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Impact of BIM on the productivity in design process

A case study within an architectural company

Master's Thesis in the Master's Programme Design & Construction Project Management

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Department of Civil and Environmental Engineering
Division of Construction Management

CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Civil and Environmental Engineering
Division of Construction Management
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

Building Information Modelling (BIM) is considered as revolutionary approach which is utilising information technology in the construction industry, and has an impact on the development of new ways of thinking about planning, design, construction and management of the buildings. BIM is likely to increase the quality of the design and construction processes. It is also believed to increase trust in the relationships between actors involved in the construction process. However, the technology presents some technical problems and is believed to cost more than traditional design methods. The purpose of this master's thesis is to investigate the impact of BIM application process on the architects' productivity during the design of the building, based on the analysis of time-effort distribution curves. Also, potential for sharing benefits and risks related to BIM application is investigated. The study may be important for design and construction companies, who aim to increase their productivity through the application of BIM. A case study of four multi-residential buildings in Gothenburg area was done. The methodology framework included: reviewing literature, collecting data, producing time-effort distribution curves and productivity diagrams, performing interviews and undertaking direct observations. The current study finds that productivity is not directly connected to the complexity levels of a particular project, if BIM is applied. The most important findings are that the application of BIM management can increase the quality of design, reduce the time and cost during the construction stage and improve collaboration between project actors. However, productivity of teams employing BIM is also reduced by the technical issues, implementation challenges and psychological barriers. Additionally, cost and time seem to be issues of BIM design process, but they are more than likely to be compensated during the construction process. Analysis of time-effort distribution curves are to a large extent consistent with theoretical curves proposed by MacLeamy (2008). However, some deviations can be observed for projects representing advanced BIM model-based collaboration. A possible explanation for this might be that lead times, administrative procedures and procurement processes are reflected in the curves. Risks and benefits of BIM employment seem to be shared with consultants to some extent. However, new procurement methods like partnering or Integrated Project Delivery are envisaged to better support the integrated BIM design.

Key words: BIM, productivity, time-effort distribution curves, design process, collaboration, Project Studio.

Contents

Preface

This master's thesis is the final part of my studies at Design & Construction Project Management at the Department of Civil Engineering, division of Construction Management at Chalmers University of Technology. The work on the thesis was carried out during spring 2015 mostly at Liljewall Arkitekter and partly at NCC, both located in Gothenburg.

There are many individuals and events that have affected my thinking and had an impact on the final shape of this thesis, since the beginning of my management studies in 2013. In particular the following deserve an honourable mention.

First of all, Mattias Roupé who inspired me to investigate Building Information Modelling as my teacher at Chalmers and later guided me through the research process during this master's thesis as my supervisor. Thank you for all the great discussions and your valuable comments.

Secondly, I would like to thank Kristen Broberg, BIM Manager at Liljewall Arkitekter for making this thesis possible to realise. Thank you for your time, willingness to share with me all information necessary to proceed with this work and for all your support. I also wanted to acknowledge the input of Janni Tjell who acted as my advisor from NCC regarding Project Studio process, providing also appreciated academic input as a PhD student at Chalmers.

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Last, I am grateful to my dear husband, who supported me constantly during my studies and in delivering this thesis.

Olga Sandberg

Gothenburg, May 2015

Notations

BIM	Building Information Modelling
D-B	Procurement method called Design and Build
D-B-B	Procurement method called Design and Bid and Build
IPD	Integrated Project Delivery
PD	Pre-design stage
SD	Schematic Design stage
DD	Design Development / Detailed Design stage
CD	Construction Detailing / Documentation stage
PR	Production stage
LEED	Leadership in Energy and Environmental Design
2D	Two-dimensional design
3D	Three-dimensional design
CAD	Computer Aided Design

1 Introduction

1.1 Background and problem definition

Building Information Modelling (BIM) is fast becoming a key approach in the construction industry. It is considered a revolutionary method which is applying information technology within the fields of architecture and construction. This new technology influences entire design and construction processes and has an impact on the development of new ways of thinking about planning, design, construction and management of the buildings (Hardin, 2009). A particularly interesting part of the process is the design stage where architects together with engineers and even contractors, are working with the BIM model. BIM can play an important role in addressing the issues of quality and cost in the construction. It gives a potential to the quality increase of completed buildings achieved by testing virtual buildings, likewise adding value during the design process which can be passed to the construction phase.

The BIM process is likely to increase efficiency during the transition between design and construction phases which is based on exchanging the 3D model, instead of using traditional 2D documentation (Eastman, et al., 2011). Since the model includes project data, it is likely to reduce information losses caused by printing and it would also have the potential to increase quality throughout the entire process (Chen, et al., 2013). According to Bryde (2013), BIM can enhance the shift from the traditional model based cooperation to the Integrated Database.

Employment of BIM can also increase the trust in the relationships between actors involved in the construction process. There is also potential to develop new methods of collaboration like Integrated Project Delivery (IPD) (Eastman, et al., 2011), when all the actors involved can see the progress or lack of progress by each other. Large meetings attended by all actors involved in the process increase the natural surveillance and monitoring of the progress between the parties. Many of the potential collisions of the building elements can be detected and removed in the virtual model, before the production even starts. Also, BIM can stimulate a more collaborative form of work between architects and contractors.

However, the technology presents some technical limitations and is believed to cost more than traditional design methods (Bryde, et al., 2013). The risk in the BIM implementation lies in the lack of commonly used BIM formats between architects and contractors (Chen, et al., 2013). The successful implementation depends a lot on surrounding factors like management and project team skills (Eastman, et al., 2011). Even if the architectural company invested time and money into software implementation and training of architects, the value adding elements can be lessened if the contractor has no expertise of a BIM model and requests 2D documentation instead. In cases where the contractor benefits financially from the utilization of BIM models produced by consultants, the financial benefits appear not to be shared with the consultants, who contributed to adding value by producing BIM documentation.

Moreover, design teams using BIM (Bryde, et al., 2013) may experience significant increase of time needed to complete the design. MacLeamy's time-effort distribution curve, illustrated in Figure 2.2 in Section 2.1.2, shows that overall workflow when BIM is applied has its peak during the detailed design stage, in contrast to the traditional drafting-centric design workflow, where the peak comes in the later construction stage (MacLeamy, 2008). However, this concept has recently been challenged by Lu et al. (2015) who demonstrate that the curves proposed by MacLeamy do not reflect the reality of BIM projects. To date, there has been no reliable evidence that applying the BIM design has a positive effect on the productivity of architects during the building design stage. Numerous authors, for example Jung & Joo (2011) and Barlish & Sullivan (2012), point out the difficulties with the assessment of BIM effectiveness and highlight the need for the evaluation of strategic advantages and business benefits resulting from BIM. Bryde et al. (2013) even suggest the need for the more detailed study assessing the impact of BIM on the particular projects.

1.2 Purpose

The purpose of this master's thesis is to investigate the impact of the BIM application process on the architects' productivity during the design of the building. The general opinion about BIM is that it will become the new standard for the entire construction industry. However, few companies today are utilizing BIM's full potential. This thesis tries to answer the question of the effect of using model-based cooperation methods in the architectural practice, by examining its effects on the time-effort distribution curves and productivity within the architectural design.

1.3 Objective

The objective of this thesis is to give answers to the following research questions:

- How does BIM application influence productivity during the design process?
- How does BIM application influence collaboration during the design process?
- How the potential benefits and risks can be shared among all actors who are involved in the process?

The impact of BIM on the productivity is analysed in numerical terms, but also its impact on the collaboration and development of the new working methods is considered. The influence of BIM on the cooperation between architects and contractors and potential increase of trust are investigated as well. Finally, the utilisation of the added value of the architectural BIM models by the contractors and potential to share the possible gains between all actors involved in the process is studied.

1.4 Limitations

The report is based on the analysis of four selected projects which were delivered for different clients. The delivery processes and project design phases differed slightly from one project to another. Additionally, the concept design and detailed design stages for one of the projects were performed by another architectural company, which limits possibilities for the time-effort distribution curve assessment in those two stages. Due to the fact that project data was historical, some information was unclear and not possible to track back accurately. Much better results could be achieved if the author had an opportunity to track the ongoing projects, but that was not feasible due to the limited time scope.

1.1 Disposition

The thesis begins with the literature review which forms the theoretical framework for this study. In this section various definitions of BIM and productivity are explained. Later, previous research studies regarding the differences between the projects in different BIM maturity stages are described, following studies analysing how BIM impacts the productivity are presented.

Thereafter, the methodology is presented in Chapter 3 describing how the comparative study of four similar residential projects was conducted. This part contains the analytical section including the projects complexity comparison, time and productivity studies as well as a more empirical part based on the direct observations and the interviews with architects, project managers and BIM managers.

The methodology is followed by presentation of results. First of all, the complexity comparisons are presented. Secondly, time-effort diagrams illustrating design process for analysed projects are described. Following, the results of analysis of the productivity in the particular design stages are shown. Finally, the summary of the data collected during the interviews and observations is presented.

The discussion in Chapter 5 opens with comparison of the study results with the MacLeamy (2008) curve and the discussion regarding the results in the light of other theories presented in the theoretical framework. Finally, concluding remarks and suggestions for future research are presented.

2 Theoretical framework

Theoretical framework presents some of the previous research findings related to the impact of Building Information Modelling (BIM) on the productivity in the design process.

This chapter begins by explaining BIM including its definitions. Secondly, the design process is defined and differences in the traditional architectural design process are compared with the BIM management, including new methods of collaboration. Later, productivity definitions are described.

Finally, the impact of BIM application on the productivity during the design process is presented, including its relation to cost, time quality but also collaboration. Both positive and negative aspects are referred to, including productivity matters, trust issues and impact on the relationships of the actors involved in the process.

2.1 Understanding of BIM

In this section of the report various definitions of BIM, present in the literature, are presented and the definition used for the purpose of this thesis defined. Following the development of BIM and its maturity levels are described.

2.1.1 BIM definitions

There is a growing body of literature that recognises the importance of Building Information Modelling (BIM) as a new method, which is rapidly gaining importance in the construction industry. As Hardin (2009) states in Chapter 1: "BIM is a revolutionary technology and process that has transformed the way buildings are designed, analysed, constructed, and managed." This phrase can be seen as a significant, because it stresses that BIM affects all aspects of the construction of the building from the design and analysis, through the construction and finally to the occupancy and facility management of a building, which is exactly where the strength of BIM lies.

A number of researchers have reported that BIM is not only a technology and process which can just be implemented but requires the whole industry to apply new ways of thinking about the projects. Aranda-Mena et al. (2009) found in their study that different people in the industry have diverse understanding of BIM and its meaning. Jung & Joo (2011) identify three perspectives of BIM including industry level, organisational level and a project level.

Overall, there seems to be some evidence to indicate that the definitions can be divided into 3 categories: BIM as a software application, BIM as a process, and BIM as "a whole new approach to practice and advancing the profession, which requires the implementation of new policies, contracts and relationships amongst stakeholders". Numerous definitions presented in the literature are followed by numerous acronyms. The abbreviation BIM is used for: Building Information Model, Building Information Modelling and Building Information Management.

Much of the available literature on BIM presents it as a tool. Commenting on BIM, Kymmell (2008) defines Building Information Model as a virtual 3D model of the building which contains all the data needed to generate various types of information like plans, facades, sections and schedules. Similarly, Barlish & Sullivan (2012, p. 150) consider Building Information Model as a "digital representation of physical and functional characteristics of a facility. Overall, these definitions focus mainly on the technical aspects of BIM.

Second group of acronyms extends the meaning of "M" from a single model to the modelling as a process. According to the National BIM Standard (2015) the Building Information Modelling is defined as: "The virtual representation of physical and functional characteristics of a facility from inception onwards. As such it serves as a shared information repository for collaboration throughout a facility cycle." This view is supported by Barlish & Sullivan (2012, p. 149) who refer to the Building Information Modelling as "The process of creating and using digital models for design, construction and/or operations of projects". Overall, these studies outline a critical role for the importance of collaboration between different actors including architects, contractors and facility managers, involved in different stages of the projects.

In recent years, a few authors have begun to define BIM as a Building Information Management. As Richards (2010, p. XV) argues BIM is a "standard and 'best-practice' method for the development, organization and management of production information for the construction industry". This definition can be seen as belonging to the third group as defined by Aranda-Mena et al. (2009), which describes BIM as a new approach to the construction management, referring to the bigger picture involving changes of the policies and a form of contract.

Considering all of this evidence, it seems that above mentioned definitions agree that the abbreviation "BIM" describes a digital form of the building. To summarise, the definitions can be divided into three following categories:

- Building Information Model – software application - project level;
- Building Information Modelling – process - organisational level;
- Building Information Management – new approach and contract - industry level.

For the purpose of this thesis BIM is interpreted as Building Information Modelling and analysed as a process on the organisational level.

According to Barlish & Sullivan (2012, p. 1) BIM is not new to the construction industry. The main concept which supports the integration of functions in the construction industry, by providing the common platform, has evolved over the years and could be found under many different names like "BIM, VC 3D CAD, IS, CIC and IT (Building Information Modelling/Management, Virtual Construction, 3 Dimensional AutoCAD, Information Systems, Computer Information Construction, and Information Technology, respectively)". This process of transformation has led to the different understanding of BIM in terms of its maturity, which is described in the following section.

2.1.2 BIM maturity levels

During the past years BIM was expanding very quickly. Jung & Joo (2011, p. 130) define BIM maturity as a "the degree of advancement of BIM utilization". Researchers refer to another study of Taylor & Bernstein who recognized four phases of BIM advancement such as visualisation, coordination, analysis and supply chain integration. In the later study by Succar et al. (2012) five components of BIM performance measurement are proposed including: BIM capability stages, maturity levels, granularity levels, organisational scale and competency sets. Succar et al. (2012) defines three BIM capability stages of the team for delivering the project, as following:

- BIM stage 1: object-based modelling;
- BIM stage 2: model-based collaboration;
- BIM stage 3: network-based integration.

BIM maturity is an important parameter which needs to be defined prior to the study of potential benefits of BIM, because it affects organisational understanding of BIM (Barlish & Sullivan, 2012). This parameter can be seen as a degree of BIM excellence which company managed to achieve. As illustrated in Figure 2.1, there are five levels of BIM maturity including: (a) initial/ad hoc, (b) defined, (c) managed, (d) integrated and (e) optimized.

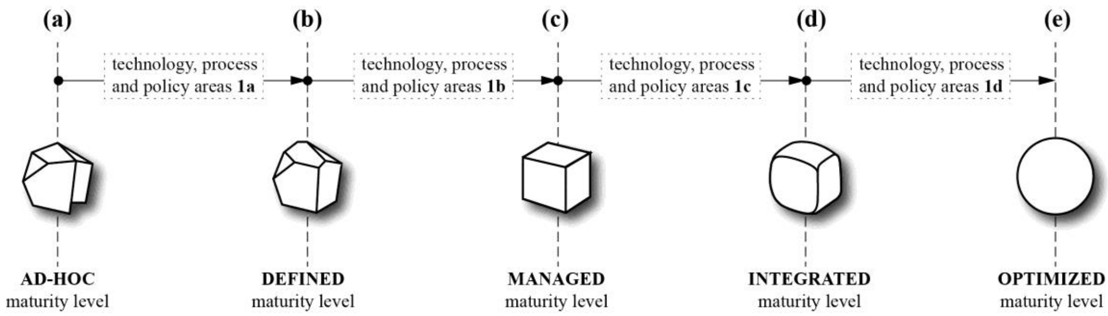


Figure 2.1 Building Information Modelling maturity levels at BIM stage 1, adapted from Succar et al. (2012).

BIM maturity levels result from implementation of new technologies, processes and policy areas. As a consequence of this operation the entire design process changes. The impact of BIM on the design process is discussed in the next section of this report.

2.2 BIM design process

In this section the architectural design process is defined. Additionally, the differences between the traditional architectural design process and BIM design are reported. Following the BIM management is described, including new methods of collaboration.

2.2.1 Design process

The architectural design process is usually divided into several stages, which can slightly overlap. Eastman et al. (2011) recognises following architectural design phases:

- Feasibility studies;
- Pre-design (PD);
- Schematic Design (SD);
- Design Development (DD);
- Construction Detailing (CD);
- Construction Review.

The feasibility studies involve delivery of non-spatial numerical and project specifications and descriptions related to cash flows, function and income generation. This stage may overlap or iterate Pre-Design (PD) stage. The purpose of PD stage is to understand why the client wants to proceed with the project, investigate space and functionality requirements, phasing and possible expansion requirements, as well as the costs (Eastman, et al., 2011).

Haines (2012) describes SD as a stage when the concept of the project is formulated. Eastman et al. (2011) adds to the definition creation of preliminary design including building plans, massing of the building and specification of potential materials. Also, building subsystems are identified at this stage.

Design Development (DD), also referred to as Detailed Design, is the stage when architects and engineers refine design (Haines, 2012). Documentation is prepared in form of detailed floor plans, general details, materials and finishes including all major construction and installation systems (Eastman, et al., 2011).

Finally, Construction Detailing (CD) also referred to as Construction Documentation, is the stage when the detailed documentation for the construction or demolition is prepared (Eastman, et al., 2011). Haines (2012) points out that in the past this phase was focused on the development of the working drawings and specifications to guide the contractor during the construction process.

The last stage described by Eastman et al. (2011) as Construction Review focuses on coordination of details, layouts, final material choice and changes if necessary. Haines (2012) adds Bidding/Negotiation and Contract Administration as two final steps of the architectural process. The prerequisite for this could be that Haines focuses on the Design-Bid-Build (D-B-B) projects only. However, the purpose of this study is to focus on the stages which are common for both D-B-B and Design-Build (D-B) and for that reason Bidding/negotiation and Contract administration will not be considered.

According to Beard et al. (2001) D-B is a contractual method making a single entity responsible. The design and construction services are contracted by a single entity, what gives a potential to reduction of the owner's administrative tasks. The D-B team is responsible for all aspects of the facility design, equipment selection, and construction necessary to produce a specified output.

The D-B method together with the above mentioned principles is believed to lead to the following advantages (Beard, et al., 2001):

- Reduced risk for the project Owner;
- Reduced project delivery cost by value engineering and constructability reviews being utilised more effectively by D-B team;
- Reduced delivery time achieved by overlapping the design phase and construction phase of a project and eliminating general contract bidding periods and redesign time;
- Increased quality and proper performance of building systems achieved by applying greater responsibilities and accountabilities of a D-B team.

During the Design-Bid-Build process the client has to work with two entities: design team (architect and engineers) and later with the contractor. The design and the construction phases are separated and the contractor is only selected once the design is completed (Hale, et al., 2009) . The main shortcoming of this method is that the client cannot work with one integrated entity which is responsible for the entire process. The implications are that the connection between design and construction phases needs to be facilitated by the client. This is a disadvantage because in some cases the client can lack the professional knowledge necessary to manage construction. The design process is interrupted, which can lead to changes and information loss (Stutz, 2000).

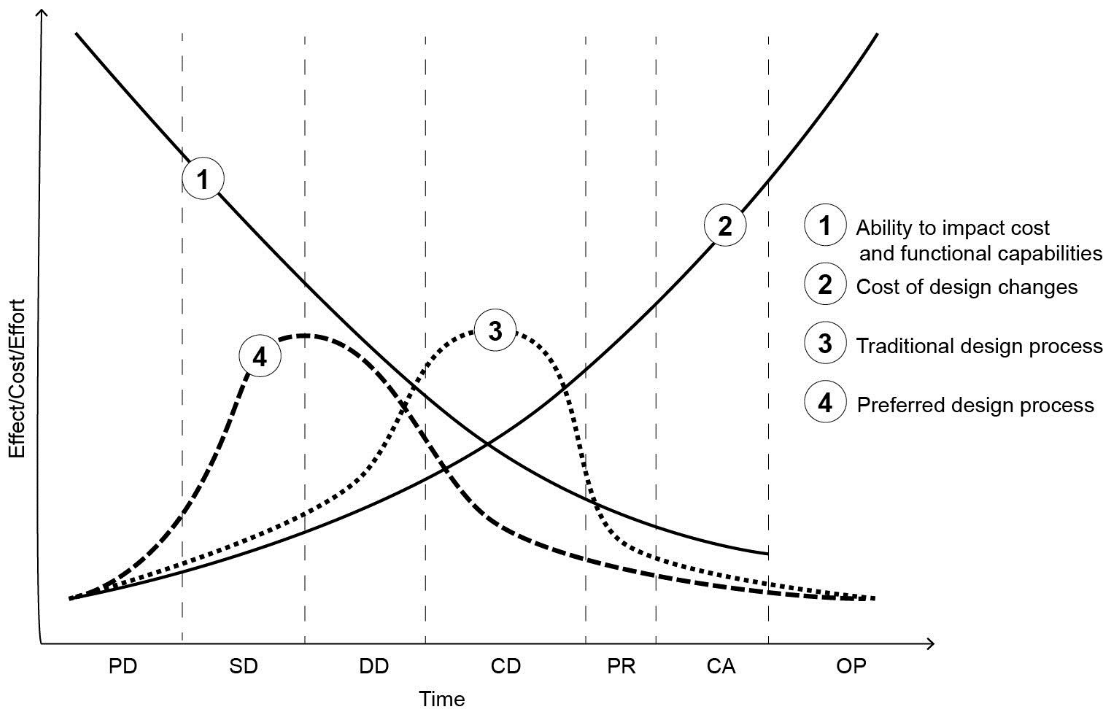
Hardin (2009) suggests that D-B is envisioned to be the best contract method for the usage of BIM because the parties involved can easier work together and exploit the collaborative possibilities of BIM. Other researchers (Eastman, et al., 2011) argue that a new form of contract called Integrated Project Delivery (IPD), which is further described in detail in Section 2.2.3 is the most suitable for BIM projects.

In the recent years architectural design was highly affected by the technical and process changes related to the rising popularity of BIM design. Many researches, including Bryde et al. (2013) demonstrate that BIM can be considered as a beneficial tool for the entire design process. The influence of BIM application in the design process is described in the following section.

2.2.2 Impact of BIM on the design process

In recent years, there has been an increasing amount of literature on BIM collaboration and many authors believe that it will become a new standard in the construction industry. Goldberg (2004, p. 56) states that: “One of the greatest benefits of using a BIM application at the design stage is the ability for the designer to understand the relationships of the building and its systems instantaneously in regard to aesthetic, performance, and program issues.”

Eastman et al. (2011) describes traditionally used payment schedule for the architectural services as 15% for the schematic design, 30% for design development and 55% for construction documentation. This is reflected in the traditional process time-effort distribution curve, as represented by curve 3 in Figure 2.2 below, developed by MacLeamy (2008).



PD – Pre-design
SD – Schematic Design
DD – Design Development
CD – Construction Documentation
PR – Production
CA – Construction Administration
OP – Operations

Figure 2.2 MacLeamy time-effort distribution curve, adapted from Eastman et al. (2011).

MacLeamy's time-effort distribution curve shows that overall workflow when BIM is applied has its peak during the DD stage, in contrast to the traditional design workflow, where the peak comes in the later construction stage (MacLeamy, 2008). It illustrates how time and effort are distributed in the traditional and BIM design. The curve number 3 represents traditional design and the curve number 4 represents BIM design efforts. The curve number 1 represents the ability to introduce changes to the design and curve number 2 represents the cost of these changes. A very interesting point is that in the traditional design the majority of work is done quiet late in the process, when the ability of change is quiet low and the cost becomes quiet high. On the contrary in BIM design majority of work is done early in the process when flexibility is high and cost of introducing changes low.

According to Eastman et al. (2011) BIM reduces time needed for delivery of the construction documentation and more effort is needed in the earlier stage. It allows changing the building in a stage where the lever is still big enough to change a lot very easily as shown in Figure 2.2. This figure illustrates the impact which BIM has on the design and construction processes in comparison with the traditional design. However, this concept has recently been challenged by Lu et al. (2015) who demonstrate that the curves proposed by MacLeamy do not reflect the reality of BIM projects.

Much of the current literature on BIM pays particular attention to its use as a passive design tool, where 3D models are used as a base for engineering analysis as for example: structure, energy, construction planning, scheduling and maintenance; or for visualisation (Jung & Joo, 2011). Researchers found out that according to analysed reports most common of BIM analysis are: “quantities take off, scheduling, estimating, energy analysis, project management, structural analysis, LEED/green analysis, storm water analysis and facility management”.

According to Jung & Joo (2011, p. 131) the core construction business functions include scheduling, estimating and design. These processes are the most demanding areas of BIM application, since they are ”bridging the geometric and nongeometric data”. Scheduling information added to the 3D model is sometimes called as a fourth dimension of BIM (Bryde, et al., 2013). Additionally, Bryde points out that information for project estimations can also be added to the model as the fifth dimension. This multidimensional potential of BIM is referred by some researcher as a “nD” modelling (Aouad, et al., 2006).

The client often has difficulties describing to the architect their needs, because of their uncertainty, frequency of purchasing a new building and asset specificity, as described in the transaction governance framework by Winch (2010). When using BIM from the early stage of the design architect can assist the client in their decision making by offering a better communication. Bryde et al. (2013) found in their study that BIM has a positive impact on the definition of the project scope, through its visualisation capacity. 3D model allows producing photorealistic visualisations, flythrough and animations, and therefore assisting the client in committing to the design. BIM can help communicating the design to the client through 3D model, what reduces significantly the risk of misunderstanding. BIM opens new ways for the collaboration, not only externally with a client, but also within the entire design team.

2.2.3 New methods of collaboration

New methods of collaboration are based on the better communication, transparency, commitments and engagement of all actors participating in the design and construction processes. Recent increase of the BIM popularity in the construction sector has a natural impact on the development of the new Project Delivery Systems (PDS) including Integrated Project Delivery (IPD) (Jung & Joo, 2011, p. 131). Researchers describe BIM as a tool which supports defining roles and areas of responsibility between the construction project participants “in terms of scope, depth and weight of the construction business function”.

In order to increase the communication and transparency between actors involved in the construction process, a new method called *Managing by Commitments* was introduced. It requires all actors to commit to the particular deadlines. Managing by commitments is described by Sull (2003, p. 82) who states that “...successful managers all excel in the making, honouring, and remaking of commitments.” Royer (1991, p. 350) defines commitment as “a psychological contract between individuals or groups to reach an agreed-on goal or objective”.

The method is supposed to solve the problem of too much communication regarding who is responsible for which task when the complexity of organisations and tasks coordination increases. According to Royer (1991) in order to succeed people need to commit to roles and responsibilities, both on the individual level as well as collective level. Management by commitments replaces the overload of communication, meaning that the responsible persons have to state once the deadline of the task to which they commit - instead of continuously reporting on their progress (Sull, 2003). The advantage of the method is that trust is increased, because collective agreements are established. However, the negative side might be that in case one actor involved has a slack in time the whole process might get delayed. Introducing the method managing by commitments may also initially take some extra time, because all actors need to understand it and be convinced to this approach.

Another method which is based on the team engagement, trust, respect and involvement is *Concurrent Engineering*, which can be defined as a method which "…provides the managerial framework for effective, systematic, and concurrent integration of all functional disciplines necessary for producing the desirable project deliverables, in the least amount of time and resource requirements, considering all elements of the project life cycle" (Thamhain, 2014, p. 282). Concurrent engineering involves many different concepts, methodologies and communication tools to support the processing of client requirements (Delgado-Hernandez, et al., 2007). Multidisciplinary teams work together on the design, project development and production in a holistic way (Love, et al., 1998).

The implementation of *Concurrent Engineering* allows achieving better results in terms of time, cost and quality factors, which makes the business more competitive (Delgado-Hernandez, et al., 2007). In addition it is an approach which has potential to reduce or even avoid the fragmentation of the construction process into its different disconnected phases (Anumba, et al., 2002). However, it is not implemented in the industry on a large scale and the traditional segmentation of the different phases is not easy to overcome. Bogus et al. (2005) propose to look at the speed of evolutions of activities and the sensitivity of an activity to information changes of a dependent activity to estimate overlapping opportunities. This unique project management concept is likely to improve communication between designers, engineers, clients and other participants by looking at the whole life-cycle of the project.

With the increasing complexity of buildings many actors are involved in the process and the communication between the actors consumes more time. Therefore, it is important to make the communication as efficient as possible (Deutsch, 2011). It is often much more effective to simply ask a colleague directly, when a question arises during the working process. If different disciplines and companies work together and see each other directly it may enhance the team building process in a psychological sense (Anumba, et al., 2002). Yet, the location has to be organised well and the participants have to be ready for being flexible. If the location is unpleasant, noisy and with bad light then this might prevent the advantages of the approach to unfold (Goczkowski, 2013).

Big Room is a unique collaboration concept which is combining both concurrent engineering and managing by a commitment. It is a meeting room, which can facilitate meetings for about 30 people equipped with a large board for visual planning, schedules, plans, space for sketches, tables for discussion groups and a screen to project a 3D model (Kemmer, et al., 2011). In Sweden this concept was further developed by one of the leading construction companies and is referred to as Project Studio (Goczkowski, 2013).

According to Kemmer et al. (2011), who did a case study in healthcare construction about Big Room together with BIM, the efficiency of the team was enhanced. Collisions in the virtual building were detected prior to construction which would not have been achieved otherwise. This can lead to major cost savings before the building is built (Kemmer, et al., 2011).

Integrated Project Delivery (IPD) is a new form of contract which combines all above mentioned approaches together with BIM. It is defined as "a project delivery method distinguished by a contractual agreement between a minimum of the owner, design professional, and builder where risk and reward are shared and stakeholder success is dependent on project success" (Cohen, 2010). Key strategies in the IPD (Parrott & Bomba, 2010) are as following: contractor, client and designers are involved in all phases; the parties involved work together in an integrated team; the relationship is based on equity, trust, openness and that all actors share potential rewards as well as risks.

According to Parrott and Bomba (2010) all actors performing the project have the fee covering their expenses guaranteed. If they manage to complete the project under the budget they can split accordingly the profit pool. However, if they deliver the project without any savings, they will not make any profit on the project as well. Eastman et al. (2011) describes IPD as "a collaborative contracting paradigm" developed in the recent years.

IPD has been tested on healthcare projects in the USA. According to many authors it is believed to improve collaboration and increase trust, openness and equity relationship between contractor, client and designers who were involved in all phases of the project (Bryde et al., 2013; Cohen, 2010). One of the reasons could be that parties involved are working together as an integrated team during the entire project. Development of IPD and similar forms of contract is likely to increase in the future, especially together with the increasing popularity of BIM. Governments in some countries are already announcing the requirements for all contractors working with public projects to work collaboratively employing BIM (Bryde, et al., 2013).

Researchers (Barlish & Sullivan, 2012, p. 158) point out that success of the BIM implementation is dependent on many different factors "such as size of the project team, team members' BIM proficiencies, and the communication of the project team, as well as other organisational external factors". Bryde et al. (2013) demonstrates that BIM can be considered as a beneficial tool for the design process, with negative aspects being mainly focused on the technical side of the implementation.

One of the issues with the collaborative team approach is the lack of knowledge transfer. Often the experiences and lessons learned by one team during one project are not transferred to another project (Bryde, et al., 2013). However, researchers do not have evidence that BIM can solve that issue. Benefits and issues of BIM and its effect on team productivity and collaboration are described in Sections 2.4.1 and 2.4.2 of this report.

2.3 Productivity

In this section the concept of productivity in the construction sector and different approaches to the productivity definition are described and analysed.

2.3.1 Productivity concept in construction-related businesses

In the last years the construction industry has been criticised for the low productivity growth ratio (Olofsson & Bröchner, 2012; Rojas & Aramvareekul, 2003), confirmed by the data collected in Europe and United States (Timmer, et al., 2010), as well as for being retrogressive and suffering from issues such as not being able to deliver projects on time, with the right quality and within the budget (Egan, 1998).

The productivity rise in the construction industry is considered relatively slow in comparison to other industries. One of the reasons may be that every building is different. Buildings are complex projects with unique characteristics (Oglesby, et al., 1989) and not as repetitive as products in other industries. In manufacturing it is much easier to compare the results due to the products recurrence, benchmarking and groups of experts who analyse how much the standard has increased from one year to another, which is difficult to apply in the construction industry because it is considered a “loosely coupled system” (Dubois & Gadde, 2002).

Construction is also affected by a number of uncertainties like: design issues, technology, market changes, geological conditions, mistakes, communication issues, labour skills etc., which cause time and cost overruns. Multi-residential buildings, houses and hotels, represent lower uncertainty and are more repetitive and standardised (Lindén & Josephson, 2013). Other buildings like schools, offices and hospitals represent high uncertainty concerning customers’ needs and are more unique. Construction of infrastructure is followed by high uncertainty regarding geological conditions.

Due to the above uncertainties it is difficult to measure performance in the construction sector. Work sampling is one of the methods measuring time devoted by workers to specific activities. However, it proved to be of little value due to changing conditions resulting from uncertainties (Josephson & Björkman, 2013). The deeper understanding of the industry is required to reflect its productivity. Therefore, a more successful model is analysis of the construction case studies over longer period and considering patterns, trends and innovation (Olofsson & Bröchner, 2012).

Construction productivity can be analysed on many various levels from the entire industry, through a single company, project or activity/task level with consideration of different relations and methods (Olofsson & Bröchner, 2012). As stated by Park et al. (2005) due to the lack of consistent systems, it is difficult to define one standard definition of productivity. Subsequently, three categories of productivity definitions are discussed.

2.3.2 Definitions of productivity

The most common is definition describing productivity as an economic concept which refers to input factor for example: labour, resources, in relation to output for example: units produced, level of sales (Park, 2005). Within this definition two types of measures can be identified. The first one focuses on a single factor productivity measures and the second one, called multi-factor, considers all input (Crawford & Vogl, 2005). The understanding of this theory is that by lowering the cost of labour and resources the profits will be increased.

Second type of the productivity definitions brings up efficiency and effectiveness concepts. The means to achieve efficiency are rationalisation of workplace through use of industrial engineering, operations research, cost planning and control (Patten, 1982).

Another aspect of efficiency is time management. Josephson and Mao (2014) analysed three time related factors of the construction delivery process and found out that long lead times caused by administrative procedures, procurement processes and forms of contract have a negative impact on construction efficiency. Another factor was inefficient use of resources, like computers and machines, considering that work is performed during 40 out of 168 available hours per week. The last factor is the human resources which bridges to the third group of definitions and is described below.

Research in the construction industry indicates that workers spend about 30% of their time on non-value adding activities and only 17.5% of times perform value adding tasks (Josephson & Mao, 2014). Thus, the third category in addition to efficiency and effectiveness includes Human Resource Management. Employees actions can be apprised in terms of attendance, accidents, turnover, work disruptions, competence of workforce, customer satisfaction etc., which is also referred to as Managing by Objectives (Patten, 1982). Approach developed by the car manufacturer Toyota, called Toyota Production System (TPS), allows to detect if people are busy and focus on value adding activities, by using one-piece-flow, which can increase productivity by 100% (Liker, 2004).

2.3.3 Strengths and weaknesses of various approaches

Out of described approaches the first concept is based on marginal utility theory that is of interest to economist and managers (Patten, 1982). Outputs/inputs methods are relatively easy to measure and commonly used (Crawford & Vogl, 2005). However, it can be noticed that if a company decides to use those methods, employees focus more on a thing or things that are measured. As a result the measurements may not reflect a real situation. Additionally, other factors of work, which are not measured, may get less attention, which may lead to a decrease of the productivity in those areas. Purely financial measures conventionally used for measuring productivity are not optimal and have faced critique because, among the others reasons, they encourage short term thinking, lack of strategic focus, fail to provide data about the quality and fail to inform about customers' needs (Neely & Gregory, 2005). For those reasons it can be considered, that despite its simplicity this definition does not define productivity concept completely.

In contrast to outputs/inputs the second approach including the efficiency and effectiveness encourages employees not only to work harder but also smarter (Patten, 1982). It considers waste and value adding activities (Josephson & Mao, 2014), but cannot be considered complete, because it does not include the human factor.

Liker (2004) points out the importance of using employee creativity in order to prevent time losses and generate improvements by using people's skills and ideas. Also learning opportunities by engaging and listening to the employees should not be underestimated. In the third group of definitions managers' focus considers influencing subordinates and changing the ineffective behaviours (Patten, 1982). It includes economic, engineering and social factors, effectiveness and efficiency also with regards to partners and clients and is reflecting TPS model (Liker, 2004). This approach can be considered as the most complete.

Olofsson & Bröchner (2012) state that it is difficult to find a common meaning of construction productivity, because of the differences in productivity definitions concepts and various reasons why the data is gathered. The trend nowadays is that companies measure a lot, but they are quite often unable to generate reflections on how to improve productivity based on measurements alone. Therefore, it is important to have a purpose before starting to measure anything and consider changing conditions and different environments, instead of putting too much focus into technical aspects of measuring, without enough attention to people and situation. Therefore, it is significant to consider human factors, as in the third definition, in order to improve productivity in the construction sector.

A number of authors have considered the effects of BIM on the design productivity (Bryde et al., 2013; Barlish & Sullivan, 2012; Lu et al., 2015) and found out that this new methodology has both a positive and negative impact. The summary of the benefits as well as issues related to BIM is presented in the following chapter.

2.4 Impact of BIM on the productivity

In this section the impact of BIM application on the productivity during the design process is presented, including its relation to cost, time quality but also collaboration. Both positive and negative aspects are referred to, including productivity matters, trust issues and impact on the relationships of the actors involved in the process.

2.4.1 Possible benefits of BIM application

Several studies investigating BIM have been carried out in the recent years and many of them point out the potential benefits resulting from BIM implementation. Bryde et al. (2013, p. 972) found that BIM "has a potential use for construction project managers in improving collaboration between stakeholders, reducing the time needed for documentation of the project and, hence, producing beneficial project outcomes". There is an unambiguous relationship between the Iron Triangle of cost, time, quality of project and collaboration of the actors involved. Therefore, the possible benefits of BIM are described below, according to the above mentioned categories.

One of the strength of BIM is that it can be used through the entire life-cycle of the building, from the project analysis, through design, construction and facility management (Grilo & Jardim-Goncalves, 2010). BIM model includes project data and it is likely to reduce information losses, common in the 2D drafting based collaboration and has the potential to increase quality throughout the entire process (Chen et al., 2013) and at the same time generate financial savings. Bryde et al. (2013) confirms that BIM is a more efficient process comparing with traditional paper-based tools. Researchers report that in their studies cost reductions were found in 60% of analysed cases.

According to study conducted by Bryde et al. (2013) time is the second most often mentioned success criterion of BIM implementation, reported in 34% of analysed projects. In most of the cases benefits were reported during the design stage of the project, with positive impact on the project schedule.

Impact of BIM on the quality improvements are mentioned by many authors as more accurate in design and higher quality of deliverables. Bryde et al. (2013) found out the possible benefits on the quality in 34% of analysed projects, with none project reporting negative effect in this area. BIM is also seen as a tool improving the sustainability of the buildings, by allowing for improved energy and daylight analysis of the future buildings, as well as more sustainable construction and "the reduced operational and maintenance costs of a green building" (Bryde, et al., 2013, p. 978).

Another benefit of BIM is that it can be a very useful communication tool which allows everyone involved to communicate and collaborate on the jointly developed product. Bryde et al. (2013) reports a positive effect on the communication in 37% of analysed cases. Benefits are referred in particular to the information exchange and availability.

To allow BIM collaboration the process has to allow the use of the model for every step and every team member no matter which discipline they represent. Anumba et al. (2002) points out that the segregation of data between the different phases (design and construction) can lead to clashes and misconception of the design. An advantage of BIM might be that some of the problems mentioned by Anumba et al. (2002) can be reduced by the usage of BIM, as it would allow integrating all data and because of the use of visualisations can improve communication regarding the design.

Another strength of BIM is the suitability for the development of the commitment protocol (Bryde, et al., 2013). BIM can have a positive impact on the increase of trust in the relations between actors involved in construction process and enhance management by commitment, since all the actors involved can see the progress or lack of progress by others. Kadefors (2004) recognises the importance of trust between the project stakeholders and its impact on the project success and highlights that partnering practices have a positive impact on the trust relationships within the team. Eastman et al. (2011) argues that BIM principles are based on trust, collaboration and transparency. The incentive to increase the productivity and the added value tends to be shared equally by all actors, because they are aware of the common benefits or loses. As a result, it increases the natural surveillance and monitoring of the process between the parties. Eventually, BIM can stimulate a more collaborative form of work between stakeholders which has a positive impact on the organisation of the project and increase the pool of capabilities within the integrated design team (Bryde, et al., 2013).

More collaborative methods like clash detection tests can result in reducing the number of costly revisions during the construction stage. BIM allows for an automatic coordination of 3D objects and spaces with actual sizes and dimensions. By applying clash detection many mistakes can be avoided early in the process and number of coordination sessions reduced. Bryde et al. (2013) reports positive impact on the coordination in 37% of analysed projects.

Another benefit listed by Bryde et al. (2013) is that companies working successfully with BIM are very likely to be recognised for their unique skills, grow the company's reputation on the market and as a result be awarded new projects. According to Zuppa et al. (2009) it is likely that architects see benefits of BIM as increasing coordination, productivity and business operations. On the other hand from the contractors' point of view benefits tend to focus on improvements in scheduling, estimating and drawing processing. However, despite many benefits, BIM also causes some issues.

2.4.2 Possible issues resulting from the use of BIM

Numerous authors point out that it is difficult to asses the BIM effectiveness. Barlish & Sullivan (2012) argue that the benefits of BIM not yet being empirically proved, which forms a barrier to the wide employment of BIM by the decision makers. Other authors even state that "the overall and practical effectiveness of BIM utilisation is difficult to justify" (Jung & Joo, 2011, p. 126). Similar, to the potential benefits, the issues are also divided into three categories affecting the cost of project, time needed to complete the project and collaboration on the project. However, no issues related to the quality decrease were found in the literature.

Owners do not see the clear business value and Return on Investment (ROI) of BIM (Barlish & Sullivan, 2012). Authors classified difficulties of the evaluation of business benefits of information technologies as: potentially intangible benefits, organisational changes, and evolution of business benefits during the life-cycle of the system, conflicting opinions of stakeholders, lack of users' skills which causes intimidation and practical difficulties. A recent study by Lu et al. (2015) also highlights that BIM employment generates extra expenses during the design stage, but they point out that the expenses are more than likely to be compensated during the construction phase. Negative impact of BIM on cost may be in the form of 2D-CAD rework or need for investment in software, training and technical support (Bryde, et al., 2013).

Negative effects of BIM are often mentioned in relation to the extra time needed to construct the 3D model as well as the need to convert drawings and standards from CAD to BIM (Bryde, et al., 2013).

However, one needs to keep in mind that to use BIM's potential fully, the entire design process has to change. Companies need to invest significant sums in the software and training of the staff and the resistance to using this method has to change. The BIM process will not be better than the weakest link, which means that all actors in the process need to have a good understanding of BIM and its collaborative way of work, otherwise it may lead to frustrations resulting from some team members not understanding fully a integrated BIM methodology (Bryde, et al., 2013). Researchers point out “lack of understanding of interoperability [of BIM systems] limitations and abilities” and software issues, related to the size of the project, as a main coordination issues (Bryde, et al., 2013, p. 977).

According to Jung & Joo (2011) the managerial issues of BIM present greater challenges than the core technical problems. A similar view is presented by Eastman et al. (2011), who reports that the successful implementation depends a lot on surrounding factors like management and project team skills, which have to be improved as well.

Lastly, BIM still presents a number of software issues (Chen, et al., 2013). This view is supported by the research conducted by Bryde et al. (2013), who found out that 20% of analysed projects experienced technical issues. The most common problems include software interoperability between different packages, problems with handling big and complex databases and inability to exchange data between different software packages. Last but not least, the lack of software skills and education among project teams needs to be highlighted.

2.5 Summary of the theoretical framework

This section aims to summarise the most relevant theories and findings from the literature review, which are relevant for this thesis. Those theories are also recalled in the following sections of the thesis as arguments towards the results of the case study.

First of all, there are three different ways to define BIM as a software application, process and new approach and contract. For the purpose of this report BIM is interpreted as Building Information Modelling and analysed as a process on the organisational level (National Institute of Building Sciences, 2015). Continued development of BIM has an impact on the maturity levels, which can represent a project or an organisation that applies BIM. Succar et al. (2012) recognises three stages of BIM maturity including: object-based modelling, model-based collaboration and network-based integration.

According to Jung & Joo (2011) the differences between stages can be assessed by the extent to which BIM is reflected in the design and collaboration processes. Within the design process the four different distinct stages can be observed including: Pre-design (PD), Schematic Design (SD), Design Development (DD) and Construction Detailing (CD) (Eastman, et al., 2011). The entire design process can be also affected by the procurement method. The contractual methods considered in this report are Design–Build (D-B) as defined by Beard et al. (2001), Design-Bid-Build (D-B-B) (Hale, et al., 2009) and Integrated Project Delivery (IPD) (Parrott & Bomba, 2010). With regards to BIM projects Hardin (2009) considers D-B as a more suitable procurement method. However, Eastman et al. (2011) argues that IPD is the most suitable for BIM projects. The form of contract, together with applied level of BIM maturity can have a significant impact on the time and effort needed for a successful project delivery.

MacLeamy (2008) introduced the time-effort distribution curve, which illustrates the relationship of the cost of design changes, flexibility of design and project advancement to the periods in the design process when most efforts are actually invested. This theoretical curve has been challenged by some authors, who argue that it does not reflect the reality of BIM projects (Lu, et al., 2015).

Other aspects which affect the productivity in the design process are new methods of collaboration including IPD (Jung & Joo, 2011), *Management by Commitments* (Sull, 2003), *Concurrent Engineering* (Thamhain, 2014) and a *Big Room* (Kemmer, et al., 2011), referred to as Project Studio (Goczkowski, 2013) in this thesis. All above collaboration methods have an impact on the time, cost and quality of delivered projects. Benefits of collaborative project work include increase of trust, openness and equity relationships between actors involved in the process (Bryde et al., 2013; Cohen, 2010). Among the issues researchers report a lack of knowledge transfer (Bryde, et al., 2013).

Productivity in the construction sector tends to be lower than in other industries, because it is affected by the number of uncertainties (Lindén & Josephson, 2013) and long lead times caused by administrative procedures, procurement processes and forms of contract (Josephson & Mao, 2014). Productivity can be defined in a number of ways. For the purpose of this study it is understood as an economic concept which refers to input factor for example: resources, in relation to output for example: units produced (Park, 2005). This method is relatively easy to measure and commonly used (Crawford & Vogl, 2005). However, it is important to consider also the human factor, when discussing productivity in the construction sector (Patten, 1982).

Some researchers report that BIM can have a positive impact on the productivity in terms of reduced time needed to prepare documentation and improved relations between projects actors (Bryde, et al., 2013). Those can lead to the increased quality of the entire process and likewise generate financial savings (Chen, et al., 2013). However, other researchers point out a number of issues related to BIM.

First of all, the cost of BIM implementation tends to be high and managers do not see the clear business value and Return on Investment of BIM (Barlish & Sullivan, 2012). Other authors report that the extra expenses are more than likely to be compensated during the construction phase (Lu, et al., 2015). Secondly, extra time needed for design is also described among the issues (Bryde, et al., 2013). Finally, the technical barriers (Chen, et al., 2013) as well as social unwillingness to change are stated among the BIM obstacles (Bryde, et al., 2013). Although, the technical issues tend to represent a much smaller problem in comparison to managerial challenges required to ensure successful BIM implementation (Jung & Joo, 2011). The shift is needed in the approach of the collaborative design across the entire industry (Eastman, et al., 2011).

3 Methodology

In this chapter, the methodology used for the study and justification for the choice of methods is presented in order to give the reader the understanding of how the research was performed and allow other researchers to reproduce the study. The procedure used for the study is described including materials, observations and survey methods.

3.1 Research approach

Most companies do not employ any systematic methodology to assess the benefits of BIM (Barlish & Sullivan, 2012). A number of researchers (Bryde et al., 2013; Frödell et al., 2008; Lu et al., 2015) have presented various methodologies exploring BIM, including: literature review, case studies, secondary data gathering and semi–structured interviews. The key method chosen for this study was a case study. However in order to carry out the case study a literature review was required as well. Other methods used to support the case study included interviews and direct observations, which are described in a more detail in the following sections of this chapter.

The first step in the process involved the extensive review of the literature regarding BIM and its impact on the productivity in the design process, which is presented in Chapter 2 of this report. The sources were accessed via Chalmers Library systems and included journal articles, conference proceedings, published case studies and book chapters. The literature review was focused on the sources describing BIM, the design process, relevant contractual methods, productivity and efficiency measurement in the construction industry.

As a next step the case study was performed to investigate the impact of BIM implementation on the design process. According to Bakis (2006) it is one of the most suitable methods of investigating the effects of new technologies. The information included in case studies is presented in relation to the actual project characteristics and project data. This view is supported by other researchers who focus particularly on BIM (Barlish & Sullivan, 2012) and state that a case study is one of the most suited methods of assessment for new information technologies, as they present information in the context of the real project.

In order to answer the research questions, four building projects were analysed and compared with focus on the impact of BIM on the efficiency of the design process. All projects examined were multi-residential buildings in Gothenburg area, designed by one architectural office. In particular, the use of resources and time necessary to complete design was examined. Involvement of the contractor in the final phase of the design process was also investigated in order to assess if the value adding process initiated by the use of BIM model and quality gains were passed on to the contractor and if the contractor was able to utilise the added value.

Four similar apartment building projects were selected, all of which were recently designed by the same architectural office and built by several different contractors.

Two of the projects used the most advanced BIM methods currently available and were issued to the contractors as BIM models as well as 2D documents, two others represented less advanced level of BIM implementation.

The particular architectural office was chosen due to their long-term experience in using BIM, implementation of advanced methods of BIM design, deep interest in the development of the collaboration methods with the contractors and outstanding quality of delivered projects.

3.2 Case study process

The methodology framework used for this study was divided into five phases, as illustrated in Figure 3.1 below, and included: collecting data, producing time-effort distribution curves and productivity diagrams, performing interviews and undertaking direct observations. Some of these activities were performed parallel to each other, for example direct observations were undertaken during the entire length of the study.

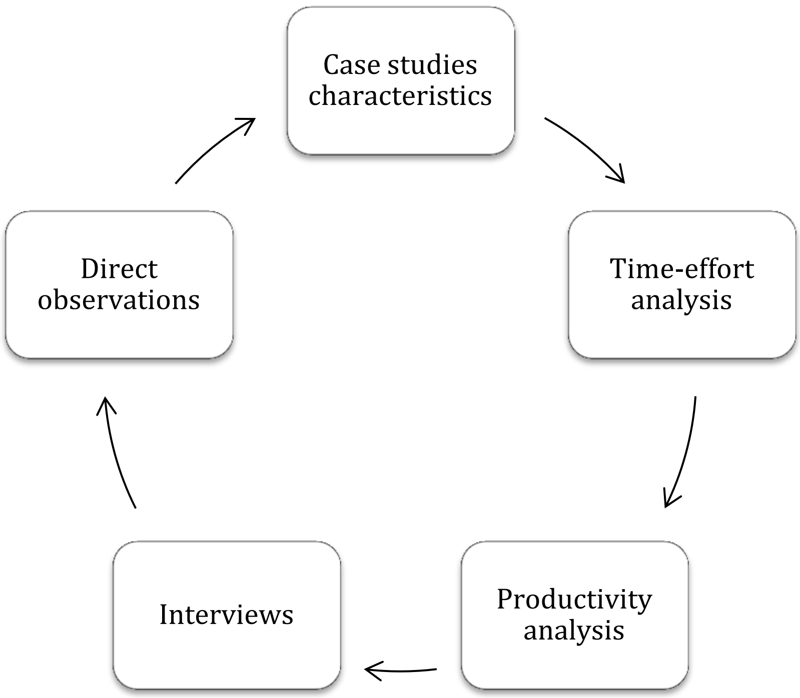


Figure 3.1 Methodology framework used in this thesis.

The case study started with the analysis of four projects, focusing on the spatial characteristics of every analysed project. Secondly, the project data was gathered and analysed for four analysed projects. This provided information necessary to produce the time-effort distribution curves based on the MacLeamy's curve (MacLeamy, 2008) and perform productivity analysis. As a next step, interviews with architectural project directors, BIM managers and project managers representing the client/contractors were conducted. Finally, findings about BIM impact on the productivity were presented in the form of diagrams and written description.

3.2.1 Projects' characteristics

Prior to the comparison, all projects were analysed and their parameters were rated in order to understand the complexity levels. Key parameters considered for rating were:

- Project size: gross total area and apartments area – gross living area;
- Number of buildings included in the scheme and number of building floors with distinction to the underground and the total number of floors;
- Repetition of design based on the number of different floor layouts produced for a particular building;
- Number and types of apartments;
- Standard of the designed building according to the architects' judgment and additional facilities.

During that stage all key drawings, site maps, plans, facades, sections, and details were reviewed to determine project scope and its complexity. All information was obtained during short informal meetings with the architectural project managers who led particular projects. Additionally, brief information about project timeline and contractors' company was gathered. The data was converted into a complexity rating matrix which is presented and described in detail in Section 4.2.1 of this thesis.

The purpose of the first part of the study reported here was to determine the complexity of four buildings prior to the investigation on how BIM can affect the design process. Appreciation of the differences between buildings seemed to be of high importance, because the difficulty levels can affect the amount of time spent on the design of a particular building. Understanding of key projects' characteristics and the design phases was a crucial step prior to the undertaking of the in-depth time-effort and productivity analysis.

3.2.2 Time-effort analysis

The second part of the study included gathering numerical data about the analysed projects that were originally collected during the work on the projects. Access to the company's accounting database was critical in the study, as the data included number of hours logged into particular accounts as well as the cost.

The term *time* is understood as "the time period during a project process" (Lu, et al., 2015, p. 331) and effort as "the amount of chargeable service time rendered by individual participants" (Lu, et al., 2015, p. 331). Participants in this case are architects and engineers working as a team in the case company.

This part of the study was based on the archive data from the architects accounting system called Brilljant. As a first step, all the relevant accounts in the system were identified for four analysed projects. Secondly, hours logged into projects were extracted month by month from all of the accounts used for the particular project and organised chronologically in the monthly steps. The Excel spreadsheet was used to generate diagrams illustrating time-effort distribution curves for all projects.

As a next step, information about particular design phases (SD, DD and CD) was added to the diagrams. The exact dates for the transition between the phases could not be established due to the common overlapping of the activities. Therefore, the best judgement of project architects was used to assign the project phases to the diagrams. The time-effort diagrams are presented and described in detail in Section 4.2.2 of this report.

3.2.3 Productivity analysis

The productivity definition used for the purpose of this study describes productivity as an economic concept which refers to the relation of the input factor to output (Park, 2005). An input - output approach was employed since this method is relatively easy to measure and commonly used (Crawford & Vogl, 2005).

As demonstrated in Section 2.2.1 of this thesis, most of the authors (Eastman et al., 2011; Haines, 2012) agree that the Schematic Design (SD), Detailed Design (DD) and Construction Documentation (CD) are the most crucial stages of the architectural design. Therefore, those stages will be used for the productivity analysis.

As a starting point, all hours logged into all accounts related to the particular projects were extracted from the accounting system and organised in phases: Schematic design (SD), Detailed Design (DD) and Construction Documents (CD). The total number of hours logged into particular stages was divided by the number of square meters for the entire project. As a result productivity per square meter of the building was calculated for all stages of the projects. That gave a basis to calculate the average productivity for the entire project.

The same database was used to calculate average production cost per square meter. The data was converted into the diagrams which are presented and described in detail in Section 4.2.3 of this thesis.

3.2.4 Interviews

As a next step, semi-structured interviews were conducted in order to gain better understanding of specific complexities of the particular projects, which could have an impact on a certain form of the numerical data. The semi-structured interview method was chosen as the most suitable since it provided the right balance between flexibility and allowed for rich data collection. Some researchers also believe that it is the most widely used format for qualitative research (DiCicco-Bloom & Crabtree, 2006).

According to some researchers (Barlish & Sullivan, 2012) it needs to be considered that the interview results can be biased by the subjectivity and perception. Therefore, managers representing various fields and companies were interviewed including: architecture managers (4), BIM managers (2) and director (1) from the contractor company. All interviewees were involved in the analysed projects.

Originally, it was intended to conduct interviews with construction project managers for all four projects. During the process it became apparent that such extensive interviews would not be feasible due to limited availability of many project managers from the contractor companies. Therefore, the interviews with BIM managers were performed instead. Interviews with BIM managers were conducted in order to gain the understanding of their perspective on the BIM application at architectural and contractor companies.

Questions were formed in a way to examine:

- Organisation of the projects;
- Collaboration methods;
- Level of BIM employment;
- Impact of BIM on the project;
- Issues with BIM;
- Benefits of BIM.

According to the semi-structured interview technique described by DiCicco-Bloom & Crabtree (2006) interviews were planned in advance, and performed based on the form of predetermined open-ended questions. The length of each interview varied between 30 and 60 minutes. In order to ensure that none of the valuable data would be lost, all the interviews were recorded and transcribed. The questions were asked in English; however, respondents had the freedom to answer in Swedish or English. All questions are presented in the Appendix 1 “Interview questions”.

Data collected during the interviews was critical to gain an understanding of the BIM impact on the productivity in the design process.

3.2.5 Direct observations

During the length of the study, the author participated in a number of the design meetings called “Project Studios”, performed for two currently on-going projects, similar to analysed case studies. The meetings were held by the contractor and a client company, which is one of the leading construction companies in Sweden. Eight visual planning meetings and two BIM coordination meetings were attended by the author as the observer. The observation notes were used as supporting material to understand the new design methods and impact of BIM on the design process.

Following the empirical data collection, the results were gathered and presented in Section 4 of this report. The results were described in the context of previous studies presented in the theoretical framework of this thesis.

4 Results and analysis

This section describes the findings of analysis and interviews performed according to the methodology described in the previous section of the thesis. The findings were organised in a way following the research process. In the beginning, the comparison of projects complexity is presented. Later on, the time-effort distribution curves and productivity analysis are described. Finally, findings from the interviews and direct observations are described.

4.1 Case company

Prior to introducing results the case company needs to be presented. The way they work with BIM and the level of their BIM maturity has an impact on the results of this study. Findings reported in this section are based on the interview with BIM manager and direct observations made by the author.

The company was started in 1980 and is today one of Sweden's major architectural offices. The company employs more than 125 architects and engineers who are based in Gothenburg, Stockholm, Malmö and Buenos Aires. They provide design services including urban design and city planning, landscape, residential, commercial, office, industrial, educational, leisure, sport, culture and healthcare projects. Additionally, visualisation, professional kitchen design, interior design, sustainability planning and project management services are among the special competencies offered by this company.

The company's structure is divided into a number of "studios" which specialise in particular service area. In the main office in Gothenburg, were the author was based, there are 5 studios including among others urban design and city planning, landscape design, residential design, healthcare and commercial design, interior design, large kitchen and project management. Work is done in house and is organised in small teams which consist of people from one or more studios, depending on the project's needs. The open plan of the office encourages informal ad hoc communication and impacts the way the architects and engineers work and communicate with each other.

4.1.1 BIM implementation and development

According to BIM manager, 3D design linked to the production of the documentation was introduced in the office in 2001. The company had the first major focus on BIM long before everybody else was interested in BIM, because they wanted to increase the quality control of plans, elevations and sections. It was a prerequisite to search for software that allows working in the integrated way, when all the changes are reflected on all of the drawings. Architects did the review of products available on the market. Autodesk's Revit was in the early stage of development and Graphisoft's Archicad has been on the market for a while. Other options considered were Vectorworks and Bentley MicroStation. Architects tested all available software and following the evaluation they decided to do a pilot project in Archicad. It happened to be a really complicated healthcare project, with many obstacles in the form of complex terrain, many different levels and underground tunnel reservation. All the plans, sections and facades were generated from the same model and despite the project's complexity architects achieved correct drawings and decided to implement BIM across the office. That was the beginning of the BIM development process which continues in the office today.

The implementation process took 3 years from when the architects started using ArchiCAD in the pilot project to the point that all projects were made in an integrated way. One of the barriers was that many employees were proficient in using 2D packages and switching to 3D meant for them the need to learn new software from scratch. Therefore, the education process took a while and was considered rather costly. These results are in line with those of previous studies by Chen et al. (2013) and Bryde et al. (2013), who point out technical issues as one of BIM disadvantages. However, once employees reached the level of proficiency in using 3D software, as they had in 2D, the cost of producing BIM documentation from the 3D model was not considered higher than producing 2D documentation. Later on, the maturing process evolved organically.

Before 2009 there were no clients who would have asked for the BIM documentation. Architects even gave a series of seminars, where they invited their clients and talked about BIM, but the first one did not bring any particular results. The second one was given at the time when the awareness of BIM was a lot greater and after that came the first requests from clients to deliver the BIM design.

About 2010 one client, a leading *Construction Company* in Sweden, wanted to work with BIM and was looking for an architect to take over the project and produce BIM documentation for the construction design. The case company was chosen, because of their experience of BIM and ability to build good accurate quality models.

During the first BIM cooperation with the client, the contractor did not really trust the model for the quantity take off. However, as the project progressed the contractor started realising that quantities generated from the model matched with the quantities that they have taken manually and they started to trust the 3D model more. The construction company performed even the 3D coordination using Navisworks. However, one of the very first 3D coordination's was done by the case company in 2006 for a school project.

Since those early years, the case company was refining BIM processes and adding more functions. Around year 2010, architects looked at Vico Software, which allowed for direct calculations and quantity take-off form the model at every stage. The number of architects attended the training, but with one exception there were no projects that required that software. Today, architects are looking at the energy evaluation from the model and at the program called BIMe, which is a web based data-base connected directly to the model.

4.1.2 BIM maturity in the case company

During the direct observations in the case company the author found that as much as BIM awareness was very high in the office, the level of BIM skills across the office tended to be rather inconsistent.

When the BIM manager was asked about BIM maturity level in the office, as described by Succar et al. (2012), she commented that it was very mixed and it tended to be on level 2, touching on level 3. However, BIM was not reflected in any contract so far. The project costs were also calculated in a traditional way, based on the number of hours spent on the project. According to the interviewee, the entire construction process in Sweden was still considered fairly traditional with architect's involvement up to a certain stage and later takeover of the project by the contractor.

BIM development in the case company is still ongoing and in combination with very dynamic growth of the company its level of maturity seems to vary. In terms of modelling it could be considered reasonably consistent, and in terms of how much more each one in the company can and wants to get out of the model it appears to be fairly inconsistent. Especially, those who have been in the office longer and those who have not come out of university within the last 3 years, tend to struggle in the BIM environment, due to its complexity and many functions and options that can be implemented.

One of the findings was that the case company has already all the necessary knowledge and skills required for the achieving BIM stage 2 (model-based collaboration), but not all of the projects are performed on that level. The BIM stage depended a lot on the technical skills of the team members. Another observation was made that some teams, including top performers continued to work in the same group from project to project. This prevented the natural spreading of knowledge across the company. This result is in line with previous studies by Bryde et al. (2013), who reports that BIM does not really support the knowledge transfer between different teams.

However, implementation of knowledge exchange is planned in the company. There are plans to begin with a number of representatives from each studio, who will receive lots of information about different programs and processes, so they can spread this knowledge down to their studio. The process of knowledge exchange is meant to work in the umbrella case. BIM manager realised that because of all these inconsistencies it is quite difficult to lift the lowest level up to the next level, however she considered it as the goal number one for the future.

Together, these results provide important insights into the level of maturity of BIM in the case company, which could be described as managed developing towards integrated, according to Figure 2.1 (Succar, et al., 2012). That impacts the level of BIM employment in the particular projects, depending on the client's requirements. In section below a comparative study of four projects representing different BIM maturity levels is described.

4.2 Project study

In this section the main characteristics of four analysed projects are presented. First of all, information about key parameters of all projects was gathered, which provided a data necessary to perform comparison of projects' characteristics complexity. Based on those parameters the complexity comparison matrix was generated. Secondly, the time-effort distribution curves for all projects were illustrated and discussed. Thirdly, results from the productivity analysis based on time and cost of the delivery were presented. Finally, the findings from seven semi-structured interviews with managers from the architectural and construction companies were conducted.

The comparative study included four similar apartment building projects, as illustrated in Appendix 2 – Case study projects. All of them were recently designed by the case company as described in Section 4.1 and built by three different contractors. Two of the projects (Project 1 and 2) used the most advanced BIM methods currently available and were delivered for the same client and built by the same construction company, which is one of the leading developers in Sweden. Those projects were issued to the contractor as BIM models as well as 2D documents. Two other projects (Project 3 and 4) represented less advanced level of BIM implementation and were issued to the contractors in form of 2D drawings only.

4.2.1 Comparison of projects' characteristics

The purpose of the study reported here was to determine the complexity of four buildings selected to investigate how BIM can affect the design process. Appreciation of the differences in the complexity was considered important, because the complexity level can affect the amount of time spent on the design of a particular building.

The complexity comparison matrix was created based on the following parameters: project size, number of buildings and floors, repetition of design, number of apartments and standard of the building; as described in the methodology Section 3.2.1 of this thesis. Table 4.1 below illustrates the relations between the key parameters for all analysed projects.

Table 4.1 Project comparison matrix.

	Project 1	**Project 2**	**Project 3**	**Project 4**
Area				
Gross total area (m2)	11107	11516	7116	4853
Gross living area (m2)	6150	6837	5251	3096
Number of floors				
Number of residential buildings	2	3	4	4
Number of supporting buildings (car park/storage)	0	0	1	6
Underground garage	1	1	0	0
Maximum number of floors	10	10	4	3

Repetition of design				
Total number of plans (excluding roof)	29	34	17	15
Total number of different floor layouts	7	7	8	4
Apartments				
Total	81	110	73	45
Types of apartments	5	4	5	4
Standard				
Separate car park / storage building	0	0	1	1
Building standard in scale 1-5	3	3	2	4

Table 4.1 which is a comparison matrix of key parameters was used to assess the complexity. Four key parameters in each row were compared against each other and rated from one to four, where the score of four was given to the highest parameters. The rating is presented in Table 4.2 below.

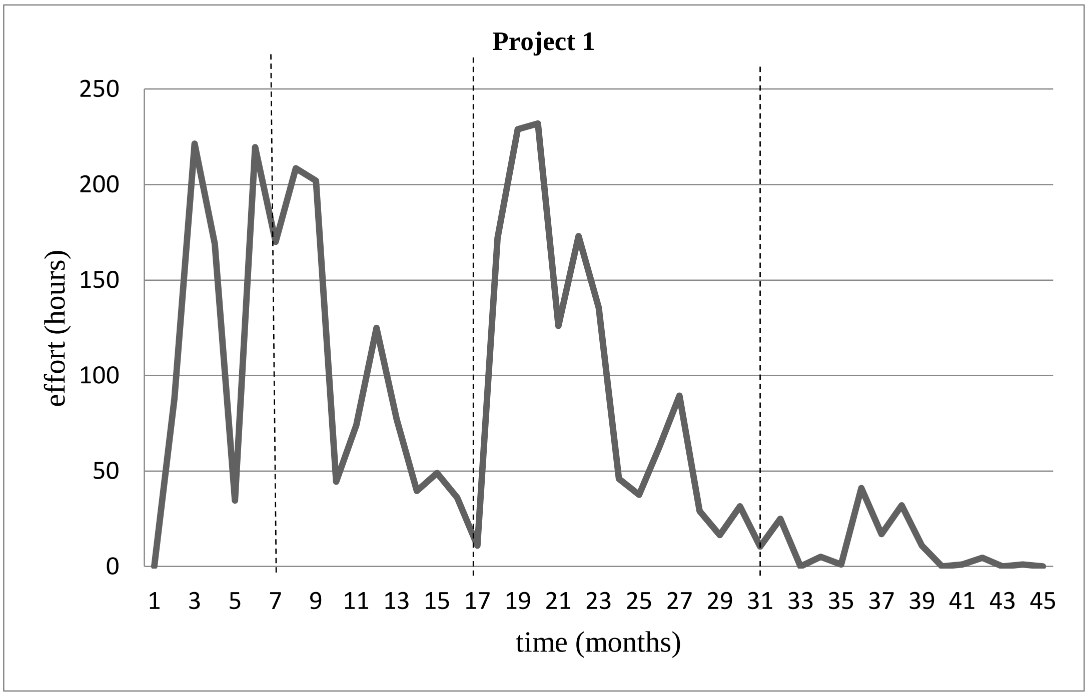
Table 4.2 Project complexity rating.

	Project 1	**Project 2**	**Project 3**	**Project 4**
Area				
Gross Total Area (m2)	4	4	3	2
Gross Living Area (m2)	4	4	3	2
Number of floors				
Number of residential buildings	2	3	4	4
Number of car park / storage buildings	0	0	1	4
Underground garage	4	4	0	0
Maximum number of floors	4	4	2	1
Repetition of design				
Total number of plans (excluding roof)	4	4	2	2
Total number of different floor layouts	4	4	4	2
Apartments				
Total	3	4	3	2
Types of apartments	4	3	4	3
Standard				
Separate car (cycle) park / storage building	0	0	4	4
Out of scale 1-5 (arch. judgment)	3	3	2	4
Total score	**36**	**37**	**32**	**30**

The total score of all key parameters was used to assess the complexity of the projects. As Table 4.2 reveals Project 2 stands out by virtue of the highest total score for all analysed key parameters, whereas Project 4 scored the lowest. Based on the total score presented in Table 4.2, Project 2 appears to represent the highest levels of complexity and Project 4 is probably the least complex of all. This implies that project 2 possibly was more time consuming to design due to higher levels of complexity compared with Project 1, 3 and 4 respectively. These results need to be considered in the next part of the study which analyses how much time was allocated to the design of those projects. Nevertheless, BIM management can have significant impact on the reduction of time allocations to projects (Bryde, et al., 2013) in a way that a more complex project supported by advanced level of BIM can be done quicker than a less complex one, where the low level of BIM was applied. In order to assess expenditure of time on the projects, time-effort distribution curves were drawn.

4.2.2 Time-effort distribution curves analysis

Monthly time-effort distribution diagrams were done according to the methodology described more in detail in the Section 3.2.2 of this report. It needs to be underlined, that curves presented below represent combined efforts of architects and engineers delivering the architectural design only. Efforts of other engineers, consultants, project managers, quantity surveyors and contractors were not analysed for the purpose of this study. The curves for all projects are illustrated and described on the diagrams below.



SD DD CD PR

SD – Schematic Design, DD – Design Development, CD – Construction Documentation, PR – Production

Figure 4.1 Time-effort distribution curve illustrating D-B Project 1.

Figure 4.1 illustrates the time-effort distribution curve for Project 1, which was one of the first projects ever that architects did in collaboration with the contractor reaching 2nd level of BIM maturity. As can be seen, there is a sharp rise in the beginning, due to the formal kick off, followed by the steep fall as an effect of summer vacation. Later on, the curve rises again and during the DD stage it has a downward trend, until reaching the CD stage, when it rises sharp reaching the peak of the entire process followed by the gradual decrease. During that stage details were drawn, as well as system errors corrected, which resulted in a spike.

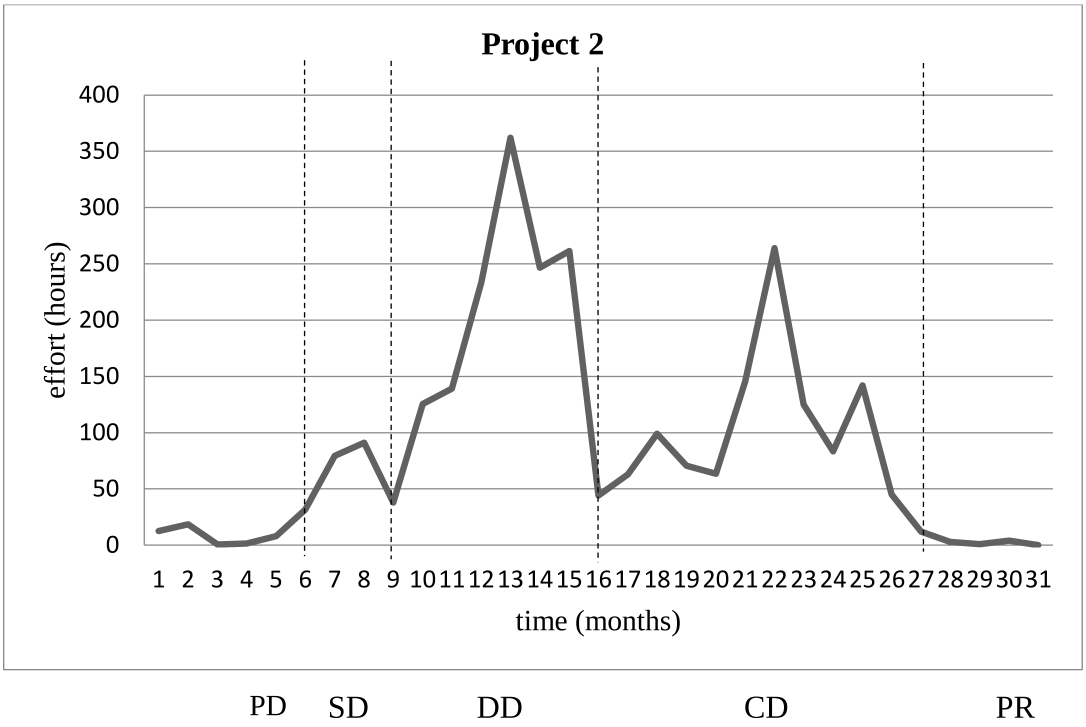
What is interesting about this curve is that instead of one major peak during the SD and DD stages, as suggested by MacLeamy (2008), it has two major peaks. The second peak comes during the CD stage, which MacLeamy considers as typical for the traditional design. This seems to suggest that the efforts were almost doubled. Results obtained during the interviews confirmed, that architects considered SD and CD stages as the most demanding during that project.

On the linear diagram each month is equally represented, but the curve is dependent on how much time architects actually commit to the project. During some months they worked 25% on the project, and during other months it was 100%, and sometimes the curve was even affected by the summer vacation. Additionally, during this project there were some external issues with municipality, which influenced the project. As can be seen the intensity of work is not constant.

As the project architect reported during the interview "This curve was quiet revealing that BIM implementation and Project Studio were actually not very successful in Project 1, because it was one of the first projects done in that way". According to the architectural manager it involved both traditional design and effort to make the process a more collaborated design. Architects made lots of 3D BIM design in the early stages which the contractor did not really use. In addition to this, regular project management meetings were performed and the traditional construction documentation was delivered.

Respondent described design process as a kind of similar to the ordinary process, but architects put more effort into it, because the contractor wanted to try to take the quantities from the model and calculate costs based on the model. The contractor took the quantities from the model, but they did it manually as well. It is rather clear that it was actually a double work. It is worthwhile, to note that the diagram reflects the curve of the pilot project, which was a learning process.

Based on those experiences Project 2 was delivered as collaboration between the architects and the same construction company. Figure 4.2 below illustrates time-effort distribution curve for the second project.



PD – Pre-design, SD – Schematic Design, DD – Design Development, CD – Construction Documentation, PR – Production

Figure 4.2 Time-effort distribution curve illustrating D-B Project 2.

As can be seen in Figure 4.2, in the beginning the curve increases gradually. This slow start was probably caused by the lack of an official kick-off, because parties already knew each other. The project started rolling in a slow speed and architects made lots of preparatory works. Between the sixth and ninth month the small peak can be observed. This stage reflects the SD followed by a short pause represented by the steep drop. Later on, the upward trend illustrates the start of DD stage, with a peak indicating the time when all the important decisions about the systems were made. The second peak starting at the month 15 indicates the delivery of documentation with a fall at the end of the stage. As can be seen, there are three smaller peaks during the CD stage, but they are much lower in comparison to Project 1. The highest peak at month 22 indicates the delivery of detailed drawings and the smaller one at month 25 reflects final delivery.

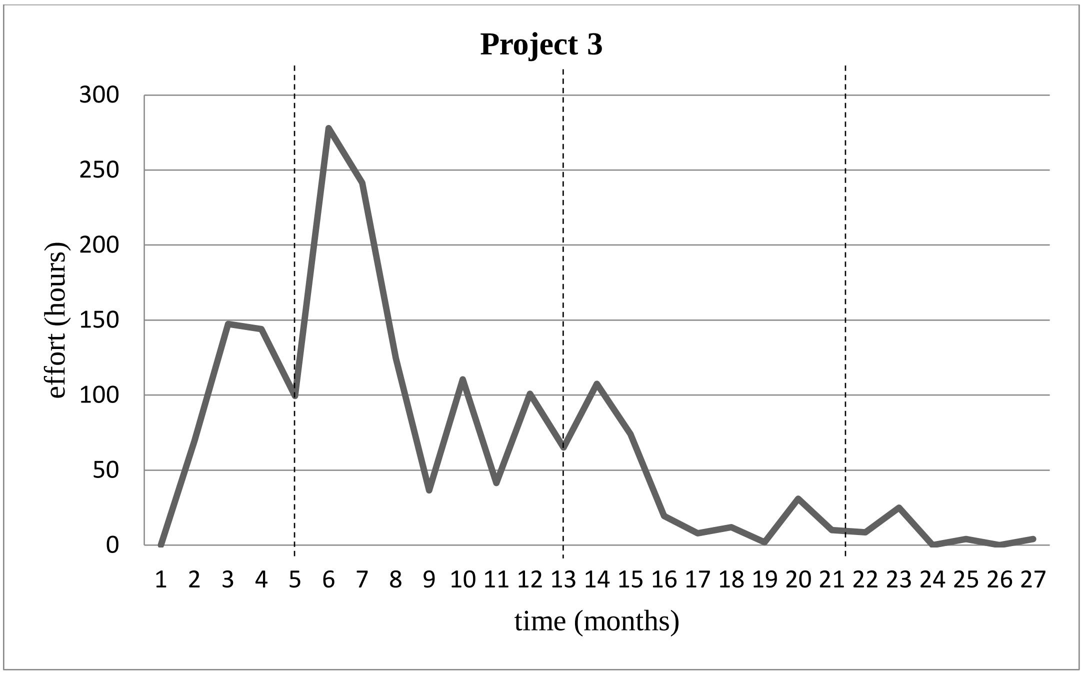
In the beginning of the CD stage it was less intensive period between the DD and CD stages. The reason for that could be that the contractor and project management teams were working intensively during this time with calculations, purchasing and construction management. Results obtained during the interviews confirmed, that architects considered DD stage as the most demanding during that project.

One of the conclusions could be that as the architects were experiencing a pause, the work was done by others. If one would consider combined effort of the entire integrated team, it is a good possibility that the drop between month 16 and 21 would not be reflected, because the work was done by engineers and a project management team.

As described by the leading architect during the interview "both curves made lots of sense and reflected the process very well". Those curves are quite revealing in several ways. Firstly, unlike the curve proposed by MacLeamy (2008), which has one major peak, they seem to have two areas of consolidated efforts. Secondly, they show that despite the theory a large portion of work was done during the CD, when the cost of changes was already quite high and flexibility low. However, it needs to be stressed, that both projects were early examples of 2nd stage BIM collaboration and reflect the learning process. Interestingly, the Project 2 was more complex according to the findings presented in previous Section 4.2.1, but the time-effort distribution curve has much more gently shape. There is a good possibility, that the lessons learned from the Project 1 helped to achieve better results for the Project 2. These results are in agreement with Bryde et al. (2013) findings which showed that BIM management can reduce the time needed for the production of building documentation and improve collaboration between project actors.

The results obtained from the time-effort distribution curves for Projects 1 and 2 can also be affected by the fact, that for both projects the client and contractor were the same companies. In consequence, the curves are probably influenced by the process and the different stages which are required for the project delivery by that client and contractor. These results are in agreement with Josephson & Mao (2014) findings which showed that long lead times caused by administrative procedures, procurement processes and forms of contract have negative impact on construction efficiency. According to the BIM manager from the contractor company, there is a goal to make the process smoother, but for analysed projects the curves most likely reflect very much how the process is structured today.

Two other projects presented below represent the 1st level of BIM maturity, where 3D models were done only for the purpose of producing 2D documentation and never shared, nor shown to the contractors. Figure 4.3 below illustrates the time-effort distribution curve for Project 3, which was delivered for the contractor who did not have BIM experience and requested only 2D drawings from architects.



SD DD CD PR

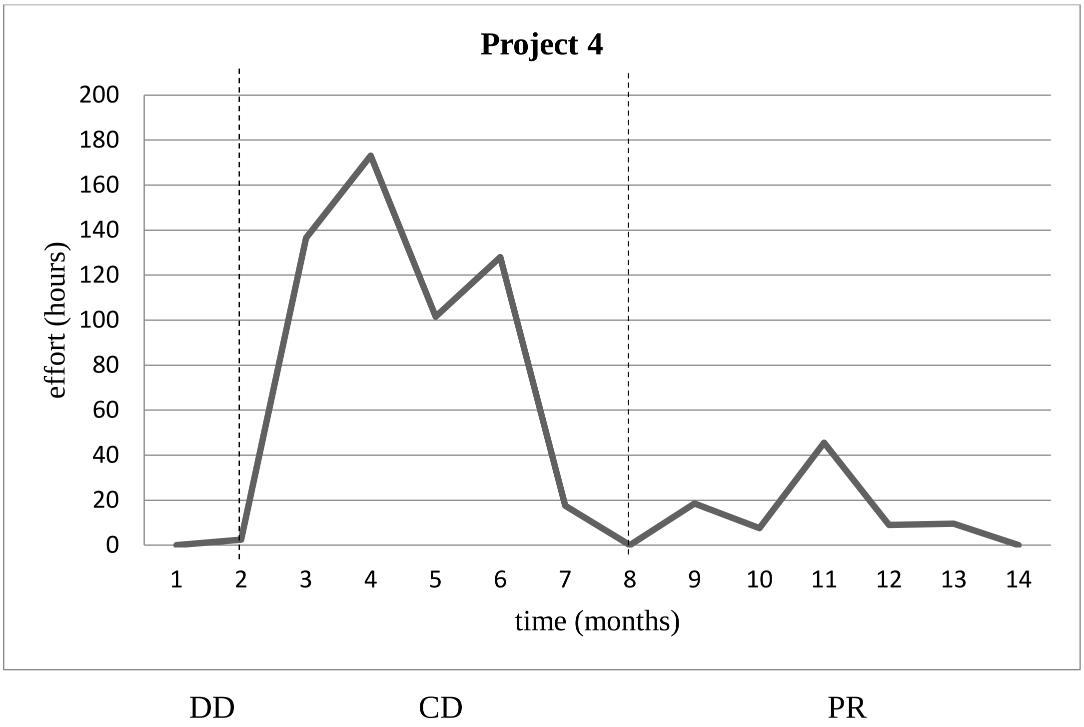
SD – Schematic Design, DD – Design Development, CD – Construction Documentation, PR – Production

Figure 4.3 Time-effort distribution curve illustrating D-B-B Project 3.

As can be seen in Figure 4.3 in the beginning of the process the curve rose sharply and then levelled off before dropping. This shape of the curve was caused by the numerous meetings with the city planning authorities and prolonged process of the design approval. Later on, the curve rose sharply and achieved its peak during the DD, followed by a sharp drop and lower peaks, indicating further issues with the design approval process. Results obtained during the interviews confirmed, that architects considered DD stage as the most demanding during that project, especially because meetings with the city planning office took a lot of time and effort.

During the CD, one peak can be noticed followed by a steady drop. During the PR phase there is also a small pick present caused by design errors discovered on the construction site. It is worthwhile to note, that this curve is very close to the theoretical curve illustrating BIM design process (MacLeamy, 2008).

Finally, the time-effort distribution curve for the Project 4 is illustrated in Figure 4.4 below. That project was taken over from another architect's company after the DD stage and the other company has put the efforts before. Due to the fact that the case company worked only with the CD stage, any earlier stages where not analysed for the purpose of this report.



DD – Design Development, CD – Construction Documentation, PR – Production

Figure 4.4 Time-effort distribution curve illustrating D-B-B Project 4.

Figure 4.4 shows a sharp rise of the curve, in the beginning of the process when the 3D model was built based on the 2D documentation. Later on, the curve drops, before rising again, when the final documentation was issued. Following, the small peaks and drops can be observed during the PR phase. The highest peak during the eleventh month was due to the increased work related to the colour scheme design.

What is interesting in Figure 4.4 is that time – effort distribution curve for Project 4, was the one which shape was the closest to the theoretical curve proposed by MacLeamy (2008) representing traditional design, despite the fact that BIM design was performed at the final stage. It may indicate that BIM application needs to be used from the very beginning of the project in order to be effective. It needs to be noticed that the delivery time for the Project 4 was only 14 month, which is much shorter in comparison with other analysed projects, where delivery time varied between 27 and 45 months. Based on the limited data available, it is a slight possibility that for the more compressed process the curves will have more defined shape closer to the theoretical MacLeamy's (2008) curve.

Overall, these results indicate that there is an association between BIM maturity and time needed to deliver the design for the construction project. In the next section of this thesis design time and cost of projects are analysed.

4.2.3 Productivity analysis

The first set of analyses examined the time needed to deliver one square meter of building design per hour. Hours from all accounts combining efforts of all team members were gathered and divided by the total number of square meters of the building. As a result, architects' productivity for all the case projects was calculated as illustrated in Figure 4.5 below.

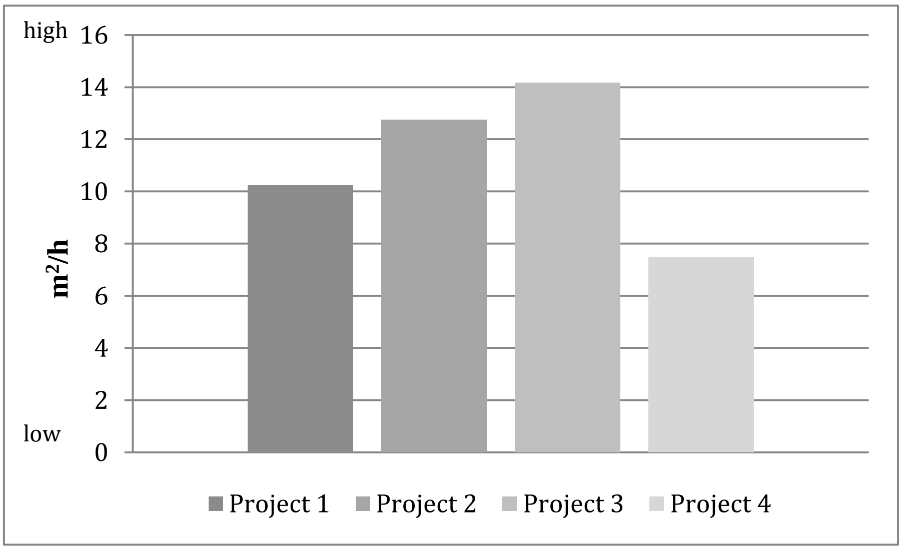


Figure 4.5 Average productivity per gross total area across the entire process.

It is apparent from Figure 4.5 that productivity level for Project 3 was 14.17m^2/h, which was the highest of all. According to the diagram, Project 4 achieved 7.48m^2/h, which was the lowest productivity level. As can be seen Projects 1 and 2, which were more complex than projects 3 and 4, scored accordingly 10.22m^2/h and 12.74m^2/h.

It needs to be pointed out that Projects 1 and 2 were delivered as D-B and Projects 3 and 4 as D-B-B. However, the design stages (PD, SD, DD, CD, PR) were consistent for all analysed projects. For Projects 1, 2 and 3 all design stages, including SD, DD and CD, were done by the same architect. It is worthwhile to note that Project 4 was taken over from another architectural company just before CD stage, therefore time and cost invested in the architectural design during SD and DD stages is not reflected in this study. Therefore, it is seen as necessary to analyse productivity separately for all the stages. Figure 4.6 below illustrates the productivity during SD stage.

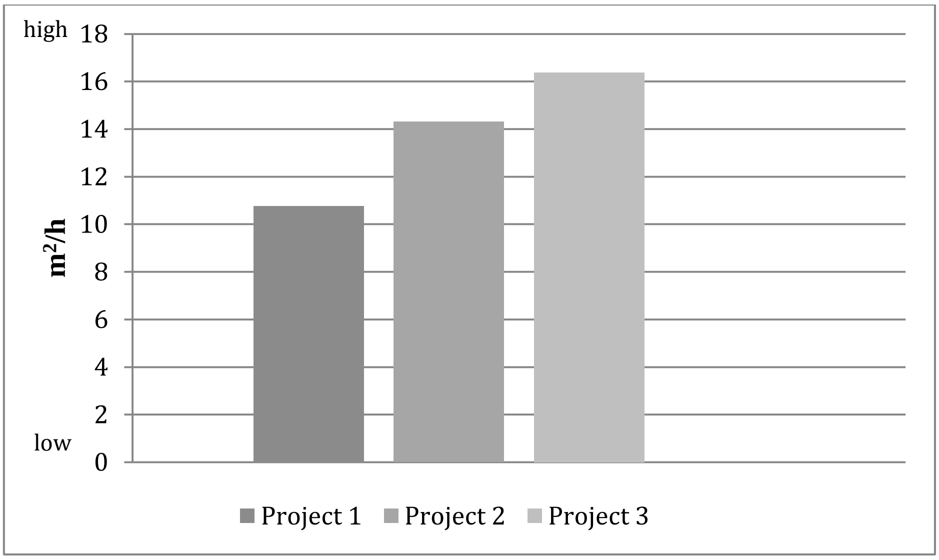


Figure 4.6 Average productivity per gross total area during SD stage.

As can be seen in Figure 4.6, productivity during SD stage was highest for Project 3, representing 1st level of BIM development, and lowest for Project 1, which was a pilot project for model-based collaboration. Besides, lessons learned during Project 1 seemed to have a significant impact on the performance during Project 2, resulting in a significant productivity increase during SD stage. Productivity during DD stage is illustrated in Figure 4.7 below.

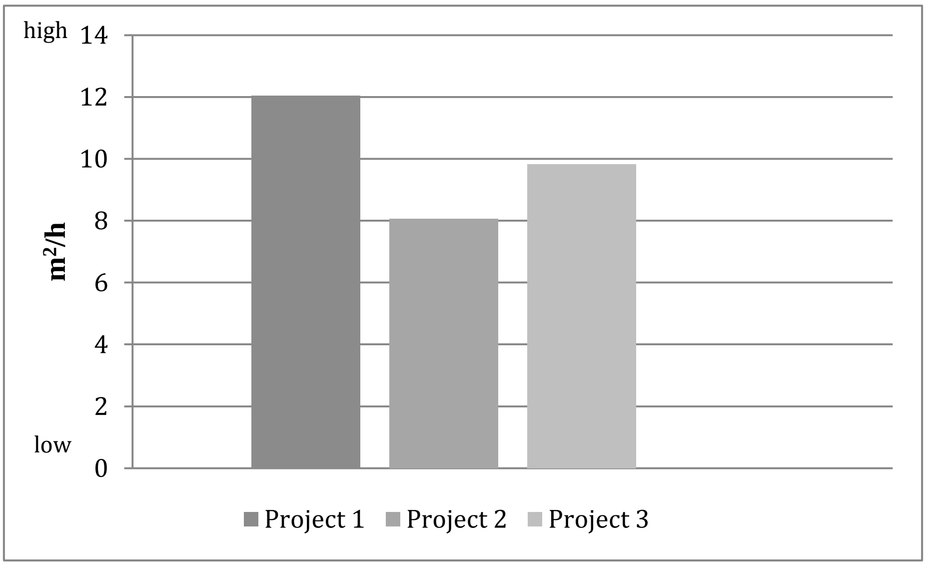


Figure 4.7 Average productivity per gross total area during DD stage.

As can be seen, productivity during this stage was highest for Project 1 and lowest for Project 2. This result is surprising, but potentially it can be explained in the contractual terms. Through Project 1 DD stage architects had a running bill agreement, and in the following CD it was a fixed price contract. Therefore, as one respondent reported during the interviews, the aim was to deliver the majority of work during CD stage. It is reflected in Figure 4.8 below, illustrating productivity during CD stage.

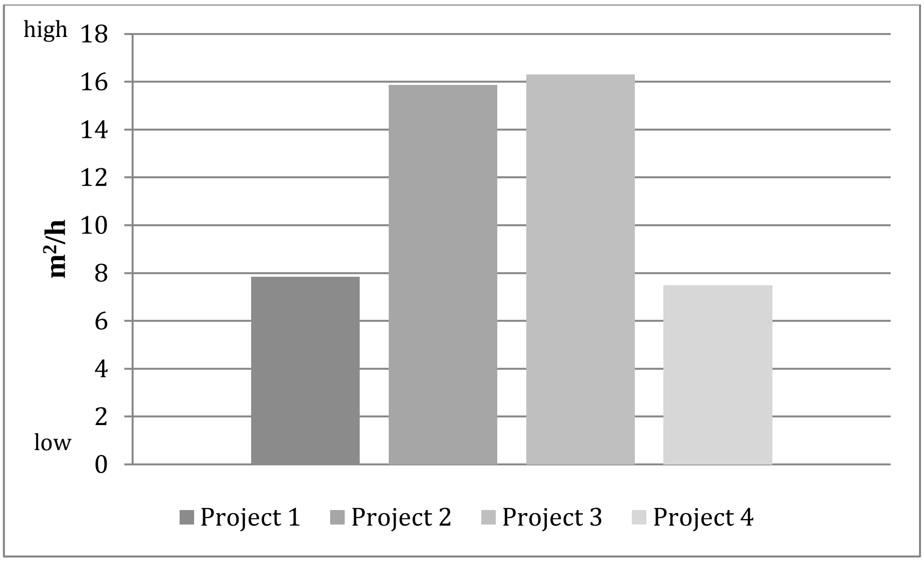


Figure 4.8 Average productivity per gross total area during CD stage.

What is interesting in this data is that Projects 2 and 3 seem to have fairly similar levels of productivity, despite Project 3 having much lower complexity level, according to the complexity matrix illustrated in Table 4.2. The most surprising aspect of the achieved data is that Project 4 seemed to be the least effective, despite its low complexity. Analysis of that project included only the final stage CD. It is possible that the low productivity was related to the need of converting 2D drawings prepared by another company to the 3D model in the final stage of the design.

Overall, it is worthwhile to note that the increase of productivity from Project 1 to Project 2 might reflect the lessons learned and the development of the methods and skills within the team; especially bearing in mind that Project 2 had higher complexity level than Project 1.

Secondly, the design production cost was analysed. Figure 4.9 below, compares the average design production cost per one square meter of gross total area of the building for analysed projects. As can be seen from figure above, the average production cost was highest for Project 1 and lowest for Project 4. Design production cost for both Project 1 and 2, which were examples of 2nd level of BIM maturity appear to be higher than Projects 3 and 4. There is a good possibility that this resulted from the higher levels of complexity as well as application of more advanced BIM design methods, like collision detection tests.

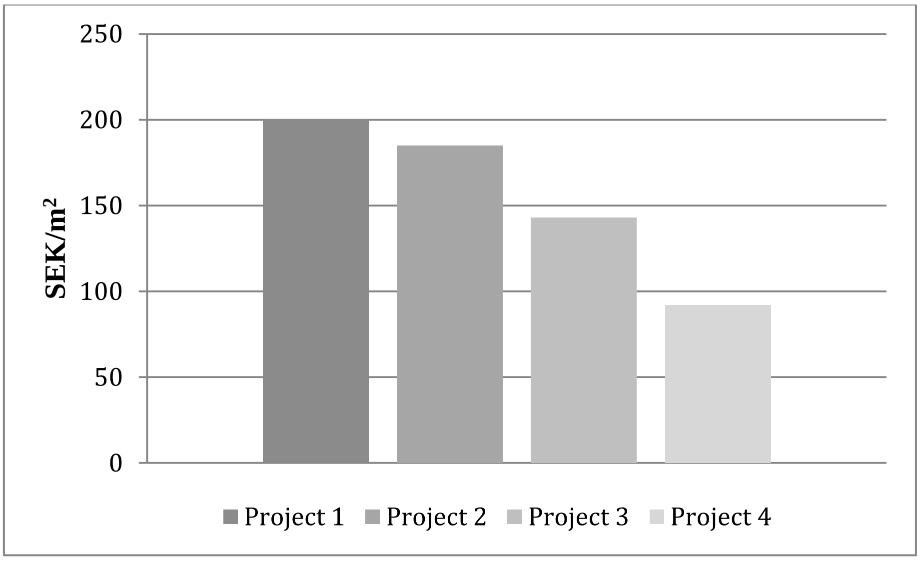


Figure 4.9 Average design production cost per gross total area.

It is not surprising, that the overall design production cost for Project 4 was lowest, since that project included only the final stage of the design. However, Figure 4.10 below, which compares the design production cost during CD stage only, reveals that Project 4 was probably the most expensive of all.

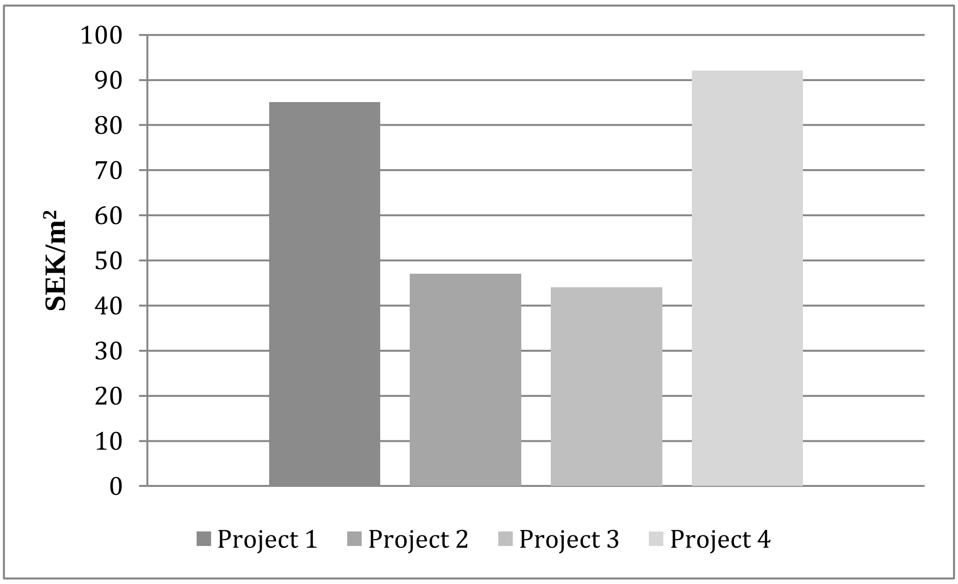


Figure 4.10 Average design production cost per gross total area during CD stage.

In summary, these results show that Project 3 seemed to be produced quickest and to the lowest cost, but from the complexity analysis it could be understood that it was not a very complex project. Project 4 tends was most expensive and the delivery time for this project was longest comparing to the other projects, though it seemed to be the least complex of all. When it comes to the projects representing 2nd level of BIM maturity it was probably faster and less expensive to produce Project 2 even though, it was more complicated than the Project 1, which indicates the development of BIM methods and skills. It can be interpreted, that the advanced

BIM process gives potential for productivity increase, even for complex projects. These results are in line with those of previous studies (Bryde et al., 2013).

Based on the limited data available, the productivity analysis revealed that time needed for the delivery of model-based collaboration projects is slightly longer comparing with object-based modelling projects. Moreover, the cost of advanced BIM design seemed to be higher. However, the decreasing tendencies of extra cost and time can be observed, as a result of learning and development processes. Advanced BIM methods including collision detection tests tend to slightly increase time and cost needed for the design, but it is very probable, that cost and time will be compensated later on. Those results are consistent with those of Lu et al. (2015) who demonstrates that extra time and costs are more than likely to be compensated during the construction process. Additionally, input from the interviews revealed that the collaboration and trust within the team were much greater for the teams in 2^{nd} stage of BIM development, which probably lead to higher quality and less defects during the construction. Those results are presented in section below.

4.3 Interview results

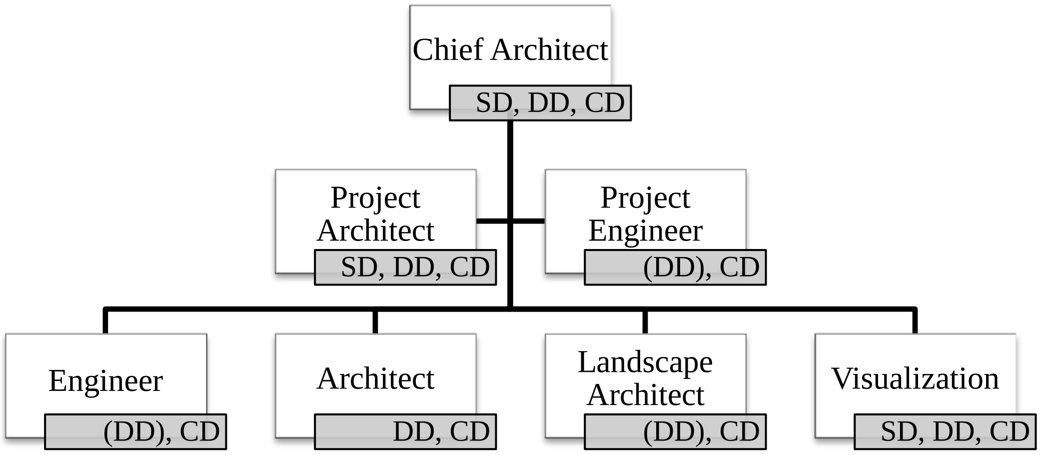
The questions asked during the interviews were meant to explore the aspects of project management, collaboration and impact of BIM on the productivity and design process. The results are presented in the following categories, according to the character of the questions and include: organisation of the projects, collaboration methods, level of BIM employment, impact of BIM on the project, issues and finally benefits of BIM.

4.3.1 Organisation of the project and collaboration methods

The first set of questions asked the informants about the organisation of the projects within the architectural office and contractor, and aimed to explore the project organisation structure and collaboration methods.

4.3.1.1 Project organisation structure

When asked about the internal team organisation within the architectural office respondents gave very consistent answers regarding all analysed projects. The project organisation structure was revealed, as illustrated in Figure 4.11.



SD – Schematic Design, DD – Design Development, CD – Construction Documentation

Figure 4.11 Typical team structure within the architectural company.

As can be seen in Figure 4.11, the chief architect and project architect were responsible for the project during all design stages. A number of respondents reported that the chief architect's role is more visible in the very early stages and later on the project architect takes over the practical responsibility. During DD stage, the teams tend to include more architects and occasionally engineers and landscape architects, according to the project needs. Later on, during the CD stage project engineer and engineer join the team and take responsibility for the details. Additionally, visualisation artists are also involved during the various stages, depending on the project requirements. These results are in agreement with Eastman et al. (2011) findings describing differences between design stages.

4.3.1.2 Multi - collaboration

In order to examine the collaboration methods across the entire design team and the ways of work used during the project life cycle, respondents were asked a number of questions. The purpose was to understand the cooperation and levels of team integration.

Table 4.3 below presents the summary of collaboration methods. The methods are listed according to how frequently they were mentioned by the interviewees.

Table 4.3 Summary of collaboration methods together with related commentaries.

Collaboration Method	Commentary
Spontaneous desktop meetings	Informal short desk meetings when the colours, plans, layouts and details are discussed. Open plan office supports the team collaboration, communication and information exchange.

Formal meetings	Meeting in a larger group held weekly or bi-weekly, for minimum 30 minutes. Subjects discussed: time and work planning, responsibilities and coordination with a timeline.
Project Studio	Longer meetings involving all parties engaged in the particular design stage, including project manager, consultants and site representatives. Held weekly between 8:30AM and 3:00PM.
Skype conversations	Shorter questions and answers exchanged between co-located architects.

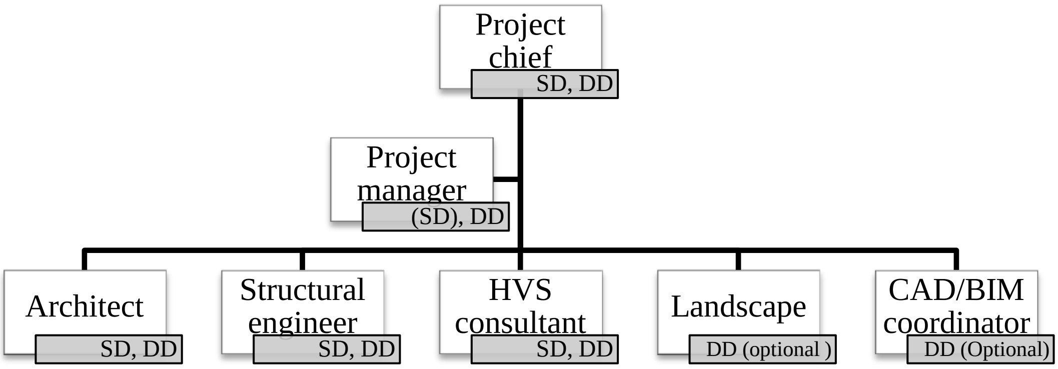
There was a significant correlation between level of BIM maturity representing the project and type of collaboration. Projects belonging to the 1st level of BIM maturity were characterised by the formal meetings combined with spontaneous desktop meetings across all design stages. Meetings were held every second week with the client, when it was decided what needs to be done before the next meeting. Between the meetings, there was continuous contact by telephone and email.

The respondent's highlighted the importance of information sharing within the team, also with members who were not attending the formal meetings. Interviewees representing this group also pointed out that communication and information exchange was very important. One of the respondents stated that it was important that people talk with each other during work, instead of drawing for one week and then meeting. However, the weekly or bi-weekly formal meetings did not seem to support this need very well.

Interestingly, projects on the 2nd level of BIM maturity were characterised by lower number of formal meetings, usually held only during the early stages of the project. Those meetings were substituted by Project Studios, which are based on the management by commitments. This form of collaboration allowed a very high level of less formal meetings held between all project actors in the same room. In between the meetings there was contact over mail and telephone, but as one of the respondents reported "Many things were discussed during Project Studios that is why there was no need for the extensive communication in between the meetings". Overall, these results are in agreement with those obtained by Sull (2003) that management by commitments reduces the need for extensive communication and increases trust.

4.3.1.3 Project management

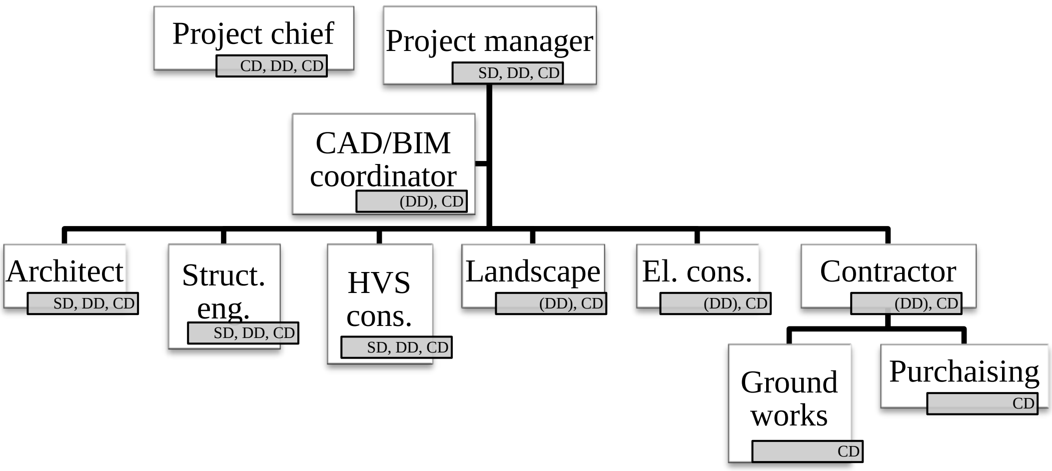
In order to get better understanding of how the collaboration during the project life time was organised including all project actors, respondents were asked about the project management structure for analysed projects. The results revealed common structure for Projects 1 and 2, as well as Projects 3 and 4 respectively. Figure 4.12 below illustrates the involvement of project actors during SD and DD stages of the design for Projects 1 and 2.



SD – Schematic Design, DD – Design Development

Figure 4.12 Project management structure during stages SD and DD, for advanced BIM projects.

Between DD and CD the formal ownership of the project was transferred from the project owner to the contractor which resulted in change of project management structure, as illustrated in Figure 4.13 below.

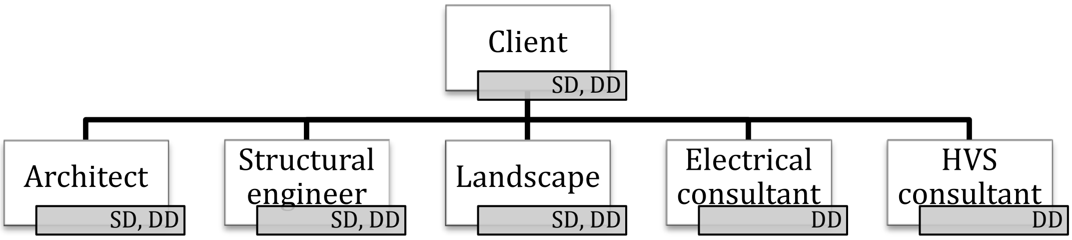


SD – Schematic Design, DD – Design Development, CD – Construction Documentation

Figure 4.13 Project management structure during stages CD, for advanced BIM projects.

During the CD stage also other consultants participated in the process from time to time, according to project needs, for example: fire consultant, sound consultant, prefabrication consultant, lift consultant and acoustics consultant. Above figures illustrate the structure typical for D-B projects (Beard, et al., 2001), which is envisioned by some researchers (Hardin, 2009), to be the best option for the usage of BIM because the parties involved can work together more easily and exploit the collaborative possibilities of BIM.

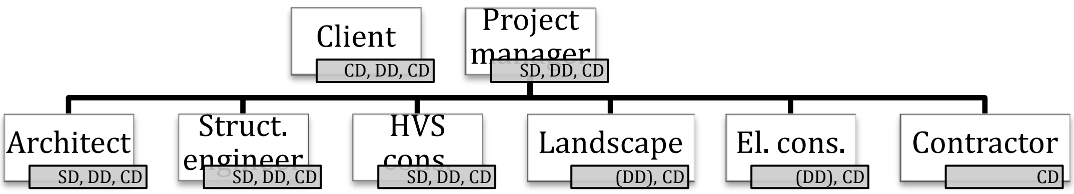
Project structure for early design stages for Projects 3 and 4, representing 1st level of BIM maturity is illustrated in Figure 4.14 below.



SD – Schematic Design, DD – Design Development

Figure 4.14 Project management structure during stages SD and DD, for 1st level of BIM maturity projects.

In similarity, to Projects 1 and 2 the management structure changes before the CD phase for Projects 3 and 4, as illustrated in Figure 4.15 below.



SD – Schematic Design, DD – Design Development, CD – Construction Documentation

Figure 4.15 Project management structure during stages CD, for 1st level of BIM maturity projects.

The main difference between Figures 4.12 and 4.14 is that in the first group of projects there is a project manager, who is present across the entire life process of the project. Another difference, visible between Figures 4.13 and 4.15, is the new function of CAD/BIM coordinator, whose role is very important since that person reports directly to the project manager.

Overall, these results indicate that for 2nd level of BIM maturity projects, the collaboration of actors tends to be greater across the entire process, due to the early involvement. Moreover, D-B type of contract seems to support better the project management of this type of projects. However, even in D-B projects the involvement of contractor, purchasing and other construction related consultants seems to be as late as CD stage, as illustrated in Figure 4.13. This could be considered too late in relation to MacLeamy's curve (MacLeamy, 2008), as illustrated in Figure 2.2, because the ability to introduce changes is already low and cost of the changes high. Due to the late involvement, a contractor seems to have a lower ability to influence the construction methods as well as potentially reduce construction cost.

It is possible, therefore, that the late contractor involvement is related to the occurrence of double peaks, as illustrated in Figures 4.1 and 4.2, in the time-effort distribution curves for Projects 1 and 2. The second peak may be a result of design changes arose due to the contractor involvement just before CD stage. It can thus be suggested that cost reductions and construction methods proposed by the contractor result in the additional late design changes during CD stage.

4.3.1.4 Delivery method

The subsequent set of questions aimed to explore the form of collaboration between architect, client and contractor. Projects 1 and 2 were done as Design-Build, with Client, Architects and Contractor being involved in the design process from early stages. According to the respondent who was the Project Manager of the Project 1, “Architects were one of the second most important participants and there was lots of cooperation with architects during the entire process”. Form of contract with architects varied during different stages. Throughout SD and DD it was a running bill, based on hours logged by architects. Later on during the CD stage it was a fixed price contract.

Projects 3 and 4 were delivered as a Design-Bid-Build. This structure is typical for D-B-B projects, where contractor is selected when the DD is already completed (Hale et al., 2009). Therefore, the entire process is interrupted, which can lead to information loss (Stutz, 2000), as was the case during project 4, when entire documentation was transferred from 2D to 3D in the CD stage, resulting in very high costs of producing documentation. For Project 3 the result of this contract form was a late contractor engagement just before the CD stage, when the design flexibility was very low and cost of changes relatively high.

4.3.2 Level of BIM employment

Respondents were asked a set of questions aimed to explore the extent to which actors were using BIM. The answers revealed the main differences between the projects in the 1st and 2nd level of BIM maturity. The results obtained from the interviews revealed that Projects 1 and 2 had 3D coordination meetings and some forms of 3D-collaboration. However, these activities did not take place during Projects 3 and 4, where the use of architect’s model was limited to production of 2D documentation and visualisations.

Project 1 was a pilot project when it comes to 3D collaboration and Project Studio was introduced during the CD stage. Project Studio is described in more detail in Section 0 of this thesis. During Project 2 architect, structural engineer and ventilation consultant worked in 3D and coordinated their 3D models during all stages. Often they corrected the models during Project Studio meetings. Additionally, the collision detection tests were performed by the BIM coordinator. They were performed once during the DD phase and several times during the CD phase.

4.3.2.1 BIM use

The results showed that during Projects 1 and 2 the 3D models were shared with the contractor, while two other projects were shared with the contractor only in form of 2D files. Architects worked in 3D, having separate models for each building, but never shared those models with other consultants or contractors. The reason why they were not shared was that the contractor did not have BIM experience and never requested 3D models, because they thought that they did not need it.

For those projects where the model was shared with the contractor, it was shared in a form of both native file format (Archicad) and IFC file format. Later on, it was used by the contractor in a number of ways as listed in Table 4.4 below. The functions are listed according to how frequently they were mentioned by interviewees.

Table 4.4 Areas of 3D model utilisation by the contractor.

3D model used for:	Comments
Collisions detection test	All models from architects and engineers, done in different software environments (Archicad, Revit) were connected and coordinated in Navisworks or Solibri Model Checker by CAD/BIM coordinator. Collision detection was done in that model.
General understanding of the design during the construction	For one of the projects there was a TV screen in the meeting room in the on-site office, with ambition for the model to be used on site for information for workers and personnel, but it was not utilised very much. However, the site manager often checked design solutions in the model and printed illustrations from the model to explain how the building should be done.
Cost estimation	Contractor used the information included in the model for estimating costs of the building according to the information from the model.
Quantity take off/ Purchasing	Quantity measurements were taken directly from the model.
Construction planning	Model used by the project management team to plan the construction.

Collision detection tests were the most common use for the 3D model, by the contractor. This method was developed a lot between Project 1 (pilot) and Project 2. The early software used was Navisworks, but due to its high complication and not very user-friendly interface it was later replaced by Solibri Model Checker, which supported the entire process much better.

During Project 1 architectural model was even used in the early stages for cost calculations, but since it was a first project like this, it had some issues, for example wrong wall modelling, not suitable for cost estimation purposes. Today calculations are done directly from the model. Models are even used for the quantity take off, construction site for planning and information meetings with the personnel on site.

Together, these results provide important insights into the development of BIM maturity. The summary of results differing projects being in the 1st maturity level from those in the 2nd is presented in Table 4.5 below.

Table 4.5 Summary of findings about level of BIM employment.

	1st level BIM maturity	2nd level BIM maturity
3D coordination	No	Yes
3D model shared with contractor	No	Yes
3D model used by the contractor	No	Yes

Data gathered during the interviews indicates that Projects 1 and 2 represented model-based collaboration, which is a 2nd stage of BIM, while Projects 3 and 4 were object-based modelling fitting to the 1st stage of BIM development (Succar, et al., 2012). Level of BIM maturity has an impact on the entire process, which is analysed in the following section.

4.3.3 Impact of BIM on the project

In this section are presented respondents' opinions about the BIM's impact on the projects with regards to time, cost and quality of the design. First of all, the comparison of productivity between BIM and traditional design is discussed. Later on, the collisions detected and errors avoided are reported.

Respondents' opinions regarding BIM impact on the project varied a lot. One respondent, who worked with 2nd level of BIM maturity projects, even expressed the opinion that there is not so much impact of BIM comparing to traditional design. Other interviewee said that it would be less work without Project Studio. Another respondent reported that one of the advantages of Project Studio was that everybody had a big exchange with other consultants and understanding of each other and that everybody spoke with each other a lot. Another interviewee thought that it was much better to work with BIM, because the facade, plans and sections are combined all the time and architects can control the effect of the changes on the entire building. As can be seen, there were a lot of contradicting opinions, depending on personal experiences.

Similarly, the BIM manager from the architectural company commented that productivity depends very much on the project and on the architect as well. There are projects were architects would like to test lots of variations, but it is still often a visual test. It is possible that BIM increased the productivity, but architects do not really see it yet. It's hidden, because architects do lots of changes in the model. When architects work in the 3D mode the observer does not notice results on paper, as in the traditional design. Probably BIM does not change the productivity level a lot, but it has allowed architects to test more alternatives. It is really difficult to judge the productivity, because it is not tangible. Additionally, things happen a lot quicker today than they did a few years ago. Expectations from the client are that the design process needs to be much faster. The amount of things that architects are expected to do is also increasing and as a result architects work faster.

Overall, these results indicate that interviewees struggled to define productivity, as suggested by Olofsson & Bröchner (2012). Moreover, the human factor needs to be considered when discussing the productivity (Patten, 1982).

Due to the limited historical data available it was not possible to receive the exact information about the number of collisions detected for each project. However, based on the information obtained during the interviews with architects and project managers, it could be estimated that for Projects 1 and 2 there were around 50 issues detected for each building. It needs to be pointed out that one issue may include many collisions, which could be solved by adjustment of one, or few elements in the building. Collisions were detected during the collision detection tests performed with specialised software as Navisworks and Solibri model checker.

Overall, respondents shared the opinion, that there would be much more collisions on the construction site, if they did not perform the collision tests. According to the respondents collision detection tests on the 3D model appear to generate large financial savings, since the cost of resolving a collision detected during the construction is estimated to be 10 000-15 000 SEK on site. These results confirm the association between advanced BIM collaboration methods and savings generated during the construction (Bryde, et al., 2013).

Due to the historical character of the projects, respondents could not recollect exact numbers of errors detected during the construction. None of the projects avoided errors, but it could be noticed that respondents involved in the advanced BIM projects, where collision detection was performed, were reporting other type of defects than those who did not work with 3D coordination.

The most typical errors described for advanced BIM included 2D related issues with sporadic 3D related collisions. Problems included wrong walls ID, detailing and technical solutions themselves. The project manager from the construction company considered those errors as more related to the human factor and experience of those who did the design, than the 3D model.

4.3.4 Issues related to BIM

Respondents reported BIM issues in relation to cost, time, quality and technical processes. The summary of issues described by the respondents during the interviews is shown in Table 4.6 below.

Table 4.6 Summary of BIM issues reported during interviews.

BIM issues	Comments
Precision of the model	It was not possible to take the quantity take offs for the walls drawn in 3D. The precision and information contained by elements is very important for material calculations.
Errors in the model	Errors were found by both architects and a contractors. There were things in the model which collide even in the architects' own model.
Higher cost	The design process was more expensive, because it took more time.
Unnecessary information	Architects put too much information in the model which was not used by the contractor.
Ownership	There were some issues with the ownership of the specification in the model.
Takes more time	The design proceeded slower compared to the traditional design.
Compatibility	Objects which architects received from the client were not 100% compatible, but they overcame the problems.
Software barrier	Lack of technical skills did not allow using the software with confidence.
Technical problems	Sometimes files could be very heavy, a lot needed to be updated which could be a problem.

Accuracy of elements in the model was very important if it was going to be used for calculations. During the pilot project quantity surveyors did not trust the model and they were taking the quantity take off from the drawings, in a traditional way, because they felt more confident that way. When they took the quantities from the model they found a couple of errors which made them feel uncomfortable.

Design costs tend to be higher and it was more expensive to design in a collaborative way. In the contractor's company there was critique: "Why shall we design in 3D, since it will be more expensive?". However, the strategic decision was made, that all design shall be in 3D, even to the higher cost. Architects also reported that it takes more time to work with Project Studio, but as long as this time is paid it is positive to invest more time in the project.

Probably, the architects invested the work in developing the 3D model which was not utilised in the full scope by the contractor. However, as one of the interviewees admitted, they learned a lot during that process, for example that each story should be modelled separately instead of full external walls and the next project had fewer issues.

Additionally, some architects reported that if one does not know the programme well enough it could be difficult to start drawing. Also, lack of skills makes it easier for some architects to express their ideas when they sketch by hand. If one does not have enough knowledge about the software, then they are not able to draw what they would like to express in 3D, because they simply do not know how to do it.

These results are consistent with data obtained by Bryde et al. (2013), who pointed out software issues, implementation challenges, extra time and psychological barriers. They are also in agreement with those obtained by Chen et al. (2013), regarding technical issues and Eastman et al. (2011), about the need for shift of approach to the collaborative design.

4.3.5 Benefits related to BIM

Respondents reported BIM benefits predominately related to BIM quality. The summary of benefits described by the respondents during the interviews is presented in Table 4.7 below.

Table 4.7 Summary of BIM benefits reported during interviews.

BIM benefits	Comments
Collision detection	Everybody can see what the problems are in the model. There are fewer collisions when everybody coordinates design with other consultants.
Awareness	Since architects and engineers have to model everything in the building they are getting more aware of the whole building. The process is more detailed, which generates more questions.
Information exchange	It was easy to pick up the information from the model and answer the questions quickly.
Quantity take-off	Information needed for cost estimation like: quantities, zones, lists, window and door schedules; can be taken directly from the model in an easy way.
Higher quality of design	There are less design errors and drawings are more proper and accurate.
Visualisations	Architect can generate working visualisations at all times, without extra expenses.

The manager from the construction company considered collision detection tests as the most positive. A benefit with the model was that fewer errors occurred during the construction.

When asked whether it cost more to produce BIM documentation in comparison with traditional 2D drawings, the BIM manager reported that it takes less time to produce BIM documentation, because all plans, facades and sections are connected to the model. Architects do not have to spend time to check, compare and coordinate separate drawings. On the other hand, architects tend to do more than necessary, because they want to produce a good model. Overall, the total production time according to the BIM manager is probably the same.

As can be seen from Table 4.7, benefits of BIM during design stage are related mostly to the quality and collaboration. On the other hand cost and time seem to be the biggest issues of BIM design, as illustrated in Table 4.6. These results confirm, that benefits of BIM have mainly impacted the quality increase, as described by Bryde et al. (2013), which can lead to cost savings during the construction process (Chen, et al., 2013).

4.3.6 Sharing BIM related risks and benefits

Respondents were asked if the financial benefit of BIM was shared with consultants who provided BIM models, in order to investigate the potential development of Integrated Project Delivery for residential projects in Sweden.

According to the architects' the financial benefits were shared, since the contractor shared the risk of increased design cost caused by the longer than expected design process. The design took more time than originally agreed, but architects were paid anyway.

Interestingly, according to the construction manager, the benefits were not shared with architects, because project budgets are calculated for zero errors and there is no budget for mistakes. Therefore, even if the collisions are detected during the design stage, it is not considered as a bonus which can be shared.

However, the respondent mentioned that practice similar to IPD (Jung & Joo, 2011) was performed on the hospital projects, as a partnering contract. In that case the contractor had an open book agreement with the client, but not with consultants who delivered the design. Sometimes the contractor has the open book agreement even with architects and other consultants, but most often only with the client. There is an economic model of how the benefits from the project should be divided, but it is usually applied for the large healthcare projects.

To summarise, constant development of BIM implementation seem to be reflected in all areas of design process from technical side, through collaboration and procurement methods. One of the new BIM management and collaboration methods called Project Studio was a subject of direct observations during this study.

4.4 Direct observations - Project studio

Direct observations were made during 10 large meetings, called Project Studio, held for residential projects, similar to the case studies, which were currently undertaken by the Construction Company. This section contains observations made during those meetings as well as comments about this new method of collaboration acquired during the interviews.

4.4.1 Structure and development

Project Studio is a large meeting held once a week, for the entire day in a specially equipped room, as described in Section 2.2.3. The meeting is attended by all actors involved in the particular stage in the design process. It is important to mention, that participants are free to move around the room and mingle, in contrast to the traditional meeting. That allows for many small, less formal meetings being held at the same time. However, team members are expected not to have too much email contact in between the meetings. There is an aim to solve issues collaboratively during the meeting time, instead of taking them home and solving in isolation from other consultants.

One interviewee reported that the first ever Project Studio management was performed during Project 1, as a pilot. At that time nobody knew what kind of frequency the meetings should be. It started with the common questions which were followed by some discussions around the table. During the first two hours in the morning there was a meeting and later it was meant for everybody to work together during the rest of the day. In general, it was not so well developed at that point of time and it looked more like a regular meeting, but longer. Some team members did not stay during the afternoons and they preferred to work in their own offices instead.

Respondents reported that there is a great difference between the first Project Studio and the ones performed nowadays. The firm have their own consultants for construction and installations who work with Project Studios all the time, because almost all projects are using this method. They are very familiar with this way of work and they encourage it, but in the beginning they were also beginners.

The large difference is that the project leaders now receive internal education about Project Studios. They lead the process much better. In the beginning it was a bit arbitrary; the project managers did not know what to do. However, it was noticed during direct observations that Project Studios are affected by the style of work of the project leader, which has an impact on the factors like team involvement and focus, work effectiveness and attendance.

One of the important fundamentals of Project Studio is the 3D design collaboration, when the collision detection tests are performed. Currently, most of the people are positive towards this method, but a few years ago it was more challenging. Navisworks was more difficult to understand for those who were involved, and it was a little bit of a threshold. People did not understand the purpose.

Currently collision detection tests are performed for almost all Design-Build projects. During the SD stage the tests are performed for the selected floors, in order to test design solutions. Later on during DD and CD stages tests are done for the entire building, and sometimes repeated, depending on the complexity.

4.4.2 Benefits

One of the main benefits of this method is increased collaboration and trust between project actors, resulting from management by commitments. Consultants often work on many projects in the same time, and tend to prioritise the projects which have higher demand. Thus, management by commitments supports consultants' involvement and psychological contract (Royer, 1991), because if they do not deliver what they promised, it is very visible for all project actors.

Additionally, application of concurrent engineering (Thamhain, 2014) encourages project actors to collaborative project solving. It was observed that methods used during Project Studio tackled problems not people. By using post-it notes issues are separated from the individuals and the entire group is stimulated to solve the problem. As a result all questions and issues are equally valid and answered. This method helps to reduce the unnecessary overload of communication and increase trust (Sull, 2003).

With regards to collision detection test introduction of Solibri model checker, helped people to understand the purpose of the collision detection tests, how to work in the model and understand collisions on a more overall level. However, there are always some people who think that collision detection is done too often, and somebody who thinks it is done too rarely.

4.4.3 Issues

The organisation of Project Studio has a big impact on its effectiveness. Based on the observations some managers stimulated more active participation in visual planning than others, and those tend to lock team's attention better. Project managers who used post-it notes, but continued to focus one by one on individual consultants seemed to lose attention of other participants and as a result the meeting was somewhere in between traditional meeting and Project Studio. This half way method tends to be less effective and it was observed that participants who did not have direct attention from the project manager at the given moment started to check emails or involved themselves in other tasks. That style appeared to stimulate much less of informal discussion in between participant during the meeting.

Additionally, it was reported by one interviewee, that Project Studios take more time compared to traditional meetings. Also, documenting the meeting becomes more complex and time consuming. However, those issues seem to be compensated by the increase in quality of the design and better collaboration. Those issues seem to be minor comparing to the improved collaboration and quality. Additionally, Project Studio tends to be in line with BIM design which is based on the trust and collaboration. Therefore, this method can be envisaged as having a potential to expand in the future and replace traditional design process.

4.5 Summary of results

Firstly, the case company was analysed in terms of BIM implementation and maturity. This revealed that education processes and technical issues present some barriers, however not the biggest ones, as described also in the literature review (Bryde et al., 2013; Chen et al., 2013). BIM capability level across the company tends to be rather inconsistent. Some projects are already performed as model-based collaboration, representing level 2 according to Succar et al. (2012), but others are still object-based modelling, which corresponds to level 1. Overall, BIM maturity level for this organisation can be estimated as "managed" developing towards "integrated", based on Succar et al. (2012).

One of the finding was, that the BIM maturity level in the case company was rather inconsistent. Some teams had very high BIM capabilities, which were not widely spread in the office, since those teams worked exclusively on BIM projects. This result is in line with previous studies by Bryde et al. (2013), who reports that BIM does not really support the knowledge transfer between different teams.

Results of BIM employment analysis indicated that Projects 1 and 2 represented model-based collaboration, which is the 2nd stage of BIM development, while Projects 3 and 4 were object-based modelling fitting into 1st stage (Succar et al., 2012). For projects belonging to the 2nd level a 3D model was used by all actors involved in the process including project management and construction teams. It was utilised for 3D coordination including collision detection tests, quantity take offs and purchasing, construction planning and general understanding of the design on site.

Following the complexity analysis of the case projects, the current study found that productivity is not directly connected to the complexity level of a particular project, when BIM is applied. The most important finding was that the application of BIM management in form of Project Studio can indeed reduce the time needed for production of building documentation and improve collaboration between project actors. These results are in line with those of previous studies (Bryde et al., 2013).

Analysis of time-effort distribution curves are to a large extent consistent with theoretical curves proposed by MacLeamy (2008). However, some deviations were observed for projects representing model-based collaboration. These results seemed to be consistent with other research which found that MacLeamy's curves do not fully reflect the reality of BIM projects (Lu et al., 2015). A possible explanation might be that lead times as well as administrative procedures and procurement processes (Josephson & Mao, 2014) were reflected in the curves. There is a good possibility that a more integrated and consolidated process will result in smoother curves, closer to those proposed by MacLeamy (2008).

Productivity analysis revealed that BIM can have a positive impact on productivity increase, regardless the complexity of the project. One interesting finding is that the complex Project 2, where model-based collaboration was applied, was delivered quicker and to a lower cost, compared to the preceding pilot Project 1. Additionally, the CD stage of Project 2 was done in a much more effective way than fairly uncomplicated Project 4, which involved only object-based modelling. These results further support the idea of BIM's potential to increase efficiency during the design process (Eastman et al., 2011).

Based on the limited data available the productivity analysis revealed that time needed for the delivery of model-based collaboration projects tend to be slightly longer compared to object-based modelling projects. However, findings from the interviews revealed that a significant number of collisions were detected in the 3D models, which resulted in less need for rework on site and quality improvement. Those results are consistent with those of Lu et al. (2015) who demonstrates that extra time and costs are more than likely to be compensated during the construction process.

Additionally, input from the interviews revealed that the collaboration and trust, within the team, were much greater for the teams in the 2nd stage of BIM development, which probably lead to higher quality and less defects during the construction. Advanced BIM projects also seem to be characterised by the reduced need for extensive communication and increased trust, due to Project Studio, which applies management by commitments and concurrent engineering. These results are in agreement with those obtained by Sull (2003).

Analysis of project management structure for all projects revealed that the D-B procurement method better supports early involvement of consultants, who can work collaboratively with BIM and contribute to the project's efficiency and increased quality. These results seem to be consistent with other research which found that D-B is envisioned to be the best option for the usage of BIM (Hardin B., 2009). Analysis of two D-B-B projects, corroborate the ideas of Hale et al., (2009) and Stutz (2000) who suggested that interruption of the process, caused by this procurement method, can lead to loss of information and late involvement of the contractor.

Analysis of impact of BIM on the productivity revealed two things. First of all, respondents had problems to assess the impact of BIM, due to lack of clear understanding of a productivity definition, which supports findings made by Olofsson & Bröchner (2012). Secondly, it was found that the productivity should be discussed in relation to the human factor, as suggested by Patten (1982).

Issues resulting from BIM application included: lack of precision and errors in the model, higher cost, unnecessary information, ownership, extra time, compatibility, software barriers and technical problems. These results are consistent with data obtained by Bryde et al. (2013), who pointed out that software issues, implementation challenges, extra time and psychological barriers are among BIM's limitations. They are also in agreement with results obtained by Chen et al. (2013), regarding technical issues and results of Eastman et al. (2011), about the need for a shift of the approach to the collaborative design.

Following, the benefits of BIM were identified as collision detection, awareness, information exchange, quantity take-off, higher quality of design and visualisations. These results confirm that benefits of BIM have mainly impacted the quality increase, as described by Bryde et al. (2013), which can lead to cost savings during the construction process (Chen et al., 2013). On the other hand cost and time seem to be issues of the BIM design. Risks and benefits of BIM employment seemed to be shared with consultants to some extent, however partnering contract was mentioned as a potential for an even better BIM collaboration.

Finally, the new collaboration method called Project Studio was described as having potential to expand in the future and replace traditional design processes, due to its impact on the improved BIM collaboration and quality of design.

5 Discussion and conclusion

This final section aims to summarise the entire study and highlight its connections to the findings by other researchers. First of all, an evaluation of the results achieved during this study is presented in relation to the research questions. Secondly, concluding remarks are described and finally, suggestions for future research are listed.

This thesis was designed to determine the effects of BIM on productivity in design processes and potential for sharing risks and benefits related to BIM implementation by all project actors. The method was based on the case studies of real projects, supported by interviews and direct observations. Since some of the researchers (Lu, et al., 2015) claim that curves proposed by MacLeamy (2008), do not reflect the reality of BIM projects, one of the objectives of this study was to illustrate the time-effort distribution curves for analysed projects.

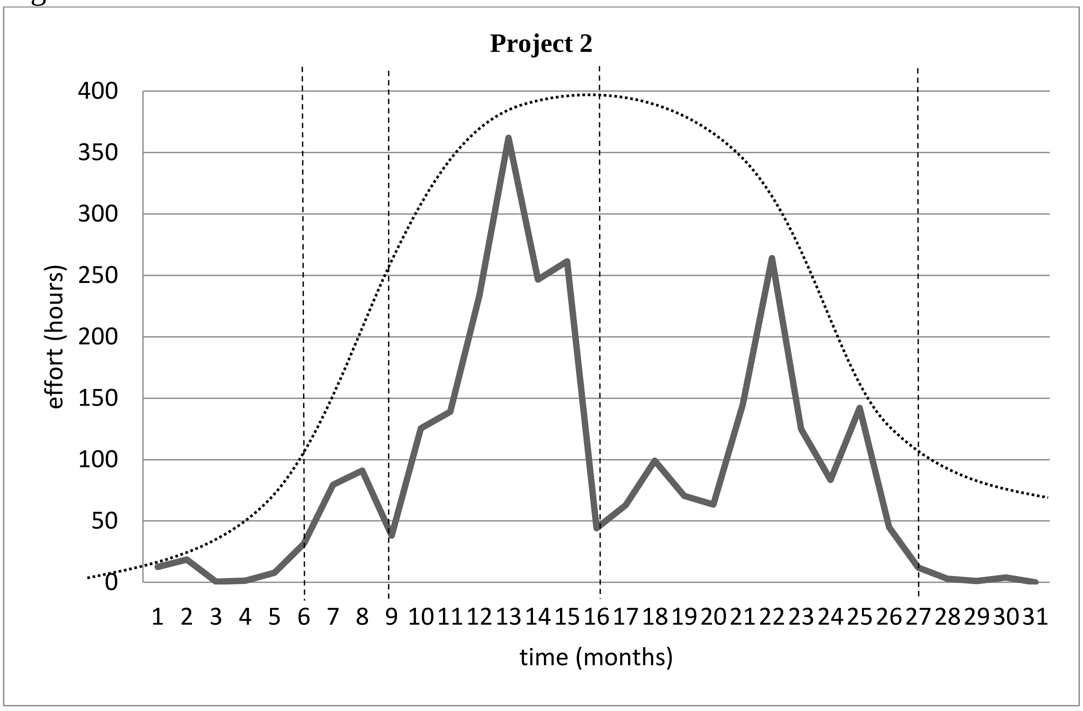
One of the interesting findings is that BIM seems to support the collaboration and quality increase. This result is in line with those of previous studies (Bryde et al., 2013; Chen et al., 2013). Productivity of teams employing BIM can be reduced by technical issues, implementation challenges and psychological barriers. Additionally, cost and time tend to be issues of the BIM design process, but they are probable to be balanced later on in the process. Those results are consistent with those of Lu et al. (2015) who demonstrates that extra time and costs are more than likely to be compensated during the construction process. Discussion of findings, including time-effort distribution curves is presented below.

5.1 Impact of BIM on the productivity and collaboration

When looking at the complete building design and construction process from the initial sketch to the moment when a building is occupied by people, the entire process is probably less costly and more time effective when BIM is applied. It has been suggested that time needed to produce construction documentation when BIM is applied can be shortened (Bryde, et al., 2013). However, this does not appear to be the case when architectural design is analysed in isolation from the production. It is surprising that architectural design at the 2^{nd} stage of BIM maturity tends to be longer and more expensive compared to projects at the 1^{st} level.

Figure 5.1, below illustrates the shape of MacLeamy’s time-effort distribution curve (MacLeamy, 2008) overlaid with a curve representing Project 2. It needs to be stressed that the design time was analysed in separation from other activities and efforts of other consultants. The time–effort distribution curves only reflect architects’ effort and do not include combined efforts of engineers and project managers who were working with cost, construction preparations and purchasing.

Therefore, it is possible, that the “missing parts” were actually not the parts of the architectural design process but, somebody else’s work. Since the work performed by architects overlapped with the work of engineers, management team and construction preparation it is possible, that combined efforts of the entire design team could make the curve more similar to the theoretical one, as illustrated in Figure 5.1.



PD SD DD CD PR

PD – Pre-design, SD – Schematic Design, DD – Design Development, CD – Construction Documentation, PR – Production

Figure 5.1 Comparison of time-effort distribution curve for Project 2 with theoretical MacLeamy’s curve (MacLeamy, 2008).

However, it is likely that the increased efforts represented in the curve illustrated in Figure 5.1 are caused by the procurement process of the Construction Company. If the processes were more smooth and requirements more clear from the beginning, maybe the double peaks could be avoided.

One of the key benefits recognised in the literature is that BIM can effectively support the project management during the design of the construction projects (Bryde, et al., 2013). Authors are of the opinion that BIM can be utilised by project managers as a tool which helps to manage construction projects. Hence, it could conceivably be hypothesised that the entire process can be overlapped even more. If project management activities are performed in parallel to design activities, this can potentially allow for a more natural progress to the next stage and a smoother design curve.

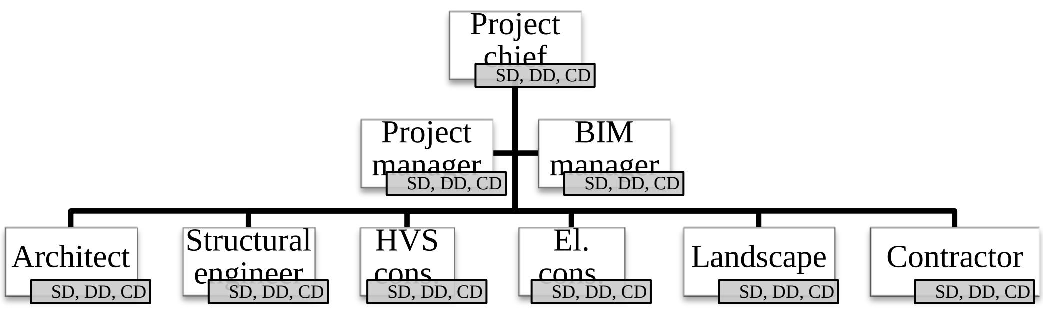
If the work performed by project management team including cost estimation, production preparation and production method selection, was done in parallel with design activities, the long waiting time, which is about four month for current projects, could be avoided. Avoidance of the gap between DD and CD stages could have several benefits. First of all, architects' work would not be interrupted which can possibly allow for better work continuity, higher level of commitment and smoother transfer between different stages. Secondly, design work parallel with project management efforts is likely to support development of new design solutions and possibly reduce the amount of changes which needs to be done during CD stage.

The results of this study indicate that challenges of BIM implementation can be seen in conjunction with change management issues. According to Bryde et al. (2013) strategies to overcome those issues may be training of staff and stakeholder engagement activities facilitating the process of understanding and acceptance for the new working methods.

The current study found that productivity is not directly connected to the complexity levels of a particular project, when BIM is applied. The most important finding was that the application of BIM management can indeed reduce the time needed for the production of building documentation, improve the quality and increase collaboration between project actors.

New collaboration methods, like Project Studio, seem to support the development of trust and enhance collaboration. However, traditional D-B-B contracts, or even D-B procurement methods, where fixed price is applied, do not seem to support productivity development in an optimal way. The view of Eastman et al. (2011), about the need for a shift of the approach to a collaborative design is confirmed by this thesis. A shift towards network-based collaboration (Succar, et al., 2012) will require even closer collaboration and trust between project actors.

Analysis of project management structure revealed that even for D-B projects the involvement of the construction team was as late as in the DD or even CD stage. As a result, the contractor comes to the process when most of the design decisions are already made, the cost of changes becomes high and design flexibility is low. Therefore, earlier involvement of the contractor is recommended, as illustrated in Figure 5.2, below.



SD – Schematic Design, DD – Design Development, CD – Construction Documentation

Figure 5.2 Proposed project management structure for advanced BIM projects.

The above illustrated structure is more common for IPD projects, when all project actors work together from the very beginning of the project. The benefits are, that the suggestions for construction methods, solutions and improvements are made early in the process. There is a good possibility, that early contractor's involvement during the SD stage, could potentially eliminate the need for the later design changes and reduce the design time and cost.

These results are in line with those of previous studies (Bryde et al., 2013). This finding, while preliminary, suggests that advanced BIM methods have a positive effect on the trust relationships and collaboration, but its implementation can be expensive. Although, the learning process and increase of productivity during two analysed advanced BIM projects allows making an assumption, that future projects may achieve design productivity comparable with those done in a traditional way, but to a much higher quality. Therefore, it is envisaged, that BIM has a huge potential to improve productivity, trust, collaboration and contribute to balancing the entire construction process, also in terms of time and cost.

5.2 Potential to share benefits and risks of BIM

The second research question remains, how benefits and risks of BIM can be shared more equally between all participants of the design process.

It was noticed, that the architectural company benefited from a successful BIM collaboration with the contractor company, by being awarded new projects. This observation is supported in the literature by Bryde et al. (2013), who reports that successful employment of BIM supports growth of the company and helps winning new projects.

On the other hand, it can be suggested that benefits of BIM have mainly impacted on the quality increase, as described by Bryde et al. (2013), which can lead to significant cost savings during the construction process (Chen et al., 2013). However, those are not shared directly with consultants who contributed to adding value. Risks and benefits of BIM employment seemed to be shared with consultants to some extent, but partnering contract was mentioned during the interviews, as a potential for even better BIM collaboration.

However, analysis of procurement methods led to the conclusion, that D-B-B corroborates the ideas of Hale et al. (2009) and Stutz (2000). Researchers suggested that interruption of the process, caused by this procurement method, can lead to loss of information and late involvement of the contractor. The D-B procurement method supports early involvement of consultants, who can work collaboratively with BIM and contribute to the project's efficiency and increase quality. However, even this method can be a limitation when a fixed price contract is in place. Therefore, other procurement methods like partnering or IPD are envisaged to better support the integrated BIM design. Especially, keeping in mind that in some countries BIM is already a legally required standard (Bryde, et al., 2013). It can therefore be assumed that the new procurement methods need to follow BIM, as a new approach to the collaborative design and construction.

5.3 Concluding remarks and suggestions

The study has shown that productivity is not related directly to the complexity of the projects and that BIM management can affect the productivity. Increased collaboration between all project actors seem to contribute greatly to the quality increase of the design and tend to result in significant savings during the construction. New collaboration methods as Project Studio appear to support development of trust and relationships between all actors involved in the process, resulting in further savings due to the collision detection tests. The results of this study confirm that BIM seems to be the future method of collaboration in the construction sector and that analysed companies are already very advanced users of BIM, sharing benefits of BIM to a large extent.

The results of this study has shown that greater efforts are needed to ensure knowledge transfer between teams who deliver BIM projects with other architects from the case company who do not work in the collaborative BIM environment. The architectural company can benefit even more if the BIM knowledge is spread more equally among the employees. Further progression from “managed” or “integrated” maturity level, to “optimised” (Succar, et al., 2012) requires knowledge spreading in the company. In order to enhance the process even better it could be recommended to encourage natural spread of BIM knowledge and experience within the organisation.

This can be achieved if, for example the top performers from advanced BIM teams start to work with other people, including older people who were in the company for a while. In the beginning it may take longer time to deliver the particular projects, since the learning process will be involved. Therefore, in a short term perspective it is likely that the productivity may go down. However, in a long term perspective, the entire company can possibly gain, because the level of BIM competence will be more equally spread among the entire office and the productivity level across the office is likely to increase.

Analysis of time-effort distribution curves revealed that procurement processes can affect the design process in a negative way. In order to achieve smoother curves project management processes need to be more integrated. Recommendations include early contractor involvement, even during SD stage and undertaking project management activities like cost estimation and choice of construction methods parallel to the design process. Clear requirements from the beginning of the process, increased collaboration and lack of unnecessary breaks in the process are more than likely to reduce cost and time needed for the design and further quality increase.

The collaborative methods like Project Studio greatly support the productivity increase of the entire team. However, it was noticed that the efficiency of those sessions is to some extent connected to the project manager leading Project Studio. Therefore, further training and continued efforts are needed to encourage managers to act even more like facilitators stimulating collaborative work.

Finally, further developments towards network-based integration and even more collaborative work will need to be reflected in new forms of contracts, which will support better BIM integration. Ensuring appropriate systems, management and procurement methods for BIM should be a priority for the decision makers. Increased productivity of design teams working with advanced BIM is likely to be achieved if the contractual form is focused on mutual understanding as well as sharing risks and benefits. Therefore, procurement methods like partnering or IPD are envisioned to have great potential for BIM collaboration.

Overall, BIM implementation seems to have huge potential on productivity increase in the design process. However, further development, training and investments cannot be avoided, prior to reaching the point, when the *Iron Triangle* of cost, time and quality will be balanced.

5.4 Suggestions for further research

A natural progression of this work is to analyse the impact of BIM and model-based collaboration on the productivity during the construction stage. This study only touched on the impact of BIM implementation in the construction phase. Further research might explore how BIM design impacts the quality of delivered building. A more complete study, including construction phase, could also reveal if combined efforts of architects, engineers and contractors reflect the shape of time-effort distribution curve as proposed by MacLeamy (2008).

More research is needed to better understand possibilities of practical implementation of partnering or IPD contracts for multi-residential building projects in Sweden. Currently, these forms of procurement seem to be applied only to the complex healthcare buildings.

Finally, the study of time-effort distribution curves could be repeated for some of the most recent projects utilising BIM collaboration. It could reveal the development of new design methods used by analysed companies and their effects on productivity.

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Appendix 1 - Interview questions

Interview questions to architects leading each of analysed projects

1. How was the design work on the project organised?
2. How did the architects collaborate with each other?
3. How did the architects collaborate with the contractor? What was the procurement method?
4. How often and how long were project coordination meetings? For what period of time?
5. Who participated (disciplines) in coordination meetings? Did they work in 3D?
6. Were 3D coordination meetings (Project Studios) performed? During which stages of design (schematic, detailed, construction drawings)?
7. Which design stage demanded the most effort?
8. Are you aware if the contractor found design errors during the construction?
9. Was the 3D model shared with the contractor? If not, why not?
10. How did BIM impact the architects' productivity comparing with traditional design?
11. What issues with BIM did you experience?
12. What benefits of BIM did you experience?
13. Did the contractor share risks and benefits of producing BIM documentation with you (architects) in any way?

Interview questions to project managers from the contractor company managing the particular project

1. How was the design work on the project organised?
2. Did you work with 3D models and how?
3. How did the contractor collaborate with the architects?
4. How often and how long were project coordination meetings? For what period of time?
5. Who participated (disciplines) in coordination meetings?
6. Were 3D coordination meetings (Project Studios) performed? During which stages of design (schematic, detailed, construction drawings)?
7. Was the 3D model made by the architects used by the contractor? If not, why not?
8. How was the 3D model used after it was received from architects?
9. What issues with BIM did you experience?
10. What benefits of BIM did you experience?
11. How many design errors were detected during the construction?
12. Do you know how many design errors were avoided due to BIM model coordination (collision detection)?
13. Was the financial benefit of BIM shared with consultants who provided BIM models?

Interview questions to the BIM coordinator at the architectural company

1. When was 3D design introduced at the office?
2. Can you describe the process of BIM maturity at the office throughout the years?
3. At which level are you now?
4. How do you judge the level of BIM maturity across the entire office? Is it consistent?
5. How would you compare costs of implementing BIM and producing BIM documentation comparing to traditional non BIM methods?
6. How does BIM impact architects' productivity comparing with traditional design?

Interview questions to the BIM coordinator at the contractor company

1. How long have you being working with BIM?
2. For what types of projects do you perform collision detection with Solibri Model Checker?
3. What types of projects are not coordinated in 3D? Why?
4. How many times do you usually check the same project and at what stages (schematic, detailed, construction drawings)?
5. What is the attitude from actors involved in the coordination meetings to collisions detection supported by Solibri?
6. How has this attitude changed over recent years?
7. Do you have any archive data about how many collisions were detected during analysed projects at different stages (schematic, detailed, construction drawings)?

Appendix 2 – Case study projects

Figure 6.1 Project 1.

Figure 6.2 Project 2.

Figure 6.3 Project 3.

Figure 6.4 Project 4.