulder, 2001). Therefore, as quantities drive project costs, the accuracy of quantity takeoff is a critical factor for the financial success of the AEC project.

The earliest estimating were done with pen and paper by the estimator manually. Later, the computer age enabled customers to experience for the first time estimating software and even early spreadsheet applications like Microsoft Excel. The process was improved from paper and pen, however a significant problem existed in estimating software: user input (Beaton, 2015). It was obvious that a solution for taking off the quantities was necessary to eliminate the problem and speed up the estimate. For instance, with the traditional estimating methods, the architect will get a cost estimate at the mid- and end-points of each phase of the design process, since it takes up to three weeks for the cost consultant to generate each estimate (Rinella & Bedric, 2006). In addition, a significant amount of time is wasted in rework. The average number of times that companies end up doing the same quantity searching/calculation is 11. According to interviewee 3, this is "totally a waste of energy and time" and "should disappear as fast as possible".

Different types of traditional estimates are performed throughout the pre-construction and construction processes, whereas the applicability of these traditional estimates are often limited. For instance, cost estimates can be made based on the historical costs per square meter of similar buildings, which is the most common type of estimate. This method can be expressed as: Total cost = cost per square meter x total project area. Another traditional type of estimating method is functional unit price: Total cost = cost per unit x number of units. In general, traditional estimates are easy to perform, but can only be used at the early stage and have fairly low degree of precision. The accuracy and scope of the estimate is greatly influenced by the amount of information available for the estimator. For estimator heavily relying on drawings, the availability of information has considerable influence on the quality of estimate. As noted by interviewee 3, "drawings are always incomplete".

With BIM software, quantities and related information can be automatically generated and reused (Interviewee 5, 2014). This is claimed by interviewees as a huge benefit, as the efficiency and accuracy of quantity takeoff in construction projects can be greatly improved. Processes within estimating, such as quantity survey and pricing, may be automated by using existing BIM software in combination with existing estimating software (Sattineni & Bradford, 2011). As explained by interviewee 6: "With BIM-enabled quantity takeoff, estimators can extract info from the model directly. This has made cost estimation much faster. Usually construction companies need to make cost plans, budgets for each project, which are all based on the quantities and materials. BIM also makes it possible to do that process much faster. The premise is that we need to make sure we have everything in the model." In addition, compared with traditional estimates, with BIM models, estimates can be made at an early stage with much higher accuracy. An example was given by interviewee 1: "From BIM, you can get total quantity information. Before it were all estimates. Nobody knew how much time they would use to finish the construction work. For instance, this building was built 7 years ago. At that time the construction team didn't know how many bricks they needed. Of course they had some estimates, which were from rules of thumb and guessing. Now from BIM you can get total quantity information and very accurate information. For example, how many cubic meters' of concrete you need."

BIM models can be used to generate accurate quantity takeoffs and assist in the creation of cost estimates throughout the lifecycle of a project (Autodesk, 2015). This is because material quantities in BIM models are automatically extracted and updated when any changes are made in the model (Azhar, 2011). In addition, using BIM models enables the project team to see the cost effects of their design decisions and proposed changes during all phases of the project, and this feedback supports better design decision-making and can help curb excessive budget overruns due to project modifications (Autodesk, 2015). It also facilitates increased control of time and costs in a construction project. As explained by Grilo A and Jardim-Goncalves (2010), since the model already contains quantitative information in its model parts, it may be linked to a cost database that produces a cost estimate based on the model quantities. Thus, the cost estimate is directly related to the content of the 3D model and will reflect changes made to the project in the model. AEC cost estimates can be derived from the model quantities throughout the development of the BIM. During the initial phase, the cost can be assessed on a conceptual level, and at a more detailed model level, the cost estimate can also become more detailed.

For construction companies that have adopted BIM, the benefit or quantity-takeoff is prominent. An inspiring fact given by one interviewee further demonstrates the reward for utilization BIM-enabled quantity takeoff: “Most of the biggest Finnish contractors say that they can save up to 70 or 80 percent in cost estimation. It’s based on that they can make quantity takeoff from BIM models provided by designers” (Interviewee 4, 2014).

4.1.6 Scheduling

The fourth frequently mentioned BEP during the interviews was project scheduling, which is one of the key processes during the development of AEC projects. This function of BIM (i.e., project scheduling) is widely understood in the AEC industry as the 4th dimension of multi-dimensional (nD) BIM. Through the utilization of BIM-enabled project scheduling (i.e., 4D BIM), construction work can be carried out with much higher efficiency. For project managers, this is a key advantage of utilizing BIM. As mentioned by interviewee 4, “when you have the quantities and know the recipe (i.e., project schedule), you can estimate the time.”

4D BIM, also referred to as 4D CAD, has been seen as a significant innovation in the evolution of construction scheduling. Before 4D BIM was introduced, traditional methods such as Gantt chart (developed in early ninety’s) and critical path method (introduced in mid ninety’s) were applied by AEC project managers for project scheduling. However, there are certain drawbacks of these two traditional planning methods. For instance, Gantt chart needs to be constantly updated during the project and therefore cannot be used to visualize a project timeline. Besides, the process of updating the chart is ignoring and can be extremely complicated. Although CPM has proven to be a very powerful technique for planning, scheduling and controlling projects, especially for complex and non-repetitive work (Kenley 2006). The criticism of CPM primarily refers to the inability to manage and monitor resource limitations in a way that corresponds to the reality of construction, i.e. work that to a large extent is characterized by repetition (Kenley 2006). With the increasing complexity of AEC projects, traditional scheduling methods became obsolete and the limits of them were hampering the development of the AEC industry. During the 1990s pioneer researchers invented a new presentation method for a construction schedule called the “4D CAD model” (Cleveland, 1989). By adding the 4th dimension, i.e., construction schedule, to 3D BIM models, 4D BIM creates the integration of design and schedule data. More specifically, 4D BIM allows the integration of traditional CPM Gantt chart visualization methods of schedules with 4D visualizations and line-of-balance visualizations (Rogier & Olofsson, 2007).

Usually, AEC projects involve multi-disciplinary teams. Moreover, as noted in the literature chapter, the AEC process is a very complex activity with the following characteristics (Zhang & Hu, 2011): 1) construction products are fixed, while the construction process is flowing, which constitutes the main conflict of spatial arrangement with time-series; 2) tasks are often co-completed by workers from different professions, using different construction machineries; 3) construction is a long-duration, comprehensive procedure with a great number of activities; and 4) the structural features during the construction period differ a lot from those during the service period, therefore it is possible that the most dangerous situation appears in the construction period. Thus, successful management of construction project demands efficient planning and communication.

4D BIM has greatly improved the on-site coordination and collaboration among construction teams. It is also useful for planning and taking control of the schedule to make sure that everything proceeds as planned (Interviewee 6, 2014). In practice, construction schedules and drawings are created at different times by different people (Vacharapoom & Bhokha, 2009). Construction teams use both of these information sources to understand and execute their work by individual implicit interpretation. The process of interpretation causes problems easily, as people could understand differently or misunderstand. This leads to collaboration problems and conflicts on sharing resources. By virtually link construction schedules with drawings, 4D BIM model can overcome these problems. It bridges the gap between the 3D-modeling in the design phase and the planning and scheduling of the construction phase (Büchmann-Slorup and Andersson, 2010), and it helps create explicit visual perceptions. Therefore, 4D BIM models can be an effective collaboration medium for construction teams. As mentioned by interviewee 6, “we can link the schedule to the components of the building, and then we can plan the installation order and schedule with the subcontractors. Besides, We can check if we meet the schedule or not.” Similar opinion was expressed by interviewee 2, “Through better planning of the installation orders (i.e., scheduling), you can avoid people from waiting.”

Figure 12 is an example of a BIM-based schedule for construction work of a structural frame. As can be seen, different color codes visualize building element implementation at different weeks. This offers an easy and direct way for construction workers to understand and share the schedule. Moreover, the visualization presents an overview of the current status of the project, which also help the project manager to monitor the construction process efficiently.

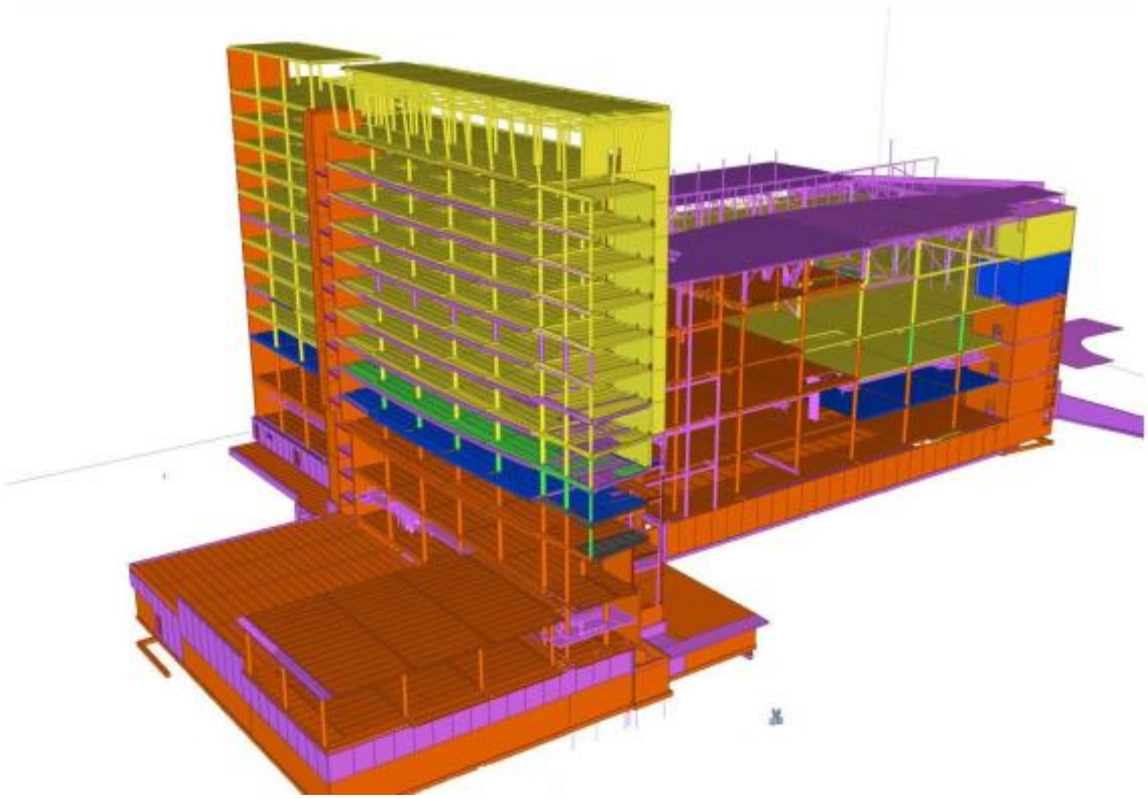
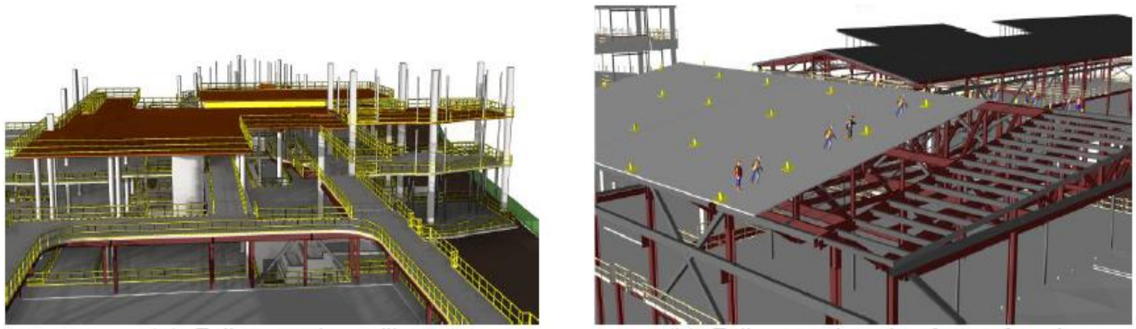


Figure 12 An example of a BIM-based schedule for construction work of a structural frame. Color codes: orange = completed/installed, blue = this week, green = next week,

yellow = scheduled, in over two weeks, purple = scheduled, in over two weeks and a different contractor (Adapted from COBIM, 2012)

There are also other benefits of 4D BIM mentioned by the interviewees. As noted in the section 4.1.3 Clash detection, the third type of clash detection that can be performed by BIM software is 4D/workflow clash detection. It means that clashes in schedules can be detected as well. With 4D BIM, at any user-specified time point, schedule conflict analysis can be carried out according to the plan schedule, actual schedule, milestones, critical path, and priorities (Zhang & Hu, 2011). This function is very beneficial for schedule conflict management. If there are conflicts, the solution can help managers adjust schedules for follow-up works according to the progress of the project (Zhang & Hu, 2011). With efficient project scheduling, logistics of materials can also be managed efficiently to avoid waste of time (Pietillä, 2014). This is because 4D BIM models can be effectively used to coordinate material ordering, fabrication, and delivery schedules for all building components (Azhar, 2011). Besides, the coordination of subcontractors can be improved by sharing 4D BIM models with them.

As an essential part of AEC projects, safety planning/analysis can be carried out with higher efficiency through utilization 4D BIM. It is because the construction team can check, plan and demonstrate beforehand to make sure everything is in the right place, as well as take actions such as falling protection to make sure the workers are safe (Interviewee 6, 2014). This can be implemented by connecting the safety issues more closely to the construction planning, providing more illustrative site layout and safety plans, providing methods for managing and visualizing up-to date plans and site status information, as well as by supporting safety communication in various situations, such as informing site staff about coming safety arrangements or warning about risks (Sulankivi, et al., 2010). See Figure 13 for an example of a BIM-based site specific safety plan.



(a) Fall protection railings (b) Fall protection plan for roof workers

Figure 13 A BIM-based site specific safety plan (Azhar et al., 2012)

4D BIM model also benefits clients by enabling them to understand and monitor the progress of the project. For clients, it is usually very difficult to form a clear overview of the ongoing construction work. It is mainly due to the lack of construction expertise of the clients and the complexity of the project. A typical example of this is shopping center, which involves many different types of construction work because of the diversity of stores. With 4D BIM models, it will be easier for clients to understand the construction process (e.g., what is the next step) and whether the construction teams meet the schedule (Interviewee 6, 2014).

4.2 The utilization of 3D CAD in Finnish shipbuilding industry

4.2.1 "One CAD" solution

Based on the interview results with the seven shipbuilding professionals, it can be concluded that ship design is generally carried out by the "one CAD" solution. It means that different ship design disciplines are using the same CAD tool or CAD tools from the same software vendor. For instance, Intergraph is used in French shipyards, and Aveva in Norwegian shipyards and in Rauma, a Finnish shipyard that was closed in 2013 (Interviewee 8, 2014). In general, each software vendor have its own CAD tool(s) for both hull and outfitting design. The reason behind the "one CAD" solution is very simple. As explained by interviewee 8, "in shipbuilding there is no widely accepted standard like IFC in AEC industry. By using the same CAD tool for different design disciplines, interoperability can be achieved as the design models are in the same data format."

The situation at Company G[3], the shipyard where four of the interviewed shipbuilding professionals work, is slightly different. Due to historical and commercial reasons (Interviewee 11, 2014), at the design stage, several designs tools are used by different disciplines such as hull, outfitting and interior. For hull design, both Napa and Aveva are used, whereas Napa is mainly used at the initial design stage, and Aveva at the detailed design. Cadmatic is used for outfitting design. Both hull and outfitting designs are conducted in 3D. As Company G is specialized in building cruise ships, interior design is also one of the key design disciplines. However, currently, Interior design is the only design discipline that is carried out with 2D CAD tool, i.e., AutoCAD. Figure 14 shows the major design disciplines and CAD tools used in Company G.

An essential process at the design stage is to integrate hull and outfitting models after they are ready. For shipyards adopted the "one CAD" solution, the integration simply means gather the models together, as they are already built in the same data format. However, at Company G, models built by different design tools (in different data format) need to be first converted into one same format. Therefore, there are experts in charge of converting the data. The conversion is carried out manually, once a week. After the conversion, data from Aveva/Napa (the hull design software) will be exported and then imported into Cadmatic (the outfitting design software) (Figure 14). In this way, the hull model is integrated into the outfitting model, and the rest of modelling work is carried out in the integrated model using Cadmatic. Therefore, Cadmatic becomes the "one CAD" solution in the shipbuilding project. As concluded by Interviewee 11, "Cadmatic can be viewed as an integrated solution in our company, although the actual design work happens in both hull (Aveva/Napa) and outfitting (Cadmatic) models."

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[3] Shipyard in Finland, specialized in building cruise ships, car-passenger ferries, technically demanding special vessels and offshore projects.

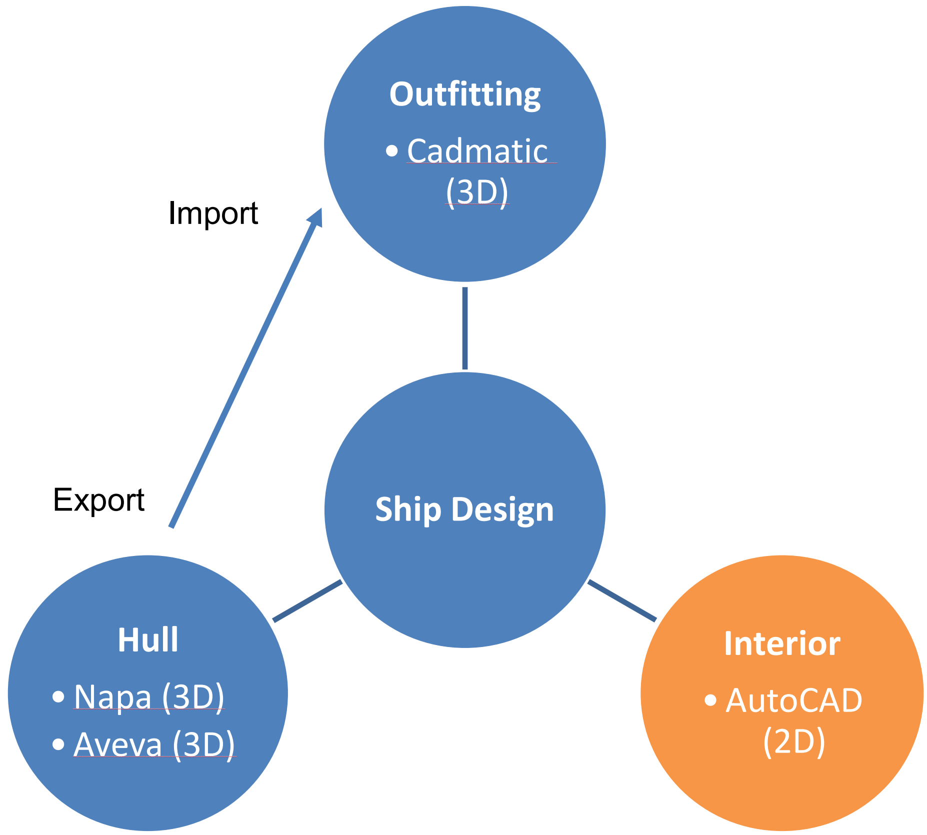

Figure 14 Major ship design disciplines and CAD tools used in Company G

4.2.2 Benefits of the "one CAD" solution

During the interviews, several benefits of utilizing the "one CAD" solution were frequently mentioned by the seven interviewees. As the interviewees have different roles in shipbuilding industry (e.g., engineers from different design disciplines, software vendor, project/operations management professionals, etc.) and relationships with CAD (user, developer, sales and etc.), their understanding of the benefits of the "one CAD" solution are from different angels. In general, the benefits can be divided into two groups, i.e., benefits of using advanced 3D CAD tools and benefits of using the same CAD tool/CAD tools from the same vendor throughout the project (i.e., the "one CAD" solution) (Figure 15).

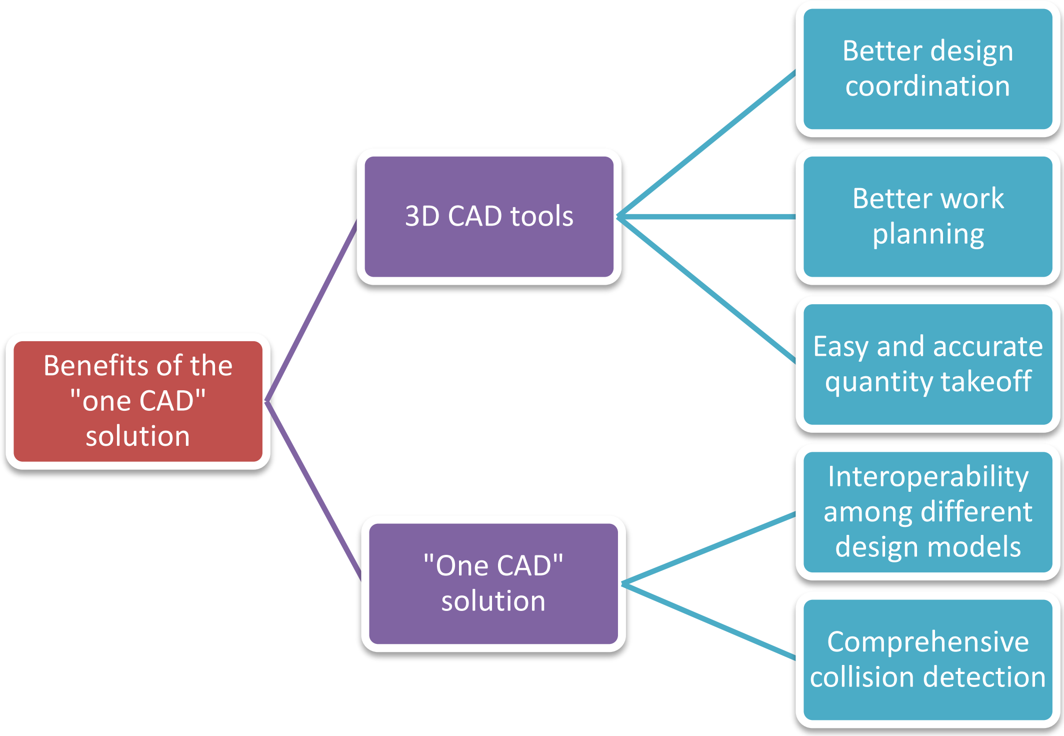

Figure 15 Benefits of the "one CAD" solution

4.2.2.1 Benefits of using 3D CAD tools

Company G has a long history of using 3D models. According to Interviewee 11 (2014), 3D models have been used by hull designers in the company since the 1970s. By using 3D CAD tools such as Aveva and Cadmatic, 3D models with information can be easily generated. Figure 16 is an example of 3D model of the ship machinery area generated by a 3D CAD tool. These models are not merely 3D visualizations of objects, but also contain up-to-date information relevant to the objects (Interviewee 10, 2014). For instance, a door model includes the position ID, system, revision information, material description and etc. Figure 17 is an example of the information that a 3D model contains.

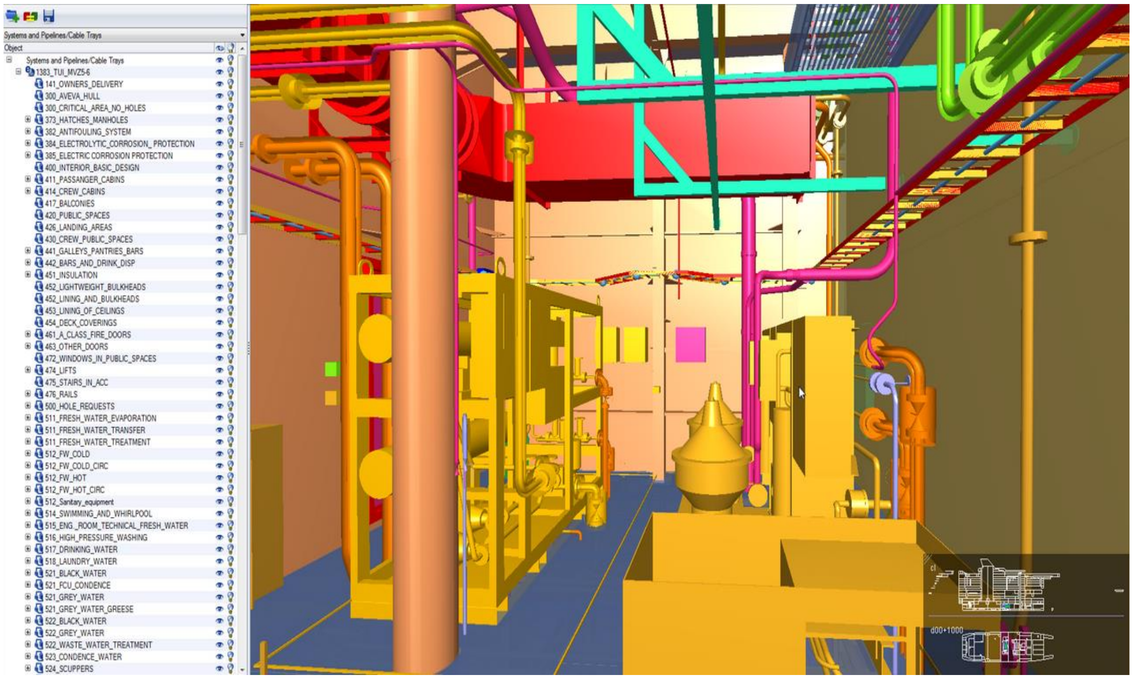

Figure 16 Example of 3D model of the machinery area

System	671_FEED_WATER
Pipeline	6713P2052
Dimensions	33.7x3.2
Finnish Description	KÄYRÄ
STX Matno prefix	614
STX Matno suffix	1290
Angle	89.997
Pipe class	3
Treatment of pipe	83M1-0
Workshop for prefabr	SOV
Fitting Pipe	1
Isometry	D.383.006D.725.602
Spool	305
Area	006D
Target	K08
Stage	YKK
Mass	0.1452
Modification time	Monday 18.2.2013 13:56
Assembly Drawing	D.383.006D.725.602
specification	671_AUX_BOILERS_steel
OutfitArea	006D
Compartment	R050101

Figure 17 Example of 3D model information

3D models enabled better design coordination

Better design coordination can be achieved by using 3D models, which contain both 3D visualizations of and information relevant to the objects. 3D visualizations, for instance, enables much more direct comprehension of design intentions than ambiguous and complex 2D drawings. Therefore, everyone involved in the project can get a clear view of the designs and avoid misunderstanding. 3D visualizations also enable workers to better understand the relationship between different areas/systems of the ship. An example was provided by Interviewee 13: “With 3D models, interfaces between different areas can be more easily identified. For instance, you can easily see with the 3D model where the pipe is coming.”

Usually the design of a ship involves different designers who are sometimes located in various places. As a result, the coordination of these designers is critical for the successful delivery of the design. Through sharing the same models, the designers are also sharing the same information contained in these models (i.e., synchronized design information). This makes remote work easier, as the designers don’t need to sit next to each other in order to share information.

3D models enabled better work planning

Benefits of using 3D models are not limited to the design stage but influence the entire shipbuilding process. This is because, in shipbuilding process, the main phases such as detailed design, procurement, production etc. are not carried out sequentially but concurrently. Instead, there are significant parts of overlap between these phases in terms of time (Figure 18). In general, for people working at different phases in a shipbuilding project, 3D models help to improve work efficiency by enabling them to understand the status of ongoing work and plan for work in advance.

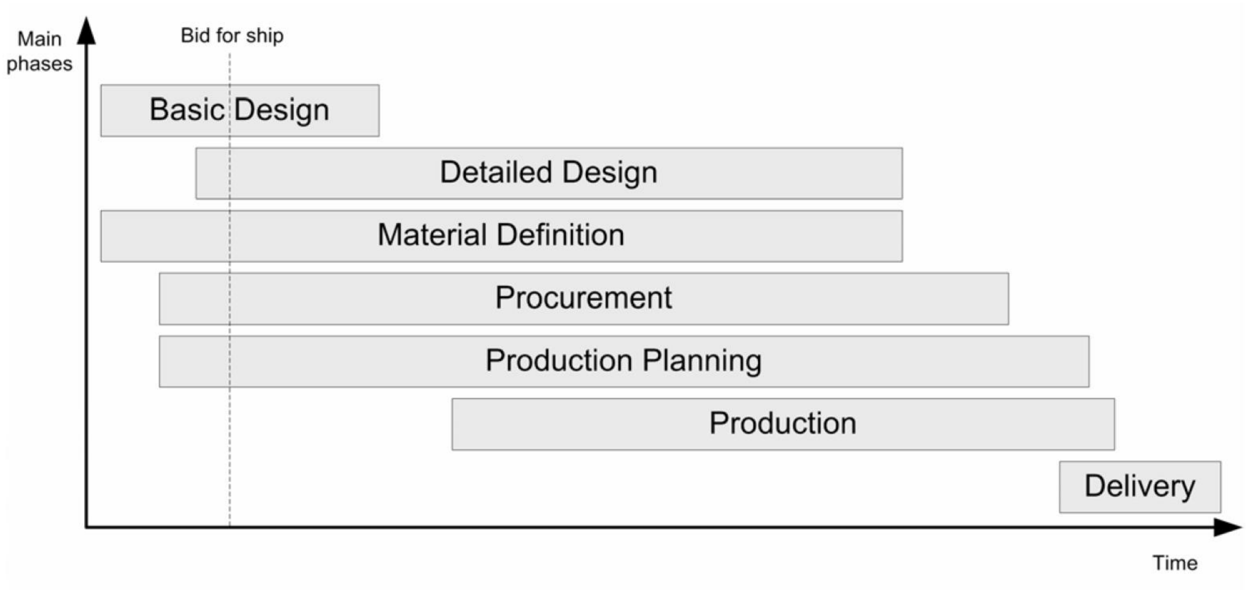

Figure 18 Main phases in the shipbuilding process.

As noted by interviewee 14, in some advanced shipyards, there are already some partial solutions that link 3D models to project management. For instance, in Damen shipyard (i.e., a Dutch shipyard), construction workers can easily understand the status of the ongoing work by referring to the constantly updated 3D models. Different colors are used to mark objects under different status, e.g., green means installed and red means not. This practice has been used in Damen since 2010 and proved to be very efficient (Interviewee 14, 2014).

With 3D models, workers can better plan their work as well (Interviewee 14). For instance, before the actual work starts, installation workers can use 3D models to get familiar with the surroundings, to check when the installation should be finished and how this area will look like after installation. For workers who are in charge of welding different blocks together, 3D models can work as detailed instructions that help the workers to better understand the welding process. For those who are responsible for planning the installation orders, 3D models enable them to check beforehand the size of the working areas so that they can make sure which objects can be carried inside of the ship. In, general, "the use of 3D models is growing everywhere", as concluded by interviewee 14.

Easy and accurate quantity takeoff

From the 3D model, a bill of materials can be exported directly, which lists quantities of all the materials needed for assembly or prefabrication. This is because when the designer is working on a detailed design drawing for a certain area using CAD software such as Cadmatic, he or she is generating the bill of materials from the software at the same time. The bill of materials essentially means easy and accurate quantity takeoff, as all the quantity information of materials is included in the 3D model and can be extracted at any time.

Accurate quantity takeoff can help the shipbuilding project to better manage materials and costs. At company G, the bill of material is combining used with the material management system – Mars. For instance, if the construction workers want to know the length of a certain pipe, the designer can extract the information from the 3D model and then import it to Mars so that the construction workers can receive the information. In addition, as prices of materials are included in Mars, the cost of materials can be easily calculated.

4.2.2.2 Benefits of using the same CAD software

As noted in section 4.2.1, Cadmatic is seen as the "one CAD" solution in Company G, despite that there are several CAD tools used at different design stages and disciplines (Napa for initial hull design, Aveva for detailed hull design and Cadmatic for outfitting design). This is because after the hull model has been integrated into the outfitting model, the rest of the modeling work happens in the integrated model by using Cadmatic. As emphasized by Interviewee 11, company G is unique in being able to implement Cadmatic as a common tool for the whole project network, regardless of where the design work is carried out, in the shipyard or in some subcontractor's office.

Interoperability among different design models

Due to that different CAD vendors usually use different data formats, using CAD tools from different software vendors in a ship design project often results in barriers of communication and coordination among design models. By using the same CAD software throughout the ship design project, designs models from different disciplines are built with the same data format. Therefore, interoperability among different design models can be achieved. This is widely understood by the shipbuilding experts as the main reason for adopting the "one CAD" solution.

Comprehensive collision detection

Collision detection is understood by the interviewees as the basic function and a key benefit of using 3D CAD tools (Interviewee 11). In shipbuilding industry, collision detection is firstly carried out automatically by CAD software and then performed by designers, i.e., the designers need to find out the critical collisions among the ones detected by the software. In other words, the collision detection process is semi-automatic (Interviewee 8). This is because in shipbuilding projects, there are usually a significant number of collisions. On one hand, the designs evolve gradually and are companied with many changes (Interviewee 13). One the other hand, there are many complex systems on a ship while very limited area. Therefore, it is important to get help from software tools to find out the collisions.

In company G, Cadmatic is used for collision. As noted by Interviewee 11, the collision detection carried out by Cadmatic is quite comprehensive. This is due to that the shipyard is able to integrate the hull and outfitting models into the same software (Cadmatic) and keep the information in the models up-to-date. Different design disciplines are working in the same integrated model at the same time. Whenever one designer makes any change to the model, e.g., placing an object in the engine room, it will be seen by all the other designers immediately. At the same time, collision detection can be carried out to check whether this object causes any collision. Especially for cruise ships that "make money by saving space" (Interviewee 14), the economic benefit of effective and comprehensive collision detection can be significant, as the utilization of space can be greatly improved.

4.2.3 Limitations of the "one CAD" solution

In spite of the prominent benefits of using the "one CAD" solution, there were several limitations of the solution brought up by the interviewees. In fact, it were some of the limitations that triggered the interest of these shipbuilding professionals in seeking for advice from BIM.

4.2.3.1 No open standard

As noted in section 2.2.2.2, the lack of interoperability among different CAD systems is widely discussed in shipbuilding literature as a major limitation of current 3D CAD tools. Different from AEC industry in which IFC is shared by different BIM software, there is no open standard in shipbuilding industry, i.e., different CAD vendors are using their own standards to develop the software. Although the "one CAD" solution can help to achieve interoperability among different design models within a single shipbuilding network (i.e., a shipyard and its contractors and subcontractors), there are still limitations that this solution cannot overcome.

In a shipbuilding project, the integration of design models built in different data formats usually results in information loss. For instance, at Company G, the hull model designed by Napa/Aveva needs to be converted before integrated with the outfitting model built by Cadmatic. The conversion of hull model causes information loss because of different data formats used by Napa/Aveva and Cadmatic. Depending on the significance of the difference between data formats adopted by the software, the level of information loss varies. As explained by Interviewee 10, since Aveva and Cadmatic use very different data formats, only key metrics can be kept; whereas with Napa more information can be kept, as the data formats used by Napa and Cadmatic are quite similar.

The lack of a widely accepted open standard also prevents different ship design disciplines from the positive synthesis of adopting the state-of-the-art CAD tools. In other words, since there is only one CAD tool used throughout the shipbuilding project, each design discipline might not be able to use the CAD tool that fit their needs best. As shipbuilding is a complex process consisting of disciplines that differs significantly in terms of design requirements and construction methods, it is very unlikely that there would be a single CAD tool that is the best for all the disciplines. For instance, the hull designer might prefer software A while the outfitting designer thinks software B is the best. By adopting the "one CAD" solution, different design disciplines end up compromising with each other (Interviewee 13). Instead, if an open standard is adopted by CAD vendors, all the design disciplines can use the CAD tool that is the most suitable without worrying about the information exchange with other CAD software.

4.2.3.2 Interior design still in 2D

Currently, interior design is the only design discipline that is carried out with 2D CAD tools such as AutoCAD (Figure 14). As explained by Interviewee 8, the lag of interior design is mainly due to the fact that most of the ships constructed are not for cruising. These ships basically consist of the engine room and the hull structure, and there is a very limited area where people can move. For instance, it is common that there are only 10 people working on a large ship. Therefore, for the design of such ships, interior is less important than hull and outfitting. As a result, software companies such as Intergraph, Aveva and Cadmatic don't provide CAD tools for interior design.

For cruise ships, interior design is of great importance as it plays a key role in attracting and retaining passengers and thus directly influences the earning power of the ship. However, the current practice of interior design is suffering from the lack of proper 3D CAD software. Therefore, in order to improve interior design, Company G is looking for help from the AEC industry, in which interior/architectural design has been greatly emphasized and carried out in 3D nowadays.

4.2.4 Other software applications in Finnish shipbuilding industry

During the interviews, it was also found that besides CAD software used for design, there are other software systems used for functions such as project management, document management, material management, etc. Processes such as reporting and checking, scheduling, cost estimation are performed in these systems. Therefore, in order to carry out a shipbuilding project successfully, it is very important to management the coordination of these software systems. Figure 19 shows the software systems used by different functions at Company G.

Figure 19 Software systems in a Finnish shipyard

5 Discussion and implications

Through the literature review on BIM in AEC industry, benefits of BIM in AEC industry were studied, which answered RQ 1" what are the benefits of BIM in AEC industry". Based on interviews with the BIM experts, four BEPs were identified and further studied. Thus, RQ 2 "what are the best BIM-enabled practices in AEC industry in Finland" were addressed. Besides, through interviews with shipbuilding professionals and the literature review on CAD in shipbuilding industry, both benefits and limitations of current 3D CAD tools were revealed, which answered RQ 3 "what is the current state of 3D CAD in shipbuilding industry; how 3D CAD are tools utilized in shipbuilding projects in in Finland".

Chapter 5 addresses the last research question, RQ 4 “Which best BIM-enabled practices can be transferred to shipbuilding industry”. Based on the interview results, discussion on the transferability of the identified BEPs into shipbuilding industry is carried out. In addition, BIM experts’ perceptions of shipbuilding industry are discussed as an interesting finding of the research as well as a foundation for further study of these two industries. Besides, other implications on future research are presented as well.

5.1 The transferability of BEPs to shipbuilding industry

Four BEPs were identified through interviews with BIM experts, i.e., clash detection, visualization, quantity takeoff and scheduling. Based on discussions with shipbuilding professionals, it was found that there are already several similar or more advanced practices enabled by 3D CAD in shipbuilding industry. Identified best BEPs and similar practices enabled by 3D CAD are summarized in Table 10.

Table 10 Best BEPs and similar practices enabled by 3D CAD

No.	BIM-enabled Practices	Similar practices enabled by 3D CAD
1	Clash detection	Collision detection
2	Visualization	Visualization
3	Quantity takeoff	Bill of materials
4	Scheduling	None

5.1.1 Collision detection

In both AEC and shipbuilding industry, collision detection is an essential practice to find out possible collisions between different models and thus to ensure the integration of these models carried out successfully. It is understood by professionals from these two industries as a key benefit of utilizing BIM (in AEC) and 3D CAD (in shipbuilding). Although there are three types of clashes that BIM software can detect (Table 9) and collision detection only refers to the detection of hard clash (i.e., the first type), the interviewed BIM experts generally thought that 3D CAD can carry out more comprehensive collision detection than BIM. This is mainly due to that collision detection in shipbuilding industry is more complicated than that in AEC.

Three factors have contributed to a higher degree of complexity of collision detection in shipbuilding industry. First of all, as there are usually a higher number of systems (e.g., machinery, electricity, interior, HVAC, outfitting and etc.) and objects in a ship than in a building, the workload of collision detection in a shipbuilding project is generally higher than that in an AEC project. Secondly, due to the very limited area on a ship, the utilization of space is more compacted in shipbuilding than in AEC. This is especially true for shipyards specialized in building cruise ships, such as company G, as cruise ship owners want to make the most use of space so that the ship can generate maximum revenue. As implied by several shipbuilding professionals, the more compacted the space is utilized, the more collisions there are likely to be. The third factor is that collision detection in shipbuilding is carried out following stricter standards than in AEC, due to the higher safety requirements of shipbuilding. This is quite understandable, as the damage can be fatal when a ship fails when sailing. Therefore, based on the fact that collision detection in shipbuilding industry is more complicated than in AEC, it can be concluded that 3D CAD is likely to be at a more advanced stage of collision detection than BIM.

5.1.2 Visualization

Besides collision detection, visualization is another practice enabled by both BIM and 3D CAD, which is understood as a basic function of these software tools. Different kinds of 3D visualizations, such as 3D renderings, 3D models, animated walk-throughs and etc. can be easily generated with these two types of software. Moreover, benefits generated from utilizing 3D visualizations are similar in AEC and shipbuilding industries. For instance, benefits such as higher quality of design, better design coordination and communication, and easier work planning were mentioned by professionals from these two industries. Basically, 3D visualizations have relieved designers in these two industries from complicated and obscure 2D drawings to a large extent.

In spite that both BIM and 3D CAD can generate fine 3D visualizations, there is a subtle difference between the perceptions of object-oriented 3D modeling in AEC and shipbuilding industries, which is probably due to that shipbuilding has a longer history of using object-oriented 3D models than AEC industry. For shipbuilding professionals, "object-oriented 3D modeling" is understood as a routine or a norm rather than a benefit. Such perception was revealed several times during the interviews, when the shipbuilding professionals were asked about object-oriented 3D models. For instance, both interview 9 and 10 (designers working with CAD tools) said that they had only worked with object-oriented 3D models since they started working at the shipyard. As mentioned by interview 13: "I had discussion with Company E[4] and got the feeling that they are far behind us." On the other hand, "object-oriented 3D modeling" is now a trendy topic in AEC industry. It is understood in the AEC industry as the key feature that differentiates BIM from traditional CAD. Moreover, object-oriented 3D modeling it has been promoted as a key benefit that AEC companies can get by utilizing BIM. In other words, it is one important reason for AEC companies to adopt BIM. Apparently, the utilization of object-oriented 3D modeling in shipbuilding industry has already come to a mature stage, whereas it is still an "in" topic in AEC industry.

5.1.3 Quantity takeoff

The processes of generating quantity takeoffs in AEC and shipbuilding industries are very similar. With BIM software, measuring quantities manually from drawings is replaced by computer-assisted measurement, and quantity information can be automatically generated and reused. Similarly, in shipbuilding industry, a bill of materials can be exported directly from the 3D model, which includes quantity

[4] One of the world's leading project development and construction groups; has implemented BIM on many types of projects

information of all the materials. In other words, in both industries, the process of quantity takeoff is carried out computer-assisted. Accurate quantity information is incorporated in 3D models and thus can be easily generated and reused.

As mentioned by interviewees from both industries, the major benefit of quantity takeoff enabled by BIM/3D CAD is accurate cost estimates, which can be realized by linking the quantity information to a cost database. For instance, in Company G, the bill of materials is combining used with Mars (i.e., the material management system that contains price information) to calculate the cost of materials. Therefore, since cost estimates in these two industries are carried out with a similar method, i.e., by linking the quantity information to a cost database, it is hard to tell which industry is more advanced in this respect.

However, there is likely to be a significant difference between shipbuilding and AEC industries regarding the accuracy of cost estimates at the very early stage of the project. In both shipbuilding and AEC industries, contractors must guarantee a price to the client to participate in the bid on the project, before knowing how much the actual price will be. At this stage, only initial design has been made and thus there is no detailed 3D model based on which accurate cost estimates can be made. Therefore, bidding price is usually calculated based on experience and historical data. As shipbuilding industry has very comprehensive data management systems, i.e., product libraries with rich historical data, cost estimates at the early stage can be made with relatively high accuracy. As told by Interviewee 13, who has vast shipbuilding project management experience, the total material overrun in shipbuilding projects is plus or minus eight percent, which is “not too bad”.

On the contrary, AEC industry is far behind shipbuilding regarding data management. In fact, BIM experts have been actively promoting the benefit of BIM as an information management tool, raising the importance of managing building information throughout the lifecycle of the building. Unlike shipbuilding projects which benefit from rich historical data, traditional AEC projects usually start from scratch without any product libraries, and each AEC project is seen as an individual. As a result, the cost estimates made at the initial stage of traditional AEC projects are rough estimates with low accuracy, due to the lack of properly maintained relevant historical data.

5.1.4 Scheduling

4D BIM, i.e., 3D BIM models with scheduling information, was seen as a significant innovation in the evolution of construction scheduling by the BIM experts. It creates the integration of design and schedule data, which is one typical feature that differentiates BIM from conventional 3D CAD.

In generally, AEC project managers are the ones most satisfied with 4D BIM. By adding the 4^{th} dimension to 3D models (i.e., linking the schedule to the components of the building), 4D BIM improves the coordination and collaboration among different project teams, e.g., design, construction, logistics. It also enables an easy overview of the status of the ongoing project, which not only the project members, but also the client can understand. In addition, with 4D BIM, schedule conflicts (i.e., the third type of clash - 4D/workflow) can be easily detected.

Unlike nD BIM in AEC industry which can incorporate multiple dimensions such as scheduling (the 4^{th} D), estimating (the 5^{th} D), and building lifecycle information (the 6^{th} D), 3D CAD in shipbuilding industry is only for design-related tasks. In shipbuilding projects, besides 3D CAD for design, there are different software systems used for functions such as project management, document management, material management, etc. (Figure 19). For instance, Company G uses Safran for project management, i.e. to schedule the operations and manage the resources of shipbuilding projects. However, as the interviews with shipbuilding professionals mainly focused on 3D CAD (i.e., Cadmatic and Aveva), Safran, as a project management tool, was not discussed thoroughly. Thus, it is unclear how processes such as scheduling are carried out in shipbuilding projects, what are the limitations of current project management tool or whether BIM can be a better solution.

Although the shipbuilding project management tool was not studied in the interviews, based on opinions of the shipbuilding professionals, it was clear that shipbuilding industry is gradually moving towards the integration of different software systems, i.e., a direction that BIM has been approaching. As mentioned by Interviewee 14, who works for a supplier of 3D CAD for shipbuilding industry: "One of our main targets in the future is to integrate Safran with the 3D model so that people can directly see the schedule from the model, e.g., which objects should be delivered this week and next. This is the 4D BIM, actually." Therefore, in terms of the integration of different software systems, AEC industry is probably at a more advanced stage than shipbuilding, based on that BIM has already been used (although not extensively) as an integrated solution for not only design, but also scheduling, estimating and etc.

5.2 Perceptions of "the other" industry

In addition to the identified BEPs, another interesting finding from the interviews is the perceptions of "the other" industry that these professionals have. Although the research was originated from shipbuilding professionals' interest in learning from AEC about BIM, it was found during the interviews that BIM experts generally had the opposite idea, i.e., AEC industry should learn from shipbuilding. As told by Interviewee 1 when first heard about the research topic, "it's amusing that shipbuilding is seeking for advice from AEC industry. We think it should be the other way around. Shipbuilding is clearly more productive than us." Similar opinions were shown by all the seven BIM experts when asked about their impression on this research topic. In addition to the adoption of CAD tools, BIM experts think the higher productivity of shipbuilding also owns to more advanced product data management, supply chain management, process management, maintenance and etc.

It was found through the interviews with shipbuilding professionals that BIM is a relatively new topic in shipbuilding industry. Two out of the seven shipbuilding professionals had never heard about BIM. For those who had previous knowledge of BIM, their understanding was generally at a preliminary level, i.e., they have "heard about" BIM, which is currently a very hot topic in AEC industry and a comprehensive tool for AEC projects. It is likely that the active promotion of BIM in recent years has greatly raised the awareness of it in not only AEC, but also other industries such as shipbuilding. In other words, regardless of the technological development of BIM, the positive image of BIM among shipbuilding professionals at least proves that the marketing of BIM has been carried out successfully.

5.3 Implications

Though surprising, it was demonstrated by the study on the transferability of identified BEPs to shipbuilding industry that BIM professionals' perceptions of shipbuilding industry were mostly right. In general, shipbuilding industry is more advanced than AEC at the adoption of CAD tools for design related tasks such as collision detection and the utilization of object-oriented 3D model. Besides, in spite that both BIM in AEC and 3D CAD in shipbuilding can generate easy and accurate quantity takeoffs, initial cost estimates of shipbuilding projects can be made with higher accuracy than AEC projects due to shipbuilding's well-maintained historical data. The only exception is the fourth identified BEP, i.e., scheduling. Although it is unclear whether the scheduling function of BIM is better than that of the project management software adopted in shipbuilding, regarding the integration of different software systems, AEC industry is at a more advanced stage than shipbuilding.

In addition to the study on the transferability of identified BEPs to shipbuilding industry, there are several other important implications from the research. For instance, based on the study of BIM in AEC and 3D CAD in shipbuilding, it became clear that there are several factors contributing to the differences of CAD adoption in these two industries. For future study on these two industries, the following two factors should be noticed beforehand.

First of all, in spite that both shipbuilding and AEC projects are complex and long-last processes that involve multi-disciplinary cooperation, the structures of the project networks of these two industries are actually different. In shipbuilding projects, the shipyard is without doubt the center of power, in other words, on the top of the hierarchical project network. The shipyard has comprehensive knowledge of the end product (i.e., the ship) and is in charge of the whole project process. Thus, most of the decisions are made by the shipyard, e.g., types of software different parties should use, ownership of the shipbuilding models and etc. On the contrary, the project network in AEC industry is rather flat. The power of different stakeholders in AEC projects is quite equal and their interest sometimes contradicts. For instance, it is common in AEC industry that the client (i.e., owner of the building) cannot give clear instructions for the project because of the lack of relevant knowledge, since many clients are one-time owner. Besides, the building constructed is not always exactly as designed due to changes made by the construction company. Therefore, the adoption of new technology or rules in AEC industry can be quite difficult due to the flat network, as no one has enough control over the whole project network. In contrast, the adoption of BIM or other technology in shipbuilding industry can be much easier and faster, as the shipyard can make the decision and implement it throughout the project network.

Secondly, there is a fundamental difference between the understanding of the roles of BIM and 3D CAD from AEC and shipbuilding industries. In shipbuilding industry, 3D CAD is only for design. Other tasks such as scheduling, estimating, and product information management are carried out with other specific software systems. In other words, in shipbuilding projects, the division of work among different software systems is very clear. On the contrary, in AEC industry, BIM is much more than a design tool. Although 3D BIM is essentially 3D CAD, multiple dimensions such as scheduling (the 4^{th} D), estimating (the 5^{th} D), and building lifecycle information (the 6^{th} D) can be added to 3D BIM to make a comprehensive building lifecycle management tool. As shipbuilding industry is now moving towards the integration of different software systems, it is likely that the boundaries between these software systems will be blurred. In order to better comply with this trend, shipbuilding professionals should also shift their understanding of these software systems from “isolated islands” to an integrated solution.

Although it was found that shipbuilding industry is generally at a more advanced stage than AEC regarding the identified BEPs, the current research also revealed the limitations of 3D CAD tools that shipbuilding is facing. In general, there are three major limitations of current 3D CAD tools: 1. the lack of interoperability among different CAD systems, 2. the lack of proper 3D CAD tools for interior design, 3. initial design is still carried out in 2D. Therefore, for future research aiming at increasing the productivity of shipbuilding industry, these three limitations can be good starting points. For instance, shipbuilding industry can learn from AEC about the implementation of open data standard, since IFC has been successfully implemented in AEC as a prerequisite for open BIM. Besides, for cruise ships, interior design is of great importance as it plays a key role in attracting and retaining passengers and thus directly influences the earning power of the ship. However, the current practice of interior design is suffering from the lack of proper 3D CAD software. Therefore, in order to improve the interior design of cruise ship, a market research can be conducted among the architectural design software in AEC industry in order to see whether there is a proper solution that can be adopted by shipbuilding.

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