Heikki Halttula

ENHANCING DATA UTILISATION IN THE CONSTRUCTION PROJECT LIFECYCLE THROUGH EARLY INVOLVEMENT AND INTEGRATION
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Abstract
The productivity of projects in the construction sector has not developed as well as in other sectors. One factor contributing to this low productivity is the weak digital intensity of the construction sector. Often, the implementation of construction projects is fragmented, and the objectives of the project stakeholders’ conflict with those of the whole project. Existing research has highlighted the importance of the use of building information modelling in the construction industry. In some other sectors, the product data lifecycle management has an essential role in their business, but in the construction industry, product data management has less attention.

The motivation for this dissertation is to help the construction industry to gain the benefits that the use of BIM can provide. The focus is on enhancing data utilisation because late and fragmented management of information during the project lifecycle leads to defects and rework. This dissertation’s aim is on how to enhance data utilisation in construction projects by enabling early integration of stakeholders. The technical description of the data transfer format has not been in the scope of this research. This dissertation does not either include descriptions of all the commercial project delivery models.

This compilation dissertation consists of qualitative studies with literature reviews, focus group interview, survey, and interviews. It identifies practical obstacles to the wider use of information modelling, how information modelling supports early involvement and integration, and the benefits of early integration. Finally, it produces a model for data and information management for construction projects.

The main contribution of this study is that it identifies a need to design a unique project product data model in the early phases of the project, according to the information of all stakeholders. One master data enables data sharing with different applications. Design for X (DfX) can be used for early integration. The client is responsible that the project delivery agreements support the well-organised use of data and information flow throughout the project’s lifecycle. The most significant barrier for achieving the benefits of BIM is that the data needs and the overall process of BIM utilisation are not planned proactively. The practical implications are written mainly from the infrastructure construction project angle. The main impact is that the project product data model is better to design specially for each unique project that matches the capability level of the project team, available data, software and hardware, project delivery type, and team motivation.

Keywords: BIM barriers, BIM capability level, building information model (BIM), construction, data and information management, data governance, design for excellence (DfX), early involvement, integrated project delivery, integration, lifecycle, master data, product data, relational project delivery
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Tiivistelmä

Tämän väitöskirjan motivaationa on auttaa rakennusalaa saamaan hyötyjä, joita BIM:n käyttö voi tarjota. Painopiste on datan käyttön parantamisessa, koska tiedon myöhäinen ja hajanainen hallinta projektin elinkaaren aikana johtaa virheiin ja korjauksiin. Tämän tutkimuksen tavoitteenä on parantaa tiedon hyödynnämistä rakennusprojekteissa mahdollistamalla sidosryhmien aikainen integrointi. Tiedonsiirtomuodon tekninen kuvaus ei kuulu tämän väitöskirjan sisältöön. Tämä työ ei myöskään sisällä kuvauksia kaikista kaupallisista projektitoimitusmalleista.

Tämän kokoomateos koostuu laadullisista tutkimuksista, joissa on tehty kirjallisuustutkimuksia, kohderyhmähaastatteluja, kyselystutkimus ja haastatteluja. Se yksilöi käytännön esteet tietomallinnuksen laajemmalle käytölle ja sille, miten tietomallinnus tukee varhaista osallistumista ja integraatiota sekä tuo esiin varhaisen integroinnin hyödyt. Lopuksi se tuottaa mallin tiedon hallintaan rakennushankkeissa.


Asiakset: aikainen osallistuminen, BIM kyykkyystaso, BIM:n käytön esteet, building information model (BIM), dataan ja informaation hallinta, design for excellence (DfX), elinkaari, integraatio, integroitut projektitoimitus, liiketoimintakriittinen perustiedot, rakentaminen, relaatioprojektimalli, tiedon hallinta, tuotetieto
To my mother
Acknowledgements

It was not typical in Seinäjoki, where I spent my childhood that a carpenter’s son starts to study. I remember that my dad was mad about me when I went to the middle school entrance examination at the age of 11. At that time, this entrance examination had a crucial role in the youngster’s life. If you did not qualify, you end up to trade school as most of the other kids did in our neighbourhood. In practice, the only path to academic studies was through middle school. I was lucky to qualify thanks to my mother, who took me to the examination without prior consent from my father. Mother encouraged me to study, to reach better-paid occupations and avoid a future as a low paid worker, who needs to go to work outside in all weather conditions like my father’s destiny was. I respect and sympathise labourers and their work; their life is not always easy. Thank you, mother, for motivation and encouraging me to study.

When I graduated from Oulu University as a Master of Science, I thought that this is it – no more academic studies for me. I kept this promise for almost 30 years. When I returned to the university, the first visit after 30 years was shocking. When I entered the building, everything looked the same as 30 years ago. The funny feeling came over me, have I actually ever graduated or am I still a student returning to university to finalising master thesis. The reason for this weird feeling was that the university building has been preserved. No changes are allowed to the original university layout. The reason I returned to university studies was a deep desire to know more about building Information modelling and lean thinking. Both methods are up-and-coming tools to disrupt the current old-fashioned practises in construction. There were even first articles that showed good results of applying BIM and lean together. I thank Professor Harri Haapasalo for introducing lean and product data management and persuading me to study these fascinating topics. I thank Harri also for supporting me and encouraging me when the energy to continue writing articles were low. Without Harri’s encouragement and guiding, I could not have done my dissertation.

My central relaxation to balance work and studies was tennis. I thank my old tennis friends like Björn Lillkål who kept on playing tennis with me although I could not give a proper challenge for a couple of years after I got a tennis ball in my eye. Most extreme and even tennis matches we had with Markku Nissinen. Ari Malmio and Jouko Saloranta were other tennis enthusiasts. Thank you, guys, these games really helped me to think something else for a while. My tennis hobby ended with a severe back problem. After a surgery, yoga came into my life. Almost
daily practices keep the pain away from my back and mindfulness ease the mental pressure. I thank my wife, Kaija, for supporting me through the challenges in work and studies. Kaija motivates me to keep on yoga practices and insists on participating in various yoga retreats around the world. My children Teemu and Essi have managed well in their studies. I hope that I have managed to pass forward the motivation to study and strive for a meaningful life and occupation. Teemu is a lean enthusiastic, as well. Thank you Essi and Teemu for just being what you are today.

I thank the pre-examiners Ali Rostami and Vishal Singh for their enthusiastic and thorough examination with valuable feedback to my dissertation, which is now much better after your comments.

29th March 2020

Heikki Halttula
### Abbreviations and definitions

<table>
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<th>Description</th>
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<tbody>
<tr>
<td>BCF</td>
<td>Building Collaboration Format</td>
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<td>BIM</td>
<td>Building Information Model</td>
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<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
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<tr>
<td>CEN</td>
<td>European Committee for Standardisation</td>
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<td>Cobie</td>
<td>Construction Building Information Exchange</td>
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<td>COBIM</td>
<td>Common Building Information Model Requirements</td>
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<td>CRM</td>
<td>Customer Relationship Management</td>
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<td>DB</td>
<td>Design-Build Project Delivery</td>
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<td>DBB</td>
<td>Design Bid Build Project Delivery</td>
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<tr>
<td>DD</td>
<td>Data Dictionary</td>
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<tr>
<td>DfX</td>
<td>Design for Excellence</td>
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<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<tr>
<td>IFC</td>
<td>Industry Foundation Classes</td>
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<tr>
<td>IoT</td>
<td>Internet of things</td>
</tr>
<tr>
<td>IPD</td>
<td>Integrated Project Delivery</td>
</tr>
<tr>
<td>IS</td>
<td>International Organisation for Standardisation</td>
</tr>
<tr>
<td>LandXML</td>
<td>XML data file format for civil engineering and survey measurement data</td>
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<tr>
<td>NBS</td>
<td>National Building Specification</td>
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<tr>
<td>PDM</td>
<td>Product Data Management</td>
</tr>
<tr>
<td>PLM</td>
<td>Product Lifecycle Management</td>
</tr>
<tr>
<td>RFI</td>
<td>Requests for information</td>
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<td>RPDA</td>
<td>Relational Project Delivery Arrangements</td>
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</table>

**Data Governance**

Data Governance is a system for organisation-level management of the quality, reliability, usability, security, and accessibility of an organisation’s data. It applies to the whole organisation’s business processes, data, and risk management. The purpose of data governance is to generate a positive control for the guidelines of data creation and usage and to retain and archive the data. An enterprise’s management can create different roles in the organisation for data governance, such as Data Steward, Data Owner, Data Manager, and Data User (Cohen, 2006).
Design for Excellence

Design for Excellence (DfX) is a set of tools that can involve main stakeholders in a project’s initial phase. In DfX, the X refers to an aspect, lifecycle phase, or specific stakeholder, like, for instance, manufacturing, construction, maintenance, supply chain, and cost (Bralla, 1996; Lehto et al., 2011; Möttönen et al., 2009).

Digitalisation

In digitalisation, traditional document-based processes are transferred into digital processes. Major digitalisation trends in construction are BIM, mobility, cloud technology, big data, 3D printing, internet of things (IoT), robotics and software as a service (SaaS) type solutions.

Digital intensity

“Digitalisation intensity is investment in technology-enabled initiatives to change how the company operates – its customer engagements, internal operations, and even business models” (Westerman, Tannou, Bonnet, Ferraris & McAfee, 2012).

Early Involvement

Early involvement refers to early and effective contribution of the core stakeholders’ competencies and knowledge. Early integration in relational contracting reduces fragmentation and improves efficiency and performance in complicated customer projects (Davis & Love, 2011; Chen, Zhang, Xie & Jin, 2012).

Integration

Integration connects stakeholders that usually work independently. Integration improves communication and decreases fragmentation. Integration between organisations is essential to enhancing a collaborative culture and project performance (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015).

Lifecycle

Projects are generally divided into several phases to enhance management control. Together, the project phases are known as the project lifecycle (Rose, 2013). In this study, the project is divided into four phases: preliminary design, design, construction, and maintenance/operation.
Master Data
Master data describe business objects and how they are categorised in several information and communication technology (ICT) systems (McKeen & Smith, 2007). Master data management (MDM) focuses on data quality, business processes, and the integration and synchronisation of information systems (Joshi, 2007).

Project Stakeholder
Project stakeholders are individuals and organisations that are actively involved in the project or whose interest may be positively or negatively affected as a result of project execution or completion (Rose, 2013).

Relational Project Delivery
RPDA (Relational Project Delivery Arrangements) is one form of network organisation (Lahdenperä, 2012; Manning, 2017). Examples of RPDA-type project deliveries are project alliancing (developed in Australia), integrated project delivery (AIA in the United States), and partnering (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). A characteristic feature of these kinds of projects is that they enable relationships between project stakeholders. In RPDA-type agreements, stakeholders are inside the same agreement, in which they are mutually responsible for the project. The agreement contains joint ‘pain and gain’ clauses (Colledge, 2005).
Original publications

This dissertation is based on the following publications, which are referred throughout the text by their Roman numerals:


The author of this dissertation is the main author of all the original articles above. The author was principally responsible for formulating the research problems, collecting the relevant literature and research articles, collecting and analysing the empirical material, concluding, and acting as the primary author on all the publications. The co-authors played a valuable role in reviewing and commenting on the primary author’s article manuscripts.
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1 Introduction

1.1 Background and research environment

The construction industry has low digitalisation intensity and low productivity development

Productivity development is one of the constant parameters under discussion in every industry (Pekuri, Haapasalo & Herrala, 2011). While the construction industry has low productivity, there are emerging technologies that may help construction business owners to improve their processes. Digital solutions like social media, mobile, and analytics are improving the businesses of several industries. According to a survey, companies that have appropriate digital technology intensity and can successfully handle the transformation have better revenue generation, profitability, and market value (Westerman et al., 2012). Major digitalisation trends in construction are building information modelling (BIM), mobility, cloud technology, big data, 3D printing, internet of things (IoT), robotics, and software as a service (SaaS) type solutions. However, in practice, the construction sector is slow in adopting new technologies and process innovations. Its digitalisation index is one of the lowest in comparison to other sectors (Friedrich, Koster, Groene & Maekelburger, 2013; Agarwal, Chandrasekaran & Sridhar, 2016). As examples of the sector’s low digitalisation index, project planning is often based on paper documents and is uncoordinated between the design office and the site (Agarwal et al., 2016).

The construction business, in a way, demands disruption. Significant projects at all asset levels characteristically take 20% longer to finish than planned, and up to 80% of the projects are over budget. In some markets, construction productivity has weakened since the 1990s; financial earnings for contractors are frequently low and unstable (Agarwal et al., 2016). At the same time, as productivity in the construction business has declined, in other industries, productivity has risen 200% since 1964 (Howard & Bjork, 2007; Eastman, Teicholz, Sacks & Liston, 2011). Low productivity is understandable when we compare the share of value-added time in construction to other industries. Value-added time in construction is 10%, while, in the manufacturing industry, it is 62% of the total work (Eastman et al., 2011). Construction’s low share of value-added time means that its processes have waste (Merikallio & Haapasalo, 2009). Process-related waste results from activities
in the process that do not add value (Womack & Jones, 1996) and can largely be avoided with efficient planning at the beginning of projects.

Moreover, project deployment is often fragmented, and the actions of stakeholders who have several parallel interests in a project also partially affect its efficiency by creating conflicts of interest (Aapaoja & Haapasalo, 2014). In addition to the complexity of projects, requirements and schedules have been unceasingly tightening (Bryde, Broquetas & Volm, 2013). Ever-increasing and ambiguous requirements heighten the need for better integration and management of the project’s team members to improve the interactive collaborations between stakeholders. It is evident that very substantial changes need to take place to increase productivity in the construction industry and to improve social and working behaviour.

The characteristics of project delivery methods

The challenges in traditional project deliveries have created a demand for other methods that establish better collaboration, such as integrated project delivery models. In integrated project delivery models, stakeholders are unified under the same agreement, and incentives encourage early integration and collaboration. On the other hand, conservative project delivery methods, like design-bid-build (DBB), are based on two-sided contracts between a stakeholder and client. Such traditional project delivery systems can be a significant barrier in maximising value and reducing waste in the construction lifecycle; the lowest bid wins, and the project stakeholders try to optimise their own benefits and risks instead of optimising them for the whole project. Different actors to optimise their processes at the expense of others and hold development ideas for themselves.

Moreover, conservative project delivery models are based on traditional management approaches, supposing that a project can be divided into a series of phases and that the overall project is optimised by optimising the individual phases. It is challenging to minimise waste and maximise value when the project delivery model constrains co-ordination, suffocates co-operation, and innovation. Rostami & Oduoza (2017) state that utilising the design-build (D&B) procurement method with an early involvement of specialist contractors can consequently reduce design defects. However, integrated project delivery models, such as Alliancing and Integrated Project Delivery (IPD), are partnering approaches that support integration and collaboration. These relational contracts allow a commercial ‘relationship’ between the parties as the responsibilities and benefits are allocated equally and trans-
Relational contracts include mechanisms that focus on trust and relationships with team-based incentives founded on value creation or successful outcomes instead of rewarding individual performance. The characteristic features of integrated contract models are early stakeholder involvement, the colocation of project teams, and the common development of design (Davies, Brady & Hobday, 2007; Lahdenperä, 2012; Aapaoja, Herrala, Pekuri & Haapasalo, 2013; Bryde et al., 2013; Dave, Koskela, Kiviniemi, Owen & Tzortzopoulos Fazenda, 2013).

**Challenges in implementing BIM**

BIM is a technology and tool that may help construction stakeholders to improve their processes. BIM has been predicted to help overcome several challenges in the construction industry, integrating of fragmented stakeholders, fixing problems in information and data flow, enhancing quality, and providing a catalyst to increase the process speed (Ashcraft, 2008; Eastman, Teicholz, Sacks & Liston, 2008; Sugcar, 2009; Becerik-Gerber & Rice, 2010). According to Ghaffarianhoseinia, Tookey, Ghaffarianhoseini, Naismith, Azhar, Efimova & Raahemifar (2017), the most substantial reasons for not implementing BIM include the lack of demand, cost and interoperability issues; furthermore, the project management process is still unclear around BIM. However, BIM needs the right type of data at the right time through the lifecycle to deliver its benefits. There are general BIM guidelines and requirements like COBIM (2012) and BIM Project Execution Planning Guide (2011). In spite of these general guides, the comprehensive plans are not in use in construction projects for data utilisation throughout the lifecycle, including maintenance and operation phases. The present BIM data utilisation through a lifecycle can be explained as resembling a jigsaw puzzle that makes up the building (National Building Specification [NBS], 2019). Data is collected into excel sheets piece by piece in the design and construction phases for maintenance and operation. Yet, this data collection process is insufficient for efficient digital maintenance. Maintenance and operation phases generate an essential part of the whole lifecycle costs. According to HM (Her Majesty's) Government (2015), the annual investment in Britain in maintenance and operations (£122bn) is more significant than the investment in construction (£89bn). If the maintenance and operation phase requirements are considered in the planning phase, the infrastructure’s functionality is better. The service sector, which utilises the infrastructure, has a share of £597bn of the GDP (Gross Domestic Product). These investment amounts indicate that all project phases, in addition to design and construction, should have an equal role in project data and
information flow planning. An ineffective valuation of the type of data flow between project teams that is essential may lead to design process problems and to rework on the site. If the data requirements are not included in a project’s delivery agreement, it may result in blocks in the data flow in the form of increased requests for information (RFI) (Love, Gunasekaran & Li, 1998; Love, Edwards & Irani, 2008; Tadt, Hanna & Whited, 2012). While most of a construction project’s budget is typically spent in the operation and maintenance phases, data needs should be given greater consideration.

**Product data management and master data**

BIM has various roles in construction. It can be understood to mean a model, tool, or process. A building information model is an outcome of modelling work. It may consist of design, construction, and maintenance data of the structure, as well as rules on how data entities behave in different situations (Associated General Contractors of America [AGC], 2006; Eastman et al., 2011).

In some cases, BIM is regarded as a process, and its vital role as a product data model is forgotten. In manufacturing organisations, product data management (PDM) has an essential role in business processes. Each product lifecycle phase needs unique data, which is accurately delivered at the right time to numerous stakeholders (Yang, Moore, Wong, Pu & Kwong Chong, 2007; Rachuri et al., 2008). PDM is a foundation for digital operations management systems in enterprises (Stark, 2005). Product lifecycle data management (PLM) systems take care of product management in all lifecycle phases. There also are other systems that handle product data, such as enterprise resource planning (ERP), customer relationship management (CRM), and computer-aided design (CAD) applications (Loshin, 2001). Master data is an important element of an organisation’s ICT system. Master data is the part of elements that are needed for data sharing and harmonising (Berson & Dubov, 2007) and therefore important for sharing information between CRM, ERP, CAD and other systems.

To summarize, several studies have evaluated the performance of the construction industry and state that it has low productivity development (Abdel-Wahab, Dainty, Ison, Bowen & Hazlehurst, 2008; Allen, 1985; Allmon, Haas, Borcherding & Goodrum, 2000; Pekuri et al., 2011; Rojas & Aramvareekul, 2003). Today, while data and information management are improving their efficiency in many directions, the construction industry has not been able to adopt such benefits. In the construction industry, BIM is anticipated to resolve several challenges. In many
studies, including Becerik-Gerber and Rice (2010), Ashcraft (2008), the BIM Handbook (2008), and Succar (2009). BIM is described as a tool that can unite stakeholders, fix problems in information and data flow, improve general quality, and speed up processes in the construction industry. However, although several studies have reported the benefits of BIM, the construction industry has not been able to realize these advantages. In current construction projects, stakeholders do not receive the data and information necessary to run BIM effectively, which leads to extra work and, hence, considerable waste in time and other resources (Love et al., 2008; Tadt et al., 2012). Conventional contract models and project delivery systems can be a major barrier in maximizing value and reducing waste in the construction lifecycle. They typically result fragmentation among different stakeholders and late involvement even with significant stakeholders. Though relative and integrated contract models, such as Alliancing and IPD, integration and collaboration, can be supported. Early involvement in the design phase can enable a more effective design, enhanced construction processes, and less scrap (Dowlatshahi, 1998; El Asmar, Hanna & Loh, 2013; Kent & Becerik-Gerber, 2010).

1.2 Objectives and scope

The data management has not been planned at the beginning of the project through the lifecycle although there is some good work done in Cobie (Construction Building Information Exchange) formats, the practical results are missing (Haapasalo, 2018; Mansoori & Haapasalo, 2019). Though there are solutions and standards to ease information and data management challenges in construction projects (Common BIM Requirements [COBIM], 2012), they mainly concentrate on individual phases of the lifecycle or technical details in data transfer formats. Most attention is given to design modelling and data transfer between the design and construction phases. Maintenance and operation data requirements receive less attention than earlier phases. Data transfer concentrates on how a particular actor in a project transfers his or her work further along in the supply chain. However, a comprehensive, whole lifecycle long approach seems to be missing, in which a previous actor in the supply chain delivers data and information according to the original needs of the next stakeholder. Rather, the data are thrown over the wall to the next actor, and the information flow is mainly one way. Hence, the requirements for the next phase are rarely met.
This research is primarily motivated by the late and fragmented management of information during the preliminary design, design, construction, and maintenance phases of a construction object which lead to defects and rework. BIM has benefits, but these have not been resulted in practical level. There is a need to plan the lifecycle data and information flow proactively Early involvement and integration of all stakeholders in the early design phase of the project can solve challenges related to fragmentation and information management. BIM, if used optimally, can be used as a tool that supports early involvement and integration. For one, BIM has several roles in construction, and its complicated nature confuses project actors. Therefore, the research problem is:

*to understand why BIM has been underutilized in the construction sector and how the planning of data utilization can solve these challenges through early involvement and integration.*

From the research problem, the main aim of this dissertation is to enhance data utilisation in construction projects by enabling early involvement and integration of stakeholders. This dissertation discusses this overall objective from four different perspectives. First, it investigates why the use of BIM has not produced the benefits that several earlier studies report (Ashcraft, 2008; Becerik-Gerber & Rice, 2010; Eastman et al., 2008; Succar, 2009). The lack of proactive design lead to a lack of data, or the data is not usable. Second, the simultaneous use of BIM and integrated contract models were studied to examine how BIM supports early involvement, which is a characteristic feature of integrated contract models. Third, the benefits of early involvement and integration were studied to ascertain how early involvement and integration tackles fragmentation or late involvement problems. Fourth, a model was developed to organize data management in a construction project. The research objective is hence condensed into four research questions (RQs), and connected into four original studies (Table 1).

- **RQ1** What are the barriers to implementing BIM?
- **RQ2** How does BIM support early involvement and vice versa?
- **RQ3** What are the benefits of early integration?
- **RQ4** How should data management be organised in an infra project?

Early involvement refers to early and effective contribution of the core stakeholders’ competencies and knowledge. Early integration in relational contracting reduces fragmentation and improves efficiency and performance in complicated customer projects (Davis & Love, 2011; Chen, Zhang, Xie & Jin, 2012). Integration connects stakeholders that usually work independently. Integration improves communication
and decreases fragmentation. Integration between organisations is essential to enhancing a collaborative culture and project performance (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015).

The objectives of each original study are to answer the corresponding research question. This dissertation is composed of four journal articles that each provide a contribution that aims to support the overall aim of the dissertation.

### Table 1. Overview on original studies.

<table>
<thead>
<tr>
<th>Article</th>
<th>RQ#</th>
<th>Research question</th>
<th>Title of original study</th>
<th>Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>RQ1</td>
<td>What are the barriers to implementing BIM?</td>
<td>Barriers for achieving benefits of BIM</td>
<td>International Journal of 3-D Information Modelling</td>
</tr>
<tr>
<td>II</td>
<td>RQ2</td>
<td>How does BIM support early involvement and vice versa?</td>
<td>The contemporaneous use of building information modelling and relational project delivery arrangements</td>
<td>Procedia Economics and Finance</td>
</tr>
<tr>
<td>III</td>
<td>RQ3</td>
<td>What are the benefits of early integration?</td>
<td>Early Involvement and Integration in Construction Projects: The Benefits of DfX in Elimination of Wastes</td>
<td>International Journal of Management, Knowledge and Learning</td>
</tr>
<tr>
<td>IV</td>
<td>RQ4</td>
<td>How should data management be organised in an infra project?</td>
<td>Managing data flows in infrastructure projects - the lifecycle process model.</td>
<td>Journal of Information Technology in Construction</td>
</tr>
</tbody>
</table>

The first study discusses the barriers to implement BIM in a construction project. The reasoning behind this dissertation and the first article is the contradiction between numerous research studies that highlight the benefits of BIM and the inquiries, like the Finnish BIM Survey (2013), that show the low utilisation of BIM. The results show that one of the biggest barriers was the lack of good quality data so that the BIM-based applications could be used.

The second article discusses the simultaneous use of BIM and integrated contract models, like IPD and Alliance, to understand how characteristic features of BIM support early involvement and integration and other key characteristics of integrated contract models. The role of BIM is to enhance the data and information needs for the whole project team during the project lifecycle. The characteristic features of early integration improve the proactive design of the project.

The third article discusses early involvement and integration and its benefits in reducing waste in construction projects. It discusses how design for excellence
(DfX), helps to enable early involvement and integration and concentrates design to the selected aspects of the project. DfX is a method used in the manufacturing industry to bring important lifecycle phases’ requirements to the early design phase. Design for manufacturing and design for assembly are good examples. The article studies how DfX can be used in the construction industry to generate early integration and reduce waste.

In the fourth article, the objective was to develop a model for data flow in construction projects. The fourth article suggests a model to plan the flow of project information among primary stakeholders in a construction project effectively. This new method is intended to enable the early involvement and integration of all stakeholders, including maintenance stakeholders, in designing product data from a project lifecycle perspective. The product data model helps to change the present information flow and allows construction projects to gain the advantages that a BIM-based process can offer.

The comprehensive contribution of all the four original studies is to help develop a framework of how data utilisation can be enhanced in the construction project lifecycle through early involvement and integration. Figure 1 highlights the evolution and content of the four original studies and how they relate and how they are logically connected to this dissertation’s scope. In the first article, definitions, as well as benefits were clarified in the literature review and barriers to implementing BIM, were perceived in the focus group interview. The results of the first article were the basis for the remaining articles. The benefits and barriers for BIM utilisation are the core elements of how to approach the enhancement of data utilisation.

In the second article, the simultaneous use of BIM and integrated contract models and how BIM supports early involvement and integration were examined as well as how early integration supports the design of the project. In the third article, the benefits of early involvement and integration were further considered. As a practical example, the research in this article examined how DfX can be used in construction to generate early involvement and integration, as well as the benefits it brings to the project. The fourth article provided a model of how to organise and manage data flows, which was developed based partly on the information of three previous articles. The model for managing the data flows is based on the early integration of key stakeholders so that they can communicate their requirements early in the design phase to ensure the appropriate data is available at the right in time in all lifecycle phases.
1.3 Research strategy process and dissertation structure

In scientific research, a scientist needs to meet fundamental philosophical questions of ontology, epistemology, and ethics. There are questions like how can one believe and know that reality is based on scientific research? How can one trust and know the scientific reality? And how is the knowledge that is obtained scientific? It is also vital to consider when a scientist misuses his or her research object or behaves unethically against the scientific community (Lancaster, 2005).

The ontology describes the reality in which the studied phenomena are understood to exist and the manner in which they relate to this reality. Scientific research routinely has ontological preconceptions on the nature of studied topics. Ontology defines whether the studied reality is objective or subjective and can affect the selection of theory and concepts (Anttila, 2005; Harisalo, 2008). Ontology can be roughly divided into objectivism and subjectivism. Objectivism is an ontological position, suggesting that research is based on facts rather than subjective analysis.
In objectivism, an enterprise or organisation is seen as a machine-like entity that acts based on standards, guidelines, rules, and legislation; individuals are operators that realise processes and values. In subjectivism, social phenomena are created by social actors and their observations. According to this view, in companies, operations are based on people’s interactions (Bryman & Bell, 2003; Saunders, Lewis & Thornhill, 2009).

Epistemology is a theory that explains what is understood as appropriate knowledge regarding the social world. One of its essential questions is whether a natural science model of the research process, including principles, procedures, and philosophy, is suitable when studying the social world (Bryman & Bell, 2003). Epistemology is roughly divided into positivism and interpretivism. If the research reflects positivism, then it takes the philosophical stance of natural science with phenomena explained through causal relationships and regularities. However, the nature of natural science makes it rather challenging to outline phenomena precisely. On the other hand, interpretivism asserts that the social environment differs fundamentally from the natural sciences (Saunders et al., 2009). Inductive logic of reasoning is used, and the understanding of the researcher and other relevant actors is applied.

A research approach can be deductive or inductive. Deductive research develops first theories or hypotheses and then tests them through empirical observation. The deductive method often requires quantitative data. Before theory testing and empirical observation, abstract concepts must be operationalised. Hence, the theory has a falsification and discarding stage. Deductive research is often used in applied research and is widely used in the natural sciences. On the other hand, inductive research develops hypotheses and theories intending to explain empirical observations of the real world. The inductive approach is also better suited to the use and interpretation of qualitative data (Lancaster, 2005; Saunders et al., 2009). This dissertation is composed of four articles that have all separate decisions of research approaches. The decisions have been so similar that it is possible to make a summary of the decisions made. In Figure 2, there are indicated this dissertation’s epistemological and ontological stance. The research is in the middle of the ontological scale and can be seen as following pragmatism, and it takes an approach closer to interpretivism than positivism. Each of the four articles are based on an inductive research approach and qualitative data collection. In Figure 3, there is a research onion modified from Saunders et al. (2009). The Figure illustrates the different aspects of research.
Fig. 2. Epistemological and ontological stance of the research.

Fig. 3. The research ‘onion’ (modified from Saunders et al., 2009).
The research process followed the same approach in each article (Figure 4). Each starts with a literature review, followed by data collection, an analysis of the data, and synthesis. However, the second article was based on a literature review with no specific data collection phase. The data collection approach was non-probability sampling. According to Saunders et al. (2009), there are no rules for sample size; instead, the sample size may depend on available resources. Other things that affect the sample size are research questions and objectives, what will be useful and what you need to find out.

Fig. 4. The overall research concepts.

Figure 4 lists the data collection methods used in this dissertation, which include focus group interviews (first article), survey as secondary data (third article), and project manager interviews (fourth article).

In the first article, the objective was to study the barriers that prevent to achieve the benefits of BIM. This information can be obtained from the construction specialists that have experience of BIM-based projects. The association of Finnish civil engineers organised a seminar where were invited a focus group of experienced construction BIM specialists. The focus group interview was based on Ishikawa diagrams. Focus groups inputted the barriers to a specific benefit from six different angles (Methods, Machines, Manpower, Materials, Measurement, and Milieu). The research approach was inductive, research strategy was a cross-sectional case study, and data collection method was a qualitative focus group interview.
The second article studied the benefits of the simultaneous use of BIM and integrated project delivery. There was literature available to investigate the characteristics of BIM and integrated project delivery to answer the specific research questions. The research approach was inductive; the research method was a conceptual framework based on literature review and the author’s experience.

The third article examines early involvement and integration in construction projects and determines what benefits design for excellence (DfX) can have for the elimination of waste. There was first a literature review of waste types, early integration, and DfX. There was available secondary data consisting of a survey made among construction project managers to find out most severe waste types. Analyses of data were based on FMEA prioritisation and AHP prioritisation. The research approach was inductive, research strategy was a cross-sectional case study, and data collection method was a qualitative survey (secondary data). The decision of the research strategy was based on that there were literature available as well as secondary data of waste type comparison.

The objective in the fourth article was to develop a model for the data flows in infrastructure projects lifecycle. The first step was to review the current knowledge of digitalisation, BIM, product data management and data governance. The second step was to clarify the current challenges in data flow in an infra construction project. After a literature review of current knowledge, it was decided to have three case studies of different kind of infra construction projects based on project manager interviews. We found three projects that had experienced project managers that could inform us of the challenges in the data flow. The research approach was inductive, research strategy was a cross-sectional case study, and data collection method was a qualitative interview. In this research, the conclusions and suggestions for implications are based on a synthesis of the empiric data and literature review.
Table 2. Research approach and material in the original studies.

<table>
<thead>
<tr>
<th>Article &amp; Case</th>
<th>Research method</th>
<th>Informants</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Barriers in the realisation of BIM benefits</td>
<td>Focus group interview, Ishikawa diagrams (Methods, Machines, Manpower, Materials, Measurement, and Milieu)</td>
<td>- 23 from top management. Professors and CEOs: - 22 Management level. Senior project managers and principal designers: - 29 from specialist level. Researchers and project engineers.</td>
<td>A group of 74 Finnish design, construction, maintenance, and R&amp;D specialists</td>
</tr>
<tr>
<td>II Benefits of the simultaneous use of BIM and RPDA</td>
<td>Conceptual framework</td>
<td>Literature review</td>
<td>BIM and RPDA have not achieved their full-scale realisation, both individually and especially together</td>
</tr>
<tr>
<td>III Waste in construction</td>
<td>Survey to rank the types of waste in the construction industry</td>
<td>Project Engineer, Contractor, Executive Director, Design Executive Director, Project Management, Account Manager, Design and Maintain Consultant, Construction Consultant, Executive Director, Developer Project Manager, Contractor</td>
<td>Interviewees represent 7 SME companies with 2-5 years’ work experience</td>
</tr>
<tr>
<td>IV Value chain and data flow in infra construction project</td>
<td>Three case studies. Interviews for the key personnel in the project</td>
<td>Infra construction Project Managers and ICT specialist</td>
<td>Three different types of project delivery (DBB, DB, Alliance)</td>
</tr>
</tbody>
</table>

1.4 Structure of the dissertation

The structure of this dissertation compiles four original studies that are all published (Figure 5). All original studies have gone through a blind review process and have been therefore validated. This compilation part follows the instructions presented by the University of Oulu, where the compilation has to be readable autonomously, and it consists of the parts in the original studies under the scope of the compilation.

This compilation part consists of the setup and scope for the whole dissertation in the introduction. Then the literature review roots the theoretical foundation from
the existing research. The third chapter presents the contribution in original studies inside the scope of this research and finally synthesising the overall contribution towards the aims of the entire dissertation. Chapter 4 contains the discussion of the results in the name of theoretical and practical implications, overall evaluation of the results in the compilation and finally further research avenues.

Fig. 5. Structure of the dissertation.
2 Theoretical foundation

2.1 Theoretical framework

The theoretical foundation of this dissertation emerges from the background and research problem of this research. The main concepts are more like discussions or concepts than specific theories, like BIM, product data, DfX, early involvement, and integration. The scope of literature review can be divided on two larger entities; “Data and information management” and “Early involvement and integration”, which also arises from the research problem of this dissertation. These concepts are applied with the purpose of forming an adequate understanding of data utilisation, how early involvement and integration affect data utilisation, and what mechanisms enable early integration in construction projects, presented in the earlier literature. Figure 6 shows the discussions included in this dissertation are related to each other. Earlier literature presented many other discussions and concepts are that are slightly related to the scope of this dissertation, however, excluded from this dissertation. The idea of outlining these in Figure 6 is to describe the wider background in the scope of this dissertation. Justification for excluded and included discussions is presented in the following.

BIM plays a crucial role in data and information management in the construction industry and in improving the industry’s efficiency. BIM has different roles in construction; it is a tool, product data model, and process. Highlighting data utilisation, this dissertation examines BIM’s role as a data model and reviews data model-related concepts like product data, master data, and data governance as a general concept for organisational- or inter-organisational-level data and information management. The transfer format is given minor attention because like the study (Article II) showed, the barriers in projects are related to missing data or its bad quality. A good description of data format does not help if the data is missing or it has poor quality. While there are standards available for data transfer, it remains challenging to create a data flow between stakeholders that is without defects and motivate stakeholders to actively employ the transfer standards. Therefore, the vast amount of information on data transfer standards, as well as less official client requirements and their development projects, are not considered in this project. These standards and guidelines include International Organisation for Standardisation (ISO) and European Committee for Standardisation (CEN) standards, Industry Foundation Classes (IFC), Data Dictionaries (DD), Information Delivery Manuals
(IDM), Model View Definitions (MVD), Building Collaboration Format (BCF), IFC Bridge, IFC Road, IFC Rail, IFC Ports & Harbours, and IFC Tunnel, Common BIM Requirements COBIM (2012). Much information about these projects can be found on international and local building Smart and ISOweb pages (BuildingSMART, 2019; ISO, 2019).

This dissertation excludes a detailed presentation of different BIM-based software as its focus is on the data flow between stakeholders and how the requirement process is organised (Dave et al., 2013). For this reason, this study also omits virtual design and construction (VDC) concepts (Kunz & Fischer, 2012), which refer to using BIM-based applications simultaneously to allow a concurrent view of the product, organisation, and process. Such BIM software features are presented, for instance, in Dave et al. (2013). Likewise, this study does not focus on detailed product structure (Saaksvuori & Immonen, 2008). There are different kinds of technology to store data; for example, cloud technology has made data storage and sharing easy and cheaper. However, data storage technologies are also outside the scope of this study, as this detail is not essential from a data utilisation concept perspective. Cloud technology makes sharing and maintenance in inter-organisational projects easier through the internet (Rajan, 2013). There is no need to store data in separate databases or try to create and maintain one common database for all project stakeholders. Instead, the data are more often stored in clouds, from where the data can be made available for named users through the internet. BIM combined with artificial intelligence, big data, IoT, advanced analytics, mobility, robotics, laser-scanned images with object detection, autonomous vehicles, higher definition surveying, geolocation, and drones are technological innovations that will solve many of today’s challenges (Agarwal et al., 2016). While these innovations are interesting, they are not the focus of this dissertation.

Moreover, many studies that expand knowledge of data and information management ad early involvement and integration are excluded from this dissertation. Pekuri (2015) has investigated the role of business models in construction business management, highlighting the possibility of customer value creation instead of managing business conventionally, project by project. Lavikka (2015) has found that collaboratively created coordination mechanisms in inter-organisational coordination promote knowledge sharing and the creation of shared knowledge about common business and, thus, the development and management of a common digitalising business. While this finding supports the idea of enhancing data utilisation through early involvement and integration, the concept of coordination for shared
knowledge creation is not in the focus of this dissertation. This dissertation discusses integration and its benefits but omits the large and interesting topic of integration mechanism (Hietajärvi, Aaltonen & Haapasalo, 2017). Supply chain capability creation is included in the literature review, but the supply chain capability creation process is (SCCC) is not (Verrollot, Tolonen, Harkonen & Haapasalo, 2017).

The PMBOK® Guide (A Guide to the Project Management Body of Knowledge) (Rose, 2013) includes a useful description of construction project management. In this study, we are interested in project actor-groups’ data utilisation rather than actors’ requirements concepts and project management. Instead of classifying the exact stakeholders (Aapaoja et al., 2013), we discuss the actor groups in different project phases. We have classified the stakeholders into four categories: planning/preliminary design, design, construction, and maintenance/operation. These groups are sufficient as we are interested only in the data flow concept between these groups. This study also discusses how integrated contract models like IPD can help data utilisation. However, it does not include detailed descriptions of all commercial project deliveries, like DBB, Multi prime, Design Build, IPD, alliancing, Public Private Partnership, Design-Build-Operate-Maintain, and Construction Manager at Risk (Eastman et al., 2011).

This dissertation introduces DfX (Lehto et al., 2011) as a concept that the manufacturing industry has used for coordinating design requirements from various stakeholders. Many other concepts facilitate early involvement and integration, like Lean construction (Ballard, 2008), Lean thinking (Liker, 2004), and Advanced Work Packaging (O’Brien, Ponticelli & Rammell, 2015), which, though worth studying, do not serve the focus of this dissertation. Other concepts that were considered but eventually omitted include Lean software development (Poppendieck & Poppendieck, 2003), New Product Development (NPD) (Cooper, Edgett & Kleinschmidt, 2001) and demand supply chain (Hoover, Eloranta, Holmström & Huttunen, 2001). Figure 6 presents the frameworks of this dissertation. In the core of the dissertation are data and information management combined on early involvement and integration. Integrated project delivery is an example of the project delivery type that enables early integration. There are a vast number of other project delivery types which detailed investigation is excluded. New technology innovation like artificial intelligence (AI) is excluded as well as a detailed investigation of production improvement methods.
2.2 Data and information management

2.2.1 The different roles of BIM and its benefits

BIM plays a substantial role in a construction project’s data and information management. BIM has a significant role as a product data model. BIM can also be regarded as a tool or process. BIM can be used in different capability stages (Succar 2009, 2010), which each delivers various benefits. Each capability level sets different requirements for used applications, processes and project teams’ capability depending on the goals set for the project work. The idea of BIM is not new anymore (Eastman et al., 2008) and the innovators of BIM can now see how well their first ideas have come true in novel BIM practises.

According to Eastman et al. (2008), the history of BIM started in 1975 when Chuck Eastman defined the first concept, “Building Description System”. The concept “Building Information Model” was first used in an article published in the American Institute of Architects (AIA) Journal at Carnegie-Mellon University about 30 years ago. Initial development and research on the topic were conducted in Europe, particularly in the United Kingdom. In the early 1980s, the concept was named “Building Product Models” in the USA and “Product Information Models”
in Europe. These two expressions were later combined into the “Building Information Model”. The name BIM was initially used in the title of Robert Aish (1986)’s paper.

In general, the abbreviation BIM is understood to stand for modelling technology with related processes to analyse, communicate, and develop building models. Modelling means the practice of making a model with modelling applications. There are several BIM (modelling) definitions, like Thompson (2016, p. 9): “[the] process of designing, constructing or operating a building or infrastructure asset using electronic object-oriented information”. BIM is also defined as a combination of products and modelling processes, instead of a separate set of technologies and processes (Kimnance, 2002).

According to Azhar, Hein & Sketo, (2008), BIM models can be used as a tool for facilities management, forensic analysis, 3D Visualisation, fabrication/shop drawings, code reviews, cost estimating, and construction sequencing, as well as conflict interference and collision detection. BIM can also facilitate the use of IPD (Ashcraft, 2008; Eastman et al., 2011; Sacks, Koskela, Dave & Owen, 2010).

Eastman et al. (2008) point out that the use of BIM generates new opportunities for relations and roles within projects. If BIM is applied correctly, it allows more integrated design and construction tasks, resulting in shorter schedules, better quality, and fewer costs. The primary benefits of BIM applications were for designers, who could better maintain consistency between different viewpoints on the component. When we change the model, we can output new versions of the drawings from different angles of the three-dimensional object so that the integrity of the data is automatically correct. To obtain data consistency is easy with BIM. When using CAD drafting tools, the changes had to be remembered to make to all drawings manually. Initially, BIM definitions were technology-oriented, but now BIM definitions describe more often the functions that BIM offers (AGC, 2006; Eastman et al., 2011). The proper use of BIM brings several benefits to construction projects, including (AGC, 2006; Ashcraft, 2008; Azhar et al., 2008; Succar, 2009; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Arayici, Coates, Koskela, Kagioglou, Usher & O’Reilly, 2011; Eastman et al., 2011; Khosrowshahi & Arayici, 2012; Vähä, Heikkilä, Kilpeläinen, Järviuluoma & Heikkilä, 2013; Wong & Fan, 2013; Attarzadeh, Nath & Tiong, 2015; Nath, Attarzadeh & Tiong, 2016):

- better quality
- cost savings
- shorter project timelines
– more sustainable construction
– less CO₂ emission
– better construction procedures
– better data and information flow
– efficient collaboration and the use of Alliance/IPD
– efficient model-based maintenance
– faster commissioning

While the most frequently reported benefits relate to cost reduction, better quality control, and significant time savings throughout the project lifecycle, common disadvantages are BIM software interoperability and its inability to effectively handle big data sets (Bryde et al., 2013). The United Kingdom Cabinet Office has observed that BIM played a substantial role in a construction cost reduction of £840 million in 2013/2014 (HM Government, 2015).

2.2.2 BIM capability stages

Succar (2009, 2010) describes the implementation of BIM as divided into three capability stages, in addition to the pre-BIM and post-BIM stages:

– stage one: object-based modelling
– stage two: model-based collaboration
– stage three: network-based integration

At stage one, only individual designers use BIM, and the process resembles the document-based pre-BIM process, which does not enable fluent collaboration between stakeholders. In this case, BIM is more like a tool for different analyses. At stage two, all designers use BIM to produce a collaboration model composed of all the design disciplines’ sub-models. During stage three, all the design objects are in use in clouds so that the stakeholders can edit object attributes and make changes to the designs. The definition ‘capability of BIM’ consists of the quality of technology, process, and policy specifications. An organisation may progress in capability stages only by taking technology, process, and policy steps. The BIM capability stage is a minimum requirement. The pre-BIM stage describes the organisation’s level before the growth of BIM usage. In an earlier study, Succar (2009) regarded IPD as a post-BIM stage where the use of BIM is optimal. However, later Succar (2010, p. 5) describes the post-BIM stage as “the ultimate goal of employing BIM
concepts and tools to achieve virtually integrated design, construction, and operation”. Succar (2010, p. 6) also defines maturity level, which “refers to the quality, repeatability, and degree of excellence within a BIM capability stage”, giving five levels “(a) Initial/ Ad-hoc, (b) Defined, (c) Managed, (d) Integrated and (e) Optimised”. Maturity levels of the project teams are important to consider while planning data deliveries during the project. It is feasible to deliver only the data that corresponds to the project team’s capability stage and maturity level.

2.2.3 BIM’s role as a product model

The abbreviation BIM also means a Building Information Model. Building models have objects with parametric rules that govern how they behave and attribute data that can be modified. Models have nonredundant and consistent data. Changes to the component are visible in all views and all assemblies. A BIM is an outcome of the modelling work, which may consist of design, construction, and maintenance data of the structure, as well as rules on how data entities behave in different situations (AGC, 2006; AIA, 2007; Succar, 2009; Eastman et al., 2011). A BIM is a model of a real-life object in the computer’s memory and refers to a product data model of a building as Bazjanac (2008, p. 2) describes: “Fundamentally, a BIM (defined as a noun), is an instance of a populated data model of buildings that contains multi-disciplinary data specific to a particular building, which they describe unambiguously”.

BIM is primarily a product data model of the project, and therefore, it is essential to design lifecycle long data needs. Otherwise, the collaborative use of BIM becomes very challenging, and its vital benefits are not gained. As many studies have shown, the user gains the benefits when BIM is in the collaborative use in the projects (Ashcraft, 2008; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Eastman et al., 2011). Hence, not only should all parties use BIM, but there should be a plan, with clear roles assigned, on how to create and maintain the BIM of the project, which covers all lifecycle phases. The importance of collaborative use of BIM has been realised and it is stated in the UK Government construction strategy (UK Cabinet Office, 2011, p. 14) “they [the government] will require fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016”. However, the construction industry does not yet have a holistic approach to data management. Building Smart is developing open BIM standards to ease data transfer. The Construction Building Information Exchange (Cobie) format also helps to collect information for asset and facility
management. Terms like product data, master data, product data management, and product data lifecycle management, which are familiar to many other industries, are not commonplace in the construction industry. Data governance organisations in the construction industry should also be put into practice.

To avoid many RFIs and better gain the benefits of BIM in the project, a description of product data is needed. To clarify the complex setting of data flow, we should first think of product data and then the process (Haapasalo, 2018; Silvola, 2018). The basis in data management is the object that is first created and then altered during different lifecycle phases. According to Silvola (2018), the lifecycle phases of the built object are as-planned, as-designed, as-built, as-sold, as-operated, and as-maintained. A process that is composed of different lifecycle phases should handle the same information through the lifecycle; as Silvola (2018) highlights, one product master data is the DNA of the product throughout the lifecycle.

In many trades, Product Lifecycle Management (PLM) has a role for shared product definition, manufacturing, and service management. PLM applications offer a link to product and process information and keep the integrity of information. BIM can benefit significantly from familiarising functionality from PLM systems. There also are challenges in taking PLM systems in use in the AEC sector. AEC companies are small, which makes it difficult to take expensive PLM systems in use. There also are different project delivery systems, building elements are custom defined, and requirements are unstructured and changing continuously (Aram & Eastman, 2013). According to Fadli, Barki, Shaat, Mahdjoubi, Boguslawski & Zverovich, (2015) the present use of BIM is custom-made for the management of new projects, while current and finished AEC projects could enormously profit from BIM integration for better Building Lifecycle Management (BLM) strategies. Master data is regarded as the foundation of business processes (Loser, Legner & Gizanis, 2004). Master data describes the different entities applied in the industry, like parties (clients, dealers, personnel, citizens), places (locations, offices), and things (accounts, assets, rules, products, and services) (White, Newman, Logan & Radcliffe, 2006; Moss, 2007). The master data defines business objects and how they are characterised in various ICT systems (McKeen & Smith, 2007). Master data is needed for data sharing and harmonising (Berson & Dubov, 2007) between different ICT systems (CRM, ERP and CAD). MDM concentrates on business processes, data quality, and the integration and harmonisation of information systems (Joshi, 2007). For instance, the electronics industry has used and managed product data, related transactions, and processes putting principles in place for managing product information in production, customer service, and maintenance. Master data
aim to organise information that is used frequently successfully. Business-related features are specified together with related metadata, attributes, definitions, roles, connections, and classifications (Dayton, 2007; Loshin, 2009). Only the portion of elements that are needed for data sharing and harmonising are master data. Master data objects are the most critical business elements, helping organisations to understand the factors and trends that can affect business (Berson & Dubov, 2007). Some features distinguish master data from other types of data (Otto & Huner, 2009):

- Master data define the essential characteristics (e.g., age, height, and weight) of an object in the real world. It contrasts with transaction data (e.g., invoices, orders, and delivery notes) and inventory data (e.g., stock on hand and account data).
- Master data have a longer lifecycle than transaction data. If the characteristic features always remain the same, there is no need to change the respective master data.

Instances of master data classes (e.g., customer data) are quite constant concerning volume, at least when compared to transaction data. Master data form a reference for transaction data. They do not need any transaction data in order to exist. Hence, master data describes the concept of finding a set of data that is created only once and does not change.

Data governance describes a system by which an organisation manages the quality, reliability, usability, security, and accessibility of its data. It applies to the whole organisation’s business processes, data, and risk management. The purpose of data governance is to generate a positive control for the guidelines of data creation and usage and to retain and archive the data. The enterprise’s management can create different roles in the organisation for data governance, like Data Steward, Data Owner, Data Manager, and Data User (Cohen, 2006).

2.3 Early involvement and integration

2.3.1 The need for early integration

There is a need for early integration in the construction industry, as the construction industry has minimal productivity growth compared with other sectors (Pekuri et al., 2011). One of the reasons for its bad productivity growth is that traditional construction projects include waste, especially process-related waste (Merikallio &
Haapasalo, 2009), meaning that there are phases that do not add value (Womack & Jones, 1996). Most of this waste can be reduced with efficient planning in the early stages of projects. Traditional construction projects consist of sequential phases in which tasks follow each other with low interaction with preceding and succeeding tasks. Weak communication may lead to a situation in which work is performed mainly to optimise the impact and contribution of one stakeholder rather than in the best interests of the whole project (Matthews & Howell, 2005; Haapasalo & Lohikoski, 2013).

Early stakeholder involvement and integration have been recognised as a potential solution for waste and productivity challenges in construction (Baiden, Price & Dainty, 2006; Ballard, 2008; Lahdenperä, 2012; Aapaoja et al., 2013). Integrated project delivery types enhance early stakeholder involvement and integration (Ballard, 2008). Design for Excellence (DfX) can involve main stakeholders in the initial phase of a project. The electronics industry has used DfX in complex product development projects. In DfX, the X refers to an aspect, lifecycle phase, or a specific stakeholder, like, for instance, manufacturing, construction, maintenance, supply chain, and cost (Bralla, 1996; Möttönen et al., 2009; Lehto et al., 2011). A key target of DfX is to recognise the most significant stakeholders (Xs) and integrate them early in the project process. DfX assists with functional integration, creates competence, and obtains the best capability for the project (Ulrich & Eppinger, 2008).

2.3.2 DfX enhance communication and create capabilities

DfX practices are methods for enhancing communication and creating the capabilities to target competitive goals (Gubi & Heikkilä, 2003). According to (Birou, Fawcett & Magnan, 1998), companies have five main competitive goals or capabilities: cost, quality, delivery, flexibility, and innovation. Different competitive goals must be emphasised depending on the lifecycle phase. Likewise, the attention to product or process should be different depending on the product phase, such as introduction, growth, maturity, and decline (Swink & Way, 1995). Magnan, Fawcett & Birou, (1999) have observed the importance of different competitive goals through a product’s lifecycle. Process and product innovations are essential during the early phases, while delivery capability and flexibility are necessary during the growth and maturity phases. Quality is seen to be important at the product introduction and growth, while cost is key during maturity.
DfX can improve requirements management (Aapaoja et al., 2014). The construction industry can take advantage of concepts developed for other branches. According to Aapaoja et al. (2014) in the DfX, the X means an aspect or a stakeholder like manufacturing, environment, maintenance, supply chain, and cost. The same Xs can be found in the construction business, but the names vary. The similarity of DfX remains the same; it is as vital to study stakeholders and their requirements in the construction business, as in product development. Managing requirements has become a major challenge for ICT companies as requirements change during development and are interpreted differently by other stakeholders in the organisation, reflecting the challenge of communication. DfX can help to efficiently coordinate and communicate the design requirements for both internal purposes and to external supply chain partners. According to Tolonen, Haapasalo, Harkonen & Verrollot, (2017), the DfX product design method facilitates the organised and cost-efficient use of existing supply chain processes for new products and related undertakings. Samarasinghe, Mendis & Vassos, (2016) had developed a BIM-based framework when they studied how to meet the MEP prefabrication requirements for each stage of the process using design for excellence. In addition to managing requirements, DfX can also be used for collecting best practices and distributing requirements information. Although there are many discussions of DfX methodologies in the existing literature, only a few suggest practical implementations regarding how organisations structure requirements management (Jablokow & Booth, 2006; Möttönen et al., 2009; Spahi & Hosni, 2009). The link between product and production has traditionally been studied from manufacturing (DfM) and assembly (DfA) points of view (Huang, 1996; Boothroyd, Dewhurst & Knight, 2001; Kuo, Huang & Zhang, 2001). Though some recent studies have concentrated on the interface between the product and demand chain, including the features of delivery and service capability (Fine, 1998; Gubi & Heikkilä, 2003).

The practical planning of DfX implementation can be divided into three domains: 1) designer, 2) methods and tools, and 3) organisation. To define these domains further, a designer is characteristically a skilled research and design (R&D) engineer, implementing DfX philosophies in practice. Methods are procedures and guidelines made for a designer, while spreadsheets, applications, databases, design structure matrix, and morphological charts and examples are tools used for communicating requirements. The organisational domain covers matters like teamwork, collaboration, communication, processes, and company policies (Poli & Knight, 1984; Eversheim & Baumann, 1991; Meerkamm, 1994; Lang, Dickinson & Buchal.
According to Bralla (1996), a successful DfX implementation requires a prototype or clear design guidelines. Designers with experience in traditional who start using DfX may continue to focus on the product and end-user value. They do not generally think about requirements related to the product lifecycle phases, such as manufacturing, service, and disposal. Later phases’ needs are frequently addressed by other employees in other departments only after the design is complete. This has resulted in awkward processes that are rigid, time-consuming, and sensitive to mistakes (Kuo et al., 2001). The literature also outlines some disadvantages when implementing DfX; in large organisations, complex organisation structures and the vast number of matters to be managed can cause challenges (Herrmann et al., 2004).

Concurrent engineering (CE) resembles DfX and can improve an organisation’s competitive capabilities and reduce ambiguousness (Koufteros, Vonderembse & Doll, 2001; Vonderembse & Doll, 2001). CE is a practice in which several development aspects, like quality, manufacturing, assembly, logistics, packaging, and service, are considered concurrently (Abdalla, 1999). It may include product and process engineering but also supply chain considerations (King & Majchrzak, 1996; Fine, 1998; Fixson, 2005). CE is often compared to DfX (Kuo et al., 2001; Yang, Chen & Shiau, 2007). However, DfX shows more precisely than CE what is being considered in the design as the DfX concept concentrates on cost competition and product lifecycle aspects. DfX moves the design activities to the early phases of the project, which is essential because up to 70% of product lifecycle costs are determined at the initial design phase (Asiedu & Gu, 1998; Anderson, 2003).

There are primarily three core business processes that provide value for customers: product development management, supply chain management, and customer relationship management (Srivastava, Shervani & Fahey, 1999). The supply chain (SC) process is composed of sub-processes and activities like demand and supply planning, acquiring, production, order management, distribution, and billing. The supply chain capability (SCC) is the performance of the operative SC process to perform its planned activities according to decided performance goals and metrics (Lummus & Vokurka, 1999; Swafford, Ghosh & Murthy, 2006).

SCC can be studied from two angles: first, the capability to supply, manufacture, and deliver the products efficiently, and, second, the capability to achieve customer demand even for tailored products and services (Lynch, Keller & Ozment, 2000). Collaboration has a positive effect on the SC value, which positively influences the company’s performance (Liao & Kuo, 2014). An excellent SC maturity level can be spoilt in various ways, such as with the absence of the right information.
in a customer order, machinery failures, and transportation failures (Fawcett, Cal-
antone & Smith, 1997).

**2.3.3 Organisational integration**

According to Turkulainen & Ketokivi (2012), organisational integration is a solid concept in management research. In a project, context integration is a process by which organisations or sub-organisations are connected to work in collaboration in order to reach the required project goals. In the 1960s and 1970s, early integration researchers concentrated on intra-organisational related topics, studying how the organisations, systems, and projects should be managed (Lawrence & Lorsch, 1967; Galbraith, 1974). Hietajärvi et al. (2017) highlight that the project organisation has become more complicated, making the inter-organisational approach more valid. Izam Ibrahim, Costello & Wilkinson, (2013) point out that, in the construction industry, project teams have become more multidisciplinary and global, and their outcomes are conditional on how well they can integrate. Walker, Davis & Steven-
son (2017) observe that integration facilitates collaboration and helps the team members to understand the big picture of the project better. Integration helps to synchronise the goals of different subprojects and advances the quest for common project goals (Pekkinen & Kujala, 2014).

Moreover, integrated project delivery models enable collaboration and open and close communication. The traditional project delivery and integrated project delivery models differ from each other in a way how they manage contingency budgets. In traditional methods of project delivery, ambiguity and some level of uncertainty are acceptable and, therefore, included in the project budget. However, integrated project delivery models decrease uncertainty and situational ambiguity by enabling collaboration and open and close communication between stakeholders. They also decrease people and process ambiguity by reducing the likelihood of prejudices and restrictive thinking (Walker et al., 2017). The collaboration in integrated contract model projects converts uncertainties into risks and opportunities; therefore, collaboration increases risks even as it decreases ambiguity (Perminova, Gustafsson & Wikström, 2008; Walker et al., 2017). Hietajärvi et al. (2017) have observed that if the stakeholders in an alliance project did not have previous experience of collaboration, the uncertainty was higher. Therefore, a higher level of integration was needed. The creation of shared knowledge and socialisation is necessary, especially in complicated cross-functional projects (Huang & Newell, 2003).
Project integration guarantees that the numerous actions within a project are properly coordinated and can then be regarded as the required process (Kirsilä, Hellström & Wikström, 2007). When projects include many technologies, as well as separate organisations, partners, and suppliers, the cooperation and coordination processes are highly complicated (Browning, Fricke & Negele, 2006; Wikström, Artoo, Kujala & Söderlund, 2010). Other sources of complexity include growing competition, customer requirements, shortened reaction times, and more substantial amounts of activities and information (Browning et al., 2006). The temporary nature of project organisation in general and international organisations comprising different nationalities and practices add complexity (Dietrich, Eskerod, Dalcher & Sandhawalia, 2010). Integration has an essential place in numerous domains, such as management, strategy, organisational theory, operations management, and information systems (Barki & Pinsonneault, 2005). PMBOK (Rose, 2013) regards integration management as one of the ten knowledge areas. During the last decades, integration has received academic interest in the framework of the management of multinational enterprises, operations, and supply chains and mega projects (Teerikangas & Gerald, 2015).

Manning (2017) defines network organisations as strategically managed sets of teams and partner pools composed of legally independent but operationally interdependent organisations and persons. Moreover, the characteristic feature of projects has changed to include more knowledge bases, technologies, and subsystems (Wikström et al., 2010). Project alliancing and collaborative arrangements are one form of network organisation (Manning, 2017), which is also called relational project delivery arrangements (Lahdenperä, 2012). Other synonyms are collaborative project procurement arrangements or relationship-based procurement (Walker & Lloyd-Walker, 2015). There are various methods to encourage collaboration; legal and obligatory requirement frameworks are used in project alliancing (Lloyd-walker, Mills & Walker, 2014); a management approach is used in collaborative arrangements; and, an early integration of key partners and a contractual agreement are used in integrated project delivery (Lahdenperä, 2012).

2.4 Synthesis of literature review

The proper use of BIM in its different roles with early involvement and integration are the most important discussions to pursue to enhance data utilisation. Figure 7
illustrates the theoretical background of the dissertation. Table 3 provides a synthesis of the main discussions concerning BIM definitions and benefits, early involvement, integration, design for excellence, and product data.

Fig. 7. The theoretical framework of the dissertation.

The purpose of this dissertation is to clarify how to enhance data utilisation in a construction project’s lifecycle. According to the literature review, BIM plays different roles in a construction lifecycle; it is a data model, a software tool to help design and construction tasks, and a collaboration tool to facilitate early involvement and integration. However, the literature review has left ambiguous the barriers that hinder a wider use of BIM. The literature review showed that BIM plays a role in supporting integrated project delivery models but did not clearly indicate how BIM supports integrated project delivery models, especially early involvement and integration. Early integration is the key characteristic feature of integrated project delivery models, and integration can be described as the sharing and processing of information. Project integration guarantees that the numerous actions within a project are properly coordinated (Kirsilä et al., 2007; Turkulainen, Kujala, Artto & Levitt, 2013). DfX practices enhance communication and create capabilities for targeting competitive goals by moving the design activities to the early phases of
the project. The benefits of early integration in construction projects need more investigation, concerning, for example, how the use of DfX affects the quality of construction projects, particularly because the design and management of product data has such an essential role in other industries. While the characteristics of product data were studied in the literature review, the question of how to organise data management in a construction project remained open and requires further investigation.

Table 3. The synthesis of main discussions.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Main concept</th>
<th>Main references</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIM definitions and benefits</td>
<td>BIM plays different roles in construction lifecycle. It is a data model, a software tool to help design and construction tasks and a collaboration tool to facilitate early involvement and integration.</td>
<td>Ashcraft (2008), Eastman et al. (2008), Succar (2009), Sacks et al. (2010), Succar (2010), Eastman et al. (2011)</td>
</tr>
<tr>
<td>Early involvement</td>
<td>Early involvement is an essential concept to ensure good quality design in which all stakeholders’ requirements are considered, ensuring that all the relevant data is available to all stakeholders through the life-cycle.</td>
<td>Dowlatshahi (1998), Love et al. (1998), Baiden et al. (2003), Bromley et al. (2003), Kent and Becerik-Gerber (2010), Lahdenperä (2012), El Asmar et al. (2013)</td>
</tr>
<tr>
<td>Integration</td>
<td>Integration can be described as the sharing and processing of information. Project integration guarantee that the numerous actions within a project are properly coordinated.</td>
<td>Kirsila et al. (2007), Turkulainen et al. (2013)</td>
</tr>
<tr>
<td>Design for excellence (DfX)</td>
<td>DfX practices enhance communication and create capabilities for targeting competitive goals. DfX moves the design activities to the early phases of the project.</td>
<td>Asiedu (1998), Anderson (2003), Gubi and Heikkila (2003)</td>
</tr>
</tbody>
</table>
3 Research contribution

3.1 Barriers to implementing BIM

In the first study, the author studies the barriers to implementing BIM in answer to research question one. The research was based on the literature review and focus group interviews, and the literature review explained both the definitions and benefits of BIM. Several benefits accrued from using BIM in construction projects, but the level of usage of BIM was quite low. Focus group interviews revealed several barriers that hinder organisations in using BIM in such a way that the benefits can be realised.

The benefits of BIM were classified into two groups. Firstly, the benefits were determined from the designers’ and constructors’ points of view and, secondly, from clients’ and owners’ perspectives. The benefits differed according to each stakeholder group in the construction project (Eastman et al., 2011).

The benefits of BIM to clients and owners were:

- increased productivity and quality
- faster and better management of processes
- efficient electronic tendering
- better data management during operation
- better information flow through project phases.

The use of BIM increases productivity and quality, project timelines are shorter, and there are fewer design defects and unbudgeted changes. The total costs of the projects decrease when BIM is used, and the construction is more sustainable. When BIM is used, the processes improve, data flow is smoother, and overall data management is better. BIM improves communication, teamwork, and rationalised practices (Ashcraft, 2008; Sacks et al., 2010; Eastman et al., 2011; Khosrowshahi & Arayici, 2012; Wong & Fan, 2013)

The benefits of BIM to designers and constructors are:

- an internationally compatible process model
- the role of designers is emphasised, and design accuracy improves.
- the number of defects decreases, and the efficiency increases
- improvement of building automation
- better management of construction processes.
BIM helps in adopting integrated project delivery (IPD) and other project delivery methods that are based on collaboration (Ashcraft, 2008; Eastman et al., 2011; Sacks et al., 2010) Open BIM standards maintained using buildingSMART, improve data exchange, even for international projects (BuildingSMART, 2019). Designers can secure their role in projects by making significant construction cost savings with the help of BIM-based clash detection. Building automation requires exact surface models, which are easier to produce with BIM (Eastman et al., 2011).

As a result of the focus group interviews, several barriers were found to hinder stakeholders in construction projects from taking advantage of BIM benefits. Focus group interviews were chosen as a research method, to receive information from experienced construction professionals and researchers, because we needed to analyse, why earlier reported benefits have not been realised. Moderators of the interview steered the discussion to the berries in BIM realisation using cause and effect diagrams with six viewpoints on a specific benefit to mapping the causes for barriers. The reasons for not adopting the named benefits were studied from six different angles: methods, machines (equipment), manpower (people), materials, measurement, and milieu (environment). The results of the expert focus groups were then analysed crosswise to map the barriers. Invitations to focus group meeting were sent to representatives of the Finnish construction branch. They were selected using the contacts of association of civil engineers in Finland. The goal was to gather known experts who were motivated to improve the industry and process (see Yin, 2009), then provide reliable information without danger of bias. We had sent several hundred invitations, and the group of 74 participants, who arrived at the meeting fulfilled our expectations. In the group, there were representatives from different organisation levels:

- 23 from top management, including professors and CEOs
- 22 from management level including senior project managers and principal designers and
- 29 from the specialist level, including researchers and project engineers.

Participants can also be classified according to their professional branch. There were five clients/owners, 26 designers and 11 constructors. Besides, there were 15 participants, which were classified as BIM system providers and 26 researchers.

The results of the focus group interviews showed that many improvements need to be made in the organisation of BIM-based construction projects. There also are challenges in everyday processes. Most of the typical procurement methods do
not support the use of BIM, and joint modelling instructions are rarely put into practice. Change resistance can also occur when adopting BIM.

Table 4. The percentage of perceived barriers for BIM benefits. Figures are given for both clients and owners, as well as for designers and constructors and total values (modified from Article I).

<table>
<thead>
<tr>
<th>The percentage of barriers in each category</th>
<th>Clients &amp; Owners</th>
<th>Designers &amp; Constructors</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICT related barriers</td>
<td>8.8%</td>
<td>8.1%</td>
<td>8.4%</td>
</tr>
<tr>
<td>Resistance to change related barriers</td>
<td>3.7%</td>
<td>21.8%</td>
<td>25.5%</td>
</tr>
<tr>
<td>Interoperability or similar barriers</td>
<td>9.7%</td>
<td>12.5%</td>
<td>11.3%</td>
</tr>
<tr>
<td>Organisational and common process related barriers</td>
<td>44.7%</td>
<td>48.8%</td>
<td>47.1%</td>
</tr>
<tr>
<td>Training and knowledge-based barriers</td>
<td>6.1%</td>
<td>8.8%</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

Table 4 lists the classifications of barriers and the percentage of the total answers. The largest category concerned organisational and process-related barriers (47%), the second largest concerned resistance to change (26%), and interoperability and ICT-related barriers each had 8–11% of all answers. Designers and constructors seem to be more enthusiastic about using BIM than clients and owners.

As an answer to the dissertation’s first research question, the barriers to implementing BIM are listed in descending order, from severe to mild:

1. organisational and common process-related barriers
2. resistance to change
3. defects in interoperability
4. ICT defects
5. defects in training and knowledge.

It seems that the use of BIM is not planned well in the early phases of projects. The resistance to change and interoperability problems suggested that process planning and discussions with stakeholders regarding BIM’s benefits in the initial stage of projects are essential in overcoming barriers, and early involvement can mitigate the barriers. The results provided the rationale for the second article’s research question: how does BIM support early involvement and vice versa?

3.2 How BIM supports early involvement

In the second article, the focus was on the simultaneous use of BIM and integrated project delivery models: for example, project alliancing (developed in Australia),
integrated project delivery (AIA in the United States) and partnering (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). A common feature of these types of integrated project delivery models is that they enable collaboration between project stakeholders. In the integrated project delivery models, stakeholders reach an agreement and are mutually responsible for the project, with joint ‘pain and gain’ clauses (Colledge, 2005). BIM is a tool for modelling, managing, and sharing all project information with all project parties. The concept of BIM is already 40 years old, and it was created to better handle integrity in design applications (Eastman et al., 2008). Design objects have a key role to play in building modelling. Designers can change the attributes of objects, which are then changed according to embedded design rules. Designers can print drawings or produce views of the project from different angles, with perfect integrity of data in all views. The role of BIM has broadened from a design tool to cover data and information needs of the whole project team throughout the project lifecycle (Eastman et al., 2008).

During the past decade, increasing efforts have been made to bridge the gap between the design and construction phases. Traditional delivery methods, like DBB (design-bid-build), have proved to be inadequate (Lahdenperä, 2012). Integrated project delivery models are based on collaboration and focus on mutual, individual project goals that are jointly agreed. Collaboration is vital in overcoming the fragmentation of supply chains and the phenomenon of stakeholders only being responsible for their own work (AIA, 2007). Maximising a stakeholder’s personal benefits usually jeopardises the project objectives and harms other team members. In integrated project delivery models, each actor has an equal opportunity to contribute to the project’s delivery and realise the full potential of the cumulative knowledge of the project team (Love et al., 1998; Baiden et al., 2003; Bromley, Worthington & Robinson, 2003; Lahdenperä, 2012).

According to Love et al. (1998), more complex projects and new technology have motivated organisations to involve suppliers, subcontractors, and stakeholders in the early phases of projects. Early involvement in the design stage improves the possibilities of better designs, efficient production processes, and less waste (Dowlatabadi, 1998; Kent & Becerik-Gerber, 2010; El Asmar et al., 2013). In addition, early involvement results in excellent customer value and satisfaction. Table 5 lists the characteristic features of integrated project delivery models. The elements are categorised according to three groups: mutual and single object, integration, and early stakeholder involvement. The project team has both joint and individual objectives, which are intended to optimise the stakeholders' activities and avoid sub-optimisation. Work is open and transparent, accounting documents are visible to all
team members, and project benefits and risks are shared. All decisions are made in
the best interests of the whole project. Free communication and extensive use of
technology, like BIM and digitalisation, are necessary when the stakeholders have
both mutual and individual objectives. The integration in integrated project deliv-
ery project teams is essential. There are no organisational boundaries (Dainty, Bris-
coe & Millett, 2001) and, to enhance collaboration and interaction, the project team
works at the same location. The focus is on solving problems, not apportioning
blame, and instead of fragmented suboptimal delivery, the goal is value co-creation.

Table 5. The characteristic features of integrated project delivery models (Alliance and
IPD type project deliveries) (under CC BY-NC-ND from Article II © 2015 Elsevier B.V.).

<table>
<thead>
<tr>
<th>Key element</th>
<th>Characteristics</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutual and single object</td>
<td>Mutual and single project objective Forques and Koskela (2009), AIA (2012) Open accounting documents shared between team members (Ross, 2003; Cohen, 2010). Shared project benefits and risks (value-based approach) Colledge, (2005). Unlimited communication and wide use of technology Aapaoja et al. (2013).</td>
<td>Comprehensive optimisation of the results, instead of sub-optimisation. ‘We win or lose together.’ (AIA, 2007) The project must be open and transparent if the results and risks are to be shared. Benefits and risks are collectively and appropriately managed. All decisions are made ‘in the best interest of the project.’ Digitally based and virtual (e.g. BIM).</td>
</tr>
<tr>
<td>Integration</td>
<td>No organisational boundaries Dainty et al.,( 2001). Co-location of a project team Dainty et al. (2001), Bromley et al. (2003), Ross (2003), AIA (2012). Focus on solving problems, not on apportioning blame (‘no blame’ culture), Dainty et al. (2001) Ross (2003), Lahdenperä (2012). Fair and respectful culture among team members) Moore and Dainty (2001), Ross (2003) Value co-creation, Dowlatshahi (1998), Kent and Becerik-Gerber (2010), El Asmar et al. (2013).</td>
<td>Solid team spirit that contributes to the outcomes. Enhances the communication and interaction between team members (tacit knowledge). Blame does not benefit value creation; thus, the focus must be on ensuring that mistakes do not recur. Collective responsibility for project performance encourages innovative thinking. Value co-creation shifts the mindset from traditional suboptimal delivery to system integration and experience co-creation.</td>
</tr>
</tbody>
</table>
Early stakeholder involvement is realised in integrated project delivery models. All team members have a similar opportunity to affect project delivery and processes. Early involvement results in increased control of costs and schedules (Baiden et al., 2003; Mossman, Ballard & Pasquire, 2010). Easy communication (Moore & Dainty, 2001; Ross, 2003) and efficient use of technology are characteristic features of integrated project delivery models, and they are realised and extensively facilitated by the use of digitalisation and BIM.

The ability to impact cost and design decisions is the biggest at the beginning of the project (Integrated Project Delivery: A Guide, 2007), and the cost of design changes are the biggest at the end of the project. It is then beneficial to move design decisions upstream as early as possible. According to the IPD guide (2007) in the IPD project, the design work has the highest intensity at the beginning of a detailed design phase. Which is this dissertation’s recommendation as well for the latest phase to involve the main stakeholder to design work. In tradition project deliveries, the highest design intensity is in construction documents design phase.

According to Eastman et al. (2008), a building information model can serve as the information centre for the whole project. The benefits of using BIM to project work are achieved in collaborative use. Technology that initially helped designers to guarantee the integrity of data in different drawings now plays a greater role in project information management. Collaborative use of BIM means that all design disciplines are modelled and combined into one model, as discussed by Azhar (2008), Eastman et al. (2011) and Laine, Alhava & Kiviniemi (2014). The UK Government (2011) has established regulations that mandate the collaborative use of
BIM because of the benefits. When a collaboration model is used, software tools can improve design quality. The clash detection of objects and 3D models presents visualisations and animations that assist in identifying design defects. Three-dimensional (3D) models can serve as information centres for all project stakeholders and can support early involvement of all stakeholders.

Table 6 provides a description of the characteristic features of BIM. Characteristic features are divided into three categories: information centre, collaboration model, and simulations. BIM can work as a common information source for all project stakeholders if data management is handled correctly. The data and information relating to the project increases during the project lifecycle and makes the reuse of data possible; there is no need to produce the same data several times during the lifecycle. A shared, continuously updated, collaboration model can help to improve design quality. A collaboration model improves mutual understanding of the project features and may serve as the primary information source for all project team members. A 3D view of the project can be viewed at any time on projection screens in large meeting rooms, and it is possible to combine schedules with the model to produce four-dimensional (4D) project simulations. A 4D model is useful in production planning. BIM also enables efficient mass haul optimisation; project volumes can be produced straight from the model, which significantly reduces the manual volume calculation work. The data model of the project can be updated and adjusted throughout the lifecycle, during design, construction, operation, and maintenance phases.

Table 6. The characteristic features of BIM (under CC BY-NC-ND from Article II © 2015 Elsevier B.V.).

<table>
<thead>
<tr>
<th>Key element</th>
<th>Characteristics</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information centre</td>
<td>All information is stored in the model or the model has direct links to the information.</td>
<td>The model works as a common information source and provides information storage for stakeholders. It enables the reuse of data throughout the project lifecycle.</td>
</tr>
<tr>
<td>Collaboration model</td>
<td>A collaboration model can be used to identify clashes between design domains and other design mistakes.</td>
<td>The quality of design improves, with less wastage, more sustainable construction, shorter timelines, and lower construction costs.</td>
</tr>
</tbody>
</table>
A common real-time collaboration model helps improve communication between stakeholders. The model can be used as a basis for communication and documentation. A continuously updated collaboration model shares the real design situation with all stakeholders, who have a common knowledge of design. BIM assists collaborative meetings, based on a shared model and virtual reality applications. All designers can follow the whole project’s progress from one common collaboration model. One common model makes the early involvement of all stakeholders easier. The model can be used to simulate the construction, operation, and maintenance processes. The model enhances the construction process, with lower operation and maintenance costs, safer operation, more efficient maintenance, and less energy consumption.

The simultaneous use of BIM and integrated project delivery models help to improve project delivery. BIM can be seen as a tool that allows integrated project delivery projects to realise their goals (Table 6). Figure 8 lists BIM and integrated project delivery models’ key elements and shows how effectively they provide benefits for the project when used simultaneously. The green colour means that BIM supports the characteristic features of integrated project delivery models; the absence of colour means that BIM has a neutral affect. The characteristic features of BIM largely support the aims of integrated project delivery models, except the one common information centre, which supports only open accounting; other characteristic features have a neutral effect. BIM also has a neutral effect on integrated project delivery models that feature a fair and respectful culture among team members.

Early involvement of key stakeholders aims to promptly and effectively maximise the core competencies and knowledge, and a collaboration model supports early involvement. A visual collaboration model, even at the beginning of the project, provides an equal opportunity for all project stakeholders to evaluate the effect of design decisions. One common centre for information, with user interfaces for both reading and providing feedback, enables free communication. Good virtual reality modelling and simulations of the project provide an opportunity for even non-technical stakeholders to estimate the feasibility of design decisions.
One of the key elements of integrated project delivery models is integration. A BIM serves as an information centre for the project, which facilitates project stakeholder integration. There are no organisational boundaries, so all stakeholders can access the project data continuously. 3D views and 4D simulations enable the whole project team to analyse the entire project in the big room. A collaboration model with appropriate 3D software tools is a sound basis for integration. BIM supports value co-creation, and a BIM project model can help to optimise costs, energy consumption, resources, or CO₂ emissions, thus ensuring that the solution adds maximum value for the customer.

Mutual and single objective help to comprehensively optimise results. All information is transparent and available to everyone; BIM supports free communication and provides a single joint information centre. A collaboration model reduces sub-optimisation and includes all design decisions, which are available for other stakeholders for simulations and other analyses.
Early involvement is the characteristic feature of integrated project delivery models. The second article answers the research question regarding how BIM supports early involvement and vice versa. Early involvement of key stakeholders aims to

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![Table showing characteristics of integrated project delivery models and BIM](image)

**Fig. 8.** The benefits of the simultaneous use of integrated project delivery models and BIM for project delivery. The green colour indicates that BIM supports the characteristic features of integrated project delivery models; the absence of colour means that BIM has a neutral affect (Article II).
promptly and effectively maximise the core competencies and knowledge. A collaboration model that covers all design disciplines is a high-quality tool for ensuring early involvement and design quality. A visual collaboration model for the whole project, even in the very early phases of a project, provides an equal opportunity for all project stakeholders to evaluate the effect of design decisions. One common centre for information, with user interfaces for both reading and providing feedback, enables unrestricted communication. Comprehensive virtual reality modelling and simulations (for instance, production, costs, energy consumption, CO₂ emissions, use of resources, operations, and maintenance simulations) of the project allow even non-technical stakeholders to estimate the feasibility of design decisions. The use of BIM thoroughly supports integration, providing the rationale for the third research question: what are the benefits of early integration?

### 3.3 The benefits of early integration

The third article examines early involvement and integration in construction projects and determines what benefits design for excellence (DfX) can have for the elimination of waste. DfX is a set of tools used to involve key stakeholders in the preliminary phase of a project. In DfX, the X refers to an aspect, lifecycle phase, or a specific stakeholder; for instance, manufacturing, construction, maintenance, supply chain, or costs (Bralla, 1996; Möttönen, Härkönen, Belt, Haapasalo & Similä, 2009; Lehto et al., 2011). Construction projects involve a great deal of waste. Waste can be waste of materials or process related (Merikallio & Haapasalo, 2009). Nonmaterial waste concerns all activities that do not create value for the customer (Womack & Jones, 1996), and a significant proportion of such waste can be avoided by efficient planning in the inception of a project. In the literature review, we studied waste and the requirements that support early involvement and integration. Based on the literature review, we used a survey to analyse and prioritise waste types in the construction industry. DfX is a method that automatically generates incentives for project team members to reduce waste with the help of early involvement and integration.

**Early involvement and integration**

Handfield, Ragatz, Petersen & Monczka (1999) highlighted that, especially in complex projects, the stakeholders should be involved as early as possible, since early involvement facilitates benefits such as:
– lower probability of poor designs
– increased likelihood of more effective design, enhanced construction operations, and less scrap, facilitated by early involvement in the design phase
– early information about end-users, leading to more satisfied clients regarding a project’s function and operation
– stakeholders’ actions better meet the purchaser’s needs and goals when they know more about the actual usage of products
– stakeholders understand the goals of design specifications and can meet or revise the specifications by altering their capabilities
– early involvement encourages the exchange of ideas and enables innovative results

Fragmentation of projects is seen as a phenomenon that causes waste; therefore, integration is needed to improve project productivity (Davis & Love, 2011; Chen et al., 2012). According to Mitropoulos and Tatum (2000), integration mechanisms can be classified into three types: contractual, organisational, and technological. Most common contractual mechanisms are objective plans and formalised rules, policies, and procedures. Organisational mechanisms are charts, printed policies, and procedures. Technological mechanisms usually include official standardised information and ICT systems (Van De Ven, Delbecq & Koenig, 1976; Turkulainen, Ruuska, Brady & Artto, 2015). In projects, several uncertainties relate to tasks and their interdependencies, which need to be coordinated. Project organisations must develop ICT systems for coordination, which can be regarded as integration mechanisms for handling external and internal uncertainty (Thompson, 1967; Morris, 2013).

The most common way to involve stakeholders in projects is on an as-needed basis. Communication with the downstream supply chain is unidirectional, and impromptu approaches are common, leading to sub-optimisation (Matthews & Howell, 2005). Stakeholders attempt to optimise their performance without adequately understanding the consequences of their efforts. In integrated contract models, customers and non-owner stakeholders form an integrated collaborative team (Ballard, 2008). The goal is to work trustingly with each other and make best-for-the-project decisions, by mutually managing all the risks of project delivery and sharing the ‘pain and gain’ (Thomsen, Darrington, Dunne & Lichtig, 2009; Cohen, 2010;
Lahdenperä, 2012; HM Government, 2015). Early stakeholder involvement and integration have been emphasised as the central aims of IPD (Baiden, Price & Dainty, 2006; Lahdenperä, 2012; Aapaoja et al., 2013). Early involvement provides benefits like greater client satisfaction, improved construction operations, innovative solutions, and synchronised tasks (Dowlatabadi, 1998; Valkenburg et al., 2008).

According to the literature review, the requirements for early involvement and integration relate to choosing a suitable project delivery type. IPD is characteristically used in complex projects and regarded as an extreme form of inter-organisational integration. Relational contracting decreases fragmentation and improves efficiency and performance in complex customer projects (Davis & Love, 2011; Chen et al., 2012). According to the literature review, there are three forms of collaborative arrangements: project alliancing (developed in Australia), integrated project delivery (AIA in the United States) and partnering (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). Integration between organisations is essential for enhancing a collaborative culture and project performance (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). DfX is a set of tools for managing design requirements with stakeholders. By using DfX, project stakeholders receive requirements on equal terms at the start of the project. DfX’s function is also to improve communication and achieve stakeholder integration (e.g., Lehto et al., 2011). Figure 9 shows a schematic diagram of traditional project delivery. The client makes separate agreements with stakeholders and is therefore responsible for the data and information flow. Figure 10 shows a schematic diagram of the integrated project delivery. In integrated project delivery, stakeholders reach the same agreement with the client where they are equal partners. Partners can agree on data transfer without liability issues; hence all stakeholders have common responsibility of the project results. Early involvement and integration of all stakeholders standardise stakeholder requirements in the early design phase, with no contract-based barriers to the data flow.
Waste in construction projects

To investigate the typical types of waste in construction, we relied on a survey, which required construction experts to define the most serious types of waste and rank them according to importance. We ranked the types of waste using a waste priority number (WPN), and an analytical hierarchy process (AHP) for pairwise comparison. The AHP facilitates decision-making for problems that involve multiple criteria (Saaty, 1980). Using these methods, we found the most severe types of waste and analysed them using DfX.
Failure mode effects analysis (FMEA) produces a risk priority number (RPN) for the failure modes by multiplying severity, occurrence, and detection (Abdelgawad & Fayek, 2010). We decided to calculate the WPN, rather than the RPN, in the same way; all three features were similarly weighted from 1 to 10. Severity refers to the consequences of project waste, occurrence means how often waste occurs, and detection describes how difficult it is to recognise the waste. We collected the data through interviews, and every informant gave values for each type of waste and each feature. During the interviews, informants were able to ask additional specific questions if necessary. The higher the WPN, the more serious the waste was. Table 7 lists the waste types, ranked according to the waste priority number. The five most severe types of waste were: inadequate communication and documentation, peoples’ unused potential, defects, making wrong products or services, and unnecessary movements.

In the pairwise evaluation, the informants compared and prioritised two alternatives, allowing the extent or ranking of the compared factors to be identified. The pairwise comparison consisted of many phases: firstly, we formulated a matrix (size n × n, where n is the amount of waste); secondly, the informants compared two factors in the interview using a relative scale measurement; and finally, the respondents compared each type of waste to the others (Al-Harbi et al., 1980). The correlation between WPN analyses and pairwise comparison was weak, and there was no clear correlation between different informants. There was a greater correlation between the impact factors of the WPN analyses and the pairwise comparison. In the pairwise evaluation we identified the five most severe waste types: making wrong products or services, inadequate communication and documentation, overproduction, defects, and poor constructability. Figure 11 illustrates a pairwise head-to-head comparison of waste types.

<table>
<thead>
<tr>
<th>Type of waste</th>
<th>WPN</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication and documentation</td>
<td>328</td>
<td>8.0</td>
<td>7.0</td>
<td>5.9</td>
</tr>
<tr>
<td>People’s unused potential</td>
<td>251</td>
<td>6.9</td>
<td>5.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Defects</td>
<td>238</td>
<td>7.0</td>
<td>7.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Making wrong products or services</td>
<td>207</td>
<td>6.9</td>
<td>5.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Unnecessary movements</td>
<td>201</td>
<td>4.8</td>
<td>7.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Inadequate processing</td>
<td>187</td>
<td>6.0</td>
<td>5.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Making do</td>
<td>186</td>
<td>6.4</td>
<td>7.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 7. List of waste types according to the waste priority number (under CC BY-NC-ND from Article III © 2017 Authors).
<table>
<thead>
<tr>
<th>Type of waste</th>
<th>WPN</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overloading</td>
<td>176</td>
<td>6.7</td>
<td>6.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Poor constructability</td>
<td>152</td>
<td>6.7</td>
<td>5.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Overproduction</td>
<td>148</td>
<td>7.1</td>
<td>6.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Waiting</td>
<td>146</td>
<td>6.0</td>
<td>5.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Unnecessary transportation</td>
<td>144</td>
<td>4.9</td>
<td>7.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Safety</td>
<td>51</td>
<td>6.5</td>
<td>2.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Inventory</td>
<td>45</td>
<td>4.3</td>
<td>6.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Other (weather conditions, theft, vandalism)</td>
<td>30</td>
<td>4.7</td>
<td>4.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Notes WPN = severity × occurrence × detection.

Fig. 11. Head-to-head pairwise comparison of waste types (under CC BY-NC-ND from Article III © 2017 Authors).

How DfX reduces waste in construction projects

We conducted a literature review to specify construction waste types. Subsequently, using two different methods, we found the five most significant waste types: poor communication and documentation, making wrong products or services, defects, people’s unused potential, and unnecessary transportation. DfX enables the coordination of requirements and delivers the requirements equally to the project stakeholders. DfX was initially developed to handle design requirements from all project
stakeholders, but it can also be used to realise early involvement, collect needs and requirements, and utilise stakeholders’ knowledge and expertise.

The defects in communication and documentation were the most serious waste type according to the waste priority number, and the second most serious type in the pairwise comparison. When using DfX, documentation systems are usually used to gather requirements from stakeholders and deliver them to designers and other stakeholders. Using DfX leads to better communication between stakeholders (Lehto et al., 2011). It facilitates early involvement by leveraging end-users’ and customers’ needs in the early stages of the project, and the earlier the stakeholders understand the requirements, the better they can plan their actions to satisfy customers’ needs (see e.g. Van de Ven et al. (1976) and Aapaoja, Haapasalo & Söderström (2013)).

End-users or customers’ needs are often not leveraged early enough to meet the needs of other stakeholders who are responsible for design and implementation. DfX embodies the procedures to be used in the project, so that the needs and requirements are acknowledged early enough to avoid the delivery of the wrong products or services.

Defects result in rework and are normally a result of wrong or insufficient working methods or instructions, leading to poor quality. DfX is a set of tools for documenting the desired quality and the correct working method for production. Defects can also be found before the implementation phase, when the process is analysed from the stakeholders’ perspective and balanced according to stakeholder importance (see e.g. Article II). Enhanced communication and documentation minimise defects, and thus prevents poor quality from accumulating along the supply chain.

Peoples’ unused potential occurs when the project does not use all the skills the team members possess. All the team members may have good ideas about improving designs or production methods, based on their experience or training. DfX collects requirements and needs from all stakeholders and facilitates this collection even from large crowds. The use of DfX does not guarantee that all team members will use their potential or have an opportunity to inform project management.

Unnecessary transportation covers the indirect transportation of materials, parts, tools, or information to the next phase of the process. The transportation of materials to inventories before the next phase starts results in waste and unnecessary transportation. DfX enables the collection of all the required information from related stakeholders to plan material flow without excess inventories and movements.
The third article answers the dissertation’s research question: what are the benefits of early integration? In this dissertation, BIM, integrated contract models, and DfX were studied as a means to enable early involvement and integration of stakeholders in construction projects. Early involvement and integration combine the collective knowledge and requirements (i.e. the relevant competencies) in the early design phase of the project. Integration enhances the collaborative culture and project performance (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). Early integration in relational contracting reduces fragmentation and improves efficiency and performance in complex customer projects (Davis & Love, 2011; Chen et al., 2012). DfX’s function is to improve communication and achieve stakeholder integration (e.g., Lehto et al., 2011). The first three articles of this research have highlighted the barriers to the usage of BIM, showing how BIM supports early involvement and integration and what benefits it brings to construction projects. This framework leads us to the fourth and final research question: how can data management be organised for infrastructure construction projects?

3.4 How to organise data management for infrastructure projects

The digitalisation of different industries has led to significant leaps in productivity (HM Government, 2015). Nevertheless, digitalisation and data are only tools to support business process development and reengineering. Corporate processes and supply chains exploit data and information, and they determine the entire framework of the industry and the outcomes of projects. Taking care of data quality is essential (Godfrey, 2002) because poor data quality can jeopardise the whole system. Data plays a crucial role, so it is vital to understand the concepts of product data, master data, and data governance. Data governance outlines who creates, modifies, utilises, or owns the data (Cohen, 2006). These roles differ according to the lifecycle phase. Business processes are essential, but products (built objects) are the starting point. The outcome of a project is a structure that is part of the built environment, but the resulting product data delivers the final service to customers. During the project lifecycle, different viewpoints need to be considered regarding the object data: planned, as-built, as-utilised, and as-maintained. Correct and current product data forms the basis for all activities (Yang et al., 2007; Rachuri et al., 2008; Khatri & Brown, 2010), but the challenge of managing product data increases when diverse organisations combine their contributions across the whole project.

The challenges regarding data flow in construction projects were studied using three case studies, and the detected challenges were divided into four groups: data
needs are not planned beforehand, resistance to change, difficulties in receiving existing data, and data must be edited before use. The biggest group was data needs not being planned beforehand. All three case study projects had different project delivery types: design-bid-build (DBB), design-build (BD), and alliance. The project delivery type seemed to affect the data flow. In all the case studies, the maintenance stakeholders had no opportunity for early involvement, and no clear guidelines regarding the data that needed to be delivered to maintenance stakeholders.

When data needs are not planned at the beginning of the project, they cause waste and extra work on site. Stakeholders do not have the necessary data or instructions on what data is required and in what format it should be delivered further down the value chain. In all the case studies, the maintenance stakeholders’ needs were not discussed, and they had no opportunity for early involvement. In all projects, there were signs of resistance to change. There might be a useful data model available, but project staff often printed paper documents, because they were used to working in this way. There were also difficulties in receiving data from other stakeholders. Liability issues affected the data flow, with data models being turned into PDF files, or existing data not being available on servers or computer hard discs. PDF file data is not as rich and usable as a full 3D data model, so the data the stakeholders received from the upstream supply chain was not in an optimal format for use. Data had to be edited before use, and constructible models needed to be modified periodically, starting with design systems surface geometry. Open BIM formats, like IFC and LandXML, were used in the case study projects, but the quality of Open BIM transfer files varied. It seemed that highway design software used many different versions of transfer file formats. Table 8 lists challenges in data flow identified in the case study projects.
Table 8. The main challenges in the data flow of infrastructure construction project lifecycles, drawn from the case projects (under CC BY from Article IV © 2020 Authors).

<table>
<thead>
<tr>
<th>The data needs are not planned beforehand</th>
<th>Resistance to change</th>
<th>Difficulties in receiving existing data</th>
<th>Data must be edited before use</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Data management was poorly organised in the bidding phase.</td>
<td>- Bidding foreman was used to having the design information in PDF format and did not use the model data, even when it was available.</td>
<td>- Constructors had difficulty in receiving all the necessary data from the client and the design organisation.</td>
<td>- Constructors had to edit the geometry information for roads to transfer the surface models to the automated machinery.</td>
</tr>
<tr>
<td>- The internal data flow in the construction phase, from the bidding to the construction team, was weak.</td>
<td>- In the construction phase, there was no specific application for mass haul planning.</td>
<td>- A challenge arose from the design organisation providing only the models that did not include any uncertainties because they were afraid of claims from the construction company.</td>
<td>- The structure’s IFC-model quality varied depending on the used design applications.</td>
</tr>
<tr>
<td>- The format of the required model for the maintenance phase was unclear.</td>
<td>- Some clients wanted PDF-files for different road construction surfaces that were then printed in paper format and archived.</td>
<td>- Characteristic features for current maintenance systems-based activities on physical paper documents.</td>
<td>- All software vendors had a modified version of the inframodel data format.</td>
</tr>
<tr>
<td>- Construction companies had no connection to maintenance organisations.</td>
<td>- The Finnish transport agency (FTA) did not name the maintenance operator for tunnels.</td>
<td>- The data model of the old road register was insufficient and not all data could be transferred.</td>
<td>- Constructors had to ask several times for more specific models during the construction project.</td>
</tr>
<tr>
<td>- Maintenance operators’ needs were not discussed in the project.</td>
<td>- In the 3D viewing software in general, there were no accurate models in use.</td>
<td>- The data flow for asset management and maintenance posed many challenges.</td>
<td>- Much information was held on different computer hard discs and databases in different folders.</td>
</tr>
<tr>
<td>- The communication between stakeholders was weak.</td>
<td>- The data flow between project phases was inadequate.</td>
<td>- Data management was a problem. Specifications were missing.</td>
<td>- As-built data was very often delivered in PDF format, meaning that some data was lost when digital information was printed as PDF files.</td>
</tr>
<tr>
<td>- Maintenance operators all had their own maintenance systems, and coordination was based on tacit knowledge.</td>
<td>- Contractors had different systems for data collection.</td>
<td>- Contractors had to edit the geometry information for roads to transfer the surface models to the automated machinery.</td>
<td>- The structure’s IFC-model quality varied depending on the used design applications.</td>
</tr>
<tr>
<td>- Contractors had difficulty in receiving all the necessary data from the client and the design organisation.</td>
<td>- Constructors had difficulty in receiving all the necessary data from the client and the design organisation.</td>
<td>- Constructors had to edit the geometry information for roads to transfer the surface models to the automated machinery.</td>
<td>- The structure’s IFC-model quality varied depending on the used design applications.</td>
</tr>
</tbody>
</table>
The choice of project delivery type affected the data flow. In DBB type projects, the client makes a separate agreement with primary stakeholders. These separate agreements cause liability issues, with designers not being willing to deliver no other data to other stakeholders than what the client had specifically ordered. A designer might become responsible for damages caused by design defects. DBB projects had the most significant number of observed challenges. DB project delivery made the cooperation easier between design and construction stakeholders, but cooperation with remaining stakeholders posed challenges. In the alliance type project, the stakeholders agreed quite unanimously regarding cooperation and data flow procedures. In the alliance case study project, the maintenance stakeholders were not part of the alliance. Table 9 shows that project delivery types that enabled greater collaboration seemed to have better data flow. Maintenance stakeholders’ requirements received only minor attention. Liability issues, especially in DBB type projects, hindered the data flow. Alliance type agreements did not hinder the data flow between alliance members.

Table 9. In the case studies, the data flow quality varied from weak to fair across a scale ranging through weak, fair, satisfactory, good, and excellent. D = Design, C = Construction, and M = Maintenance (under CC BY from Article IV © 2020 Authors).

<table>
<thead>
<tr>
<th>Project</th>
<th>Project Type</th>
<th>Data Flow D =&gt; C</th>
<th>Data Flow D, C =&gt; M</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jännevirta</td>
<td>DBB</td>
<td>Weak</td>
<td>Weak</td>
<td>Liability issues impeded data flow. No requirements for maintenance. No plan for lifecycle data delivery.</td>
</tr>
<tr>
<td>Bridge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keropudas</td>
<td>DB</td>
<td>Fair</td>
<td>Weak</td>
<td>Cooperation enabled between D and C stakeholders. Not enough construction-specific applications in use. No requirements for maintenance. No plan for lifecycle data delivery.</td>
</tr>
<tr>
<td>Bridge renewal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valtari</td>
<td>Alliance</td>
<td>Fair</td>
<td>Weak</td>
<td>Cooperation enabled between all stakeholders. Not enough construction specific applications in use. No specific requirements from maintenance stakeholders. No plan for lifecycle data delivery.</td>
</tr>
<tr>
<td>Highway 12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to this study, the primary reason for many challenges in infrastructure construction projects’ data utilisation was the absence of proactive planning of the data flow. Projects did not have a plan for data delivery, and the project managers did not know how to design, organise, monitor, and control data and data flow during the project lifecycle. The further we went in the lifecycle from design, the more necessary proper data flow planning became. Maintenance stakeholders were quite
often left alone to collect whatever pieces of information they happened to find. Based on the earlier studies and our case studies (Article IV), we created a lifecycle model for data flow (Figure 12). The essential task is defining the product, product data, and their lifecycle management. All other temporal products, services, or a combination of those during the lifecycle must assist this purpose in order to minimise total cost versus benefits.

The purpose of the product data management process is to ensure evolutionary data storage and sharing for planned, designed, built, sold, used, and maintained built objects, where master data is the ‘DNA’ of the object. The management of product data throughout the lifecycle requires a predefined product structure for the built object. All stakeholders must contribute to the product structure during the lifecycle. Even when the stakeholders during the lifecycle use parallel systems (CAD, BIM, CRM, ERP, etc.), they must comply and connect with one type of product data, utilising or modifying it according to their roles and responsibilities. The key element is that data sharing has been planned in the early phase of the project. From the start, all the related actors, such as design, construction, and maintenance stakeholders, must be able to express their data requirements, and the requested data should be available at the right time during the project. The most common method of handling data sharing during a project is cloud technology.

In addition to product data, many other systems are needed to manage and run the daily business effectively. Enterprise resource planning (ERP) systems are essential in the construction and maintenance phase to control the progress of work, sourcing, supply chain, and inventory. These functions require the transfer of as-designed and as-built data from product data management (PDM) to ERP systems. This kind of well-functioning connection between a PDM and ERP is rare in practice. Construction stakeholders should, crucially, be involved in design to ensure ‘design for construction’ and minimise request for information (RFI) on construction. Maintenance stakeholders should have a significant role in design to ensure ‘design for maintenance’ and easy to maintain solutions. Construction stakeholders should deliver as-built information to a PDM/PLM (product lifecycle management) system for sharing, to ensure a smooth maintenance operation that is based on the actual as-built materials (i.e., right product attribute data). When a failure or malfunction of the structure occurs, it is essential to find spare parts and responsible sub-contractors to fix the problem. Operation and maintenance are usually undertaken by different organisations than the design and construction, which makes the role of updated PDM/PLM systems central.
Master data management (MDM) is critical to ensure that a central repository of all product-related data is updated, and that the data quality is excellent (Loshin, 2009). MDM is a set of best data management practices for key stakeholders, participants, and businesses for the whole lifecycle of product data. The primary storage of all product-related data gives all project stakeholders a single system of record for their product master data, allowing better-quality operational processes for business efficiency. MDM means that project stakeholders cooperate with ICT specialists to harmonise, clean, publish, and protect shared data assets across the project organisations (White et al., 2006).

Fig. 12. Organising and managing the data flow for infrastructure projects. Data needs and delivery needs should be planned in the early stages of the project according to stakeholders’ requirements.

The fourth article answers the research question: how should data management in infrastructure projects be organised? Figure 12 presents a schematic diagram of how to organise and manage the data flow for infrastructure projects. The key element is that the data needs and deliveries in the project lifecycle are planned in the early phase of the project in collaboration with all relevant stakeholders. The project team’s capability level in BIM usage must be considered. Designers need the initial data for the project that enables the design work. Designers deliver an as-designed model to the client and to the construction stakeholders according
to their specific requirements. Construction stakeholders produce constructible models and a final as-built model to the client and maintenance stakeholders. If the project is successful, the maintenance stakeholder has a digital twin of the project that includes all relevant location and attribute information for the facility and its structures and equipment at the appropriate accuracy level. The product data model should be designed using master data to enable the easy use of data. Data transfer formats and data sharing technology need to be agreed, and data governance should outline the roles for data creation, data modification, data utilisation, and data ownership. These roles differ according to the current lifecycle phase.

3.5 Synthesis of the research contribution

In answer to the dissertation’s first research question, the barriers to implementing BIM were found to be:

- organisational and common process-related barriers
- resistance to change
- defects in interoperability
- ICT defects
- defects in training and knowledge.

It seemed that the use of BIM was not usually planned well in the early phases of projects, because the process and organisation for managing BIM-base project was ambiguous. Resistance to change, challenges in interoperability and defects in ICT and training also indicated that the planning of process and stakeholders’ communication at the start of the project was weak. Early involvement could have mitigated the barriers. The results provided the rationale for the second article’s research question: how does BIM support early involvement and vice versa?

Early involvement of key stakeholders facilitates prompt and effective optimisation of core competencies and knowledge. A collaboration model comprising all the design disciplines is a high-quality tool for ensuring early involvement and design quality. A visual collaboration model of the whole project, even in the very early phases of the project, provides an equal opportunity for all project stakeholders to evaluate the effect of design decisions. One common centre for information, with user interfaces for both reading and providing feedback, facilitates unlimited communication. Comprehensive virtual reality modelling and simulations (of, for instance, production, costs, energy consumption, CO₂ emissions, use of resources, operations, and maintenance) for the project provide an opportunity for even non-
technical stakeholders to estimate the feasibility of design decisions. Early involvement of key stakeholders enables early and effective utilisation of the core competencies and knowledge which also is needed in the design of the project data management. The results of the second article provided the rationale for the third research question: what are the benefits of early integration?

In this dissertation, BIM, integrated project delivery models, and DfX were studied as a means to enable early involvement and integration in construction projects. The early involvement and integration of stakeholders contribute collective knowledge and requirements (i.e. the relevant competencies) to the early design phase of the project. Integration encourages a collaborative culture and enhances project performance (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015). Early integration in relational contracting reduces fragmentation and improves efficiency and performance in complex customer projects (Davis & Love, 2011; Chen et al., 2012). DfX’s function is to improve communication in order to achieve stakeholder integration (e.g., Lehto et al. (2011)). The three first articles highlighted the barriers to the usage of BIM, explained how BIM supports early involvement and integration, and described the benefits early integration brings to construction projects. This framework led to the fourth and final research question: how can data management in infrastructure construction projects be organised?

Figure 12 presents a schematic diagram of how to organise and manage the data flow in infrastructure projects. The key element is that the data needs and deliveries in the project lifecycle are planned in the early phase of the project in collaboration with all relevant stakeholders. In other words, the project product data model should be designed at the beginning of the project latest at the beginning of the design phase. The data needs for the later phases of the project need to be designed at the beginning of the project. Otherwise, it might be difficult to produce the needed data.
Fig. 13. Data utilisation in a construction project's lifecycle can be enhanced through the early involvement and integration. The product data model for the project should be designed in the early phase of the project in collaboration with stakeholders. Integration improves communication and decreases fragmentation. Design for X concept can be used to help early integration. The project team’s capability level in BIM usage must be considered. Product data and information sharing is carried out using cloud technology. Data governance organisation controls data creation, data modification, data utilisation, and data ownership.

The aim of this dissertation was to clarify how data utilisation could be enhanced in the construction project lifecycle through early involvement and integration. In Table 10, there is a summary of the research contribution and Figure 13 provides a schematic diagram of the results of this dissertation. Based on the literature review, and the results of the dissertation’s case studies, data utilisation in a construction project’s lifecycle can be enhanced through the early involvement and integration of stakeholders. Early integration of key stakeholders leads to prompt and effective optimisation of core competencies and knowledge. Integration improves communication and decreases fragmentation. Design for X concept can be used to help early integration. Communication between all stakeholders should be enabled throughout the project lifecycle. The key element in organising data management is that the product data model for the project should be designed in the early phase of the project in collaboration with all relevant stakeholders, and also with the client. The project team’s capability level in BIM usage must be considered. Data deliveries need to be designed according to the team’s capability level. Product data and
information sharing is carried out using cloud technology. Data governance organisation control data creation, data modification, data utilisation, and data ownership.

Table 10. Summary of the research contribution.

<table>
<thead>
<tr>
<th>Research Question</th>
<th>Main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  What are the barriers to implementing BIM?</td>
<td>Organisational and common process-related barriers, resistance to change related barriers, interoperability or similar barriers, ICT related barriers and training and knowledge-based barriers.</td>
</tr>
<tr>
<td>II  How BIM supports early involvement and vice versa?</td>
<td>The characteristic features of BIM: information centre, collaboration model, simulations, and facilitate early involvement of key stakeholders. Early involvement of the key stakeholders improves the design of the project.</td>
</tr>
<tr>
<td>III What are the benefits of early integration?</td>
<td>More effective design, enhanced construction operations, and less bad quality. Early information about end-users leads to better product’s function and operation. Stakeholders actions meet better the purchaser’s needs and goals Early involvement empowers the exchange of ideas and enables innovative results. Early involvement enables synchronised tasks that run in phases. Integration improves communication and decreases fragmentation.</td>
</tr>
<tr>
<td>IV  How to organise data management in infra project?</td>
<td>Data needs and deliveries in the project lifecycle are planned in the early phase of the project in collaboration with all relevant stakeholders. The essential task is defining the product structure, product data, master data, and their lifecycle management. The purpose of the product data management process is to ensure evolutionary data storage and sharing for planned, designed, built, sold, used, and maintained built objects. Parallel systems (CAD, BIM, CRM, ERP), must comply and connect on one product data during the lifecycle. Data governance outlines the roles for data creation, data modification, data utilisation, and data ownership.</td>
</tr>
<tr>
<td>Research Question</td>
<td>Main results</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Overall contribution</td>
<td>The most significant barrier to achieving the benefits of BIM is the lack of proactive design of the process. There are challenges in the project data flow. The data utilisation in the construction project’s lifecycle can be enhanced through the early involvement and integration. DfX- concept helps the early integration. The project product data model needs to be designed in the early phase of the project. The project team’s capability level in BIM usage must be considered. Data governance outlines the roles for data creation, data modification, data utilisation, and data ownership.</td>
</tr>
</tbody>
</table>
4 Discussion

4.1 Theoretical implications

This dissertation discusses the foundations necessary for enhanced data utilisation in a construction project lifecycle. Features of early involvement and integration are studied and investigated regarding their role in enhancing data utilisation.

This dissertation provides a new contribution to existing scholarship by presenting how early involvement and integration is realised in construction projects using DfX—a method that was earlier used mainly in other industries. The early involvement of key stakeholders in the project aims to create a productive contribution of core competencies and knowledge. In turn, integration improves communication and decreases fragmentation performance (Davis & Love, 2011; Chen et al., 2012). This study clarifies the role of BIM in construction, illuminating the numerous and sometimes confusing set of BIM definitions to show BIM’s true versatility. BIM and building information modelling can be used as a tool, process, and data model. The project team’s skill level affects the planning of the data deliveries, and the user gains benefits when BIM is in collaborative use in the projects (Ashcraft, 2008; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Eastman et al., 2011). According to Succar (2009), the collaborative use of BIM requires a certain capability level that only can be reached by taking progressive technology, process, and policy steps from the initial BIM capability level (Succar 2009, 2010). Data play a crucial role, and, therefore, it is vital to understand concepts like product data, master data, and data governance. Data delivery must be planned to fit the project team’s competences. Master data concept has effect on how the data models are designed. BIM may include product data for instance in as-designed-models, as-built-models and as-maintained-models. The one master data makes it possible to use and share the data to all stakeholders and applications.

Moreover, it is essential to take care of the data quality (Godfrey, 2002) as bad quality data may jeopardise the whole system. Data governance outlines who creates, modifies, utilises, or owns the data (Cohen, 2006). This dissertation highlights the importance of product data, their management, and data governance roles in construction. In Table 11, there is a summary of the theoretical contribution of each article.
Table 11. The summary of the theoretical contribution of each article.

<table>
<thead>
<tr>
<th>Article # and title</th>
<th>Theoretical contribution</th>
<th>Implementations</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barriers for achieving benefits of BIM</td>
<td>The barriers to implementing BIM. The clarification of BIM definitions. The benefits of BIM for clients, owners, designers, and constructors.</td>
<td>Confirms that the overall berries of implementing BIM is inadequate planning of product data and its governance and implementation (Matthews &amp; Howell, 2005).</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The contemporaneous use of building information modeling and relational project delivery arrangements</td>
<td>The framework how BIM supports early involvement. The characteristic features of BIM. The characteristic features of integrated contract models. The benefits of simultaneous use of collaborative project delivery and BIM.</td>
<td>Confirms that BIM supports collaborative project delivery. Confirms that BIM support early involvement and integration and vice versa. (Ashcraft, 2008; Eastman et al., 2011; Sacks et al., 2010)</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early Involvement and Integration in Construction Projects: The Benefits of DfX in Elimination of Wastes</td>
<td>The benefits of early integration. The framework how DfX respond to the typical types of waste. The fundamental requirements for early involvement and integration. The typical types of waste in construction projects.</td>
<td>The new contribution is that DfX can be used in facilitating early involvement and integration in construction projects. Confirms the benefits of early integration (Aapaoja et al., 2013; Baiden et al., 2006; Ballard, 2008; Lahdenperä, 2012)</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managing data flows in infrastructure projects - the lifecycle process model</td>
<td>A framework how to organise data management in infra project. The cornerstones of data management over the project lifecycle. The main challenges in data flow of infra construction project lifecycle.</td>
<td>This dissertation confirms that there are challenges in the data flow (Love et al., 2008). Early integration of all stakeholders for product data model planning help data utilisation in construction project lifecycle (Love et al., 2008). Confirms that traditional project delivery types hinder data flow (Matthews &amp; Howell, 2005).</td>
</tr>
</tbody>
</table>
Enhancing Data Utilisation in the Construction Project Lifecycle through Early Involvement and Integration

The new contribution is that early planning of product data by all stakeholders improves data utilisation. Confirms early integration benefits in construction projects (Aapaoja et al., 2013; Baiden et al., 2006; Ballard, 2008; Lahdenperä, 2012). Confirms that the project team’s capability level needs to be considered (Succar, 2009, 2010).

In the first article, the objective was to investigate why BIM is not in wider use in the construction sector and why its benefits, as highlighted in the literature review, are being not gained. The study listed several benefits for different stakeholders in the construction project and classified the benefits for clients/owners and designers/constructors (AGC, 2006; Ashcraft, 2008; Azhar et al., 2008; Succar, 2009; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Arayici et al., 2011; Eastman et al., 2011; Khosrowshahi & Arayici, 2012; Wong & Fan, 2013; Vähä et al., 2013; Attarzadeh et al., 2015; Nath et al., 2016). Overall, barriers related to poor planning of the organisation and workflow of the project, resistance to change, and ICT. It was found that clients and owners are more conservative than designers and constructors. Moreover, the article examined the many definitions of BIM (AGC, 2006; Eastman et al., 2008; Succar, 2009; Calvin, Senaratna, Xiao & McKinney, 2013) and highlighted the importance of the project team’s maturity to apply BIM (Succar, 2009).

The second article investigated the outcomes of the simultaneous use of BIM and relation project delivery arrangements, like IPD. The study summarised the characteristic features of BIM (Azhar et al., 2008; Succar, 2009; Eastman et al., 2011; Laine et al., 2014) and relational projects (Dowlatabadi, 1998; Love et al., 1998; Moore & Dainty, 2001; Kent & Becerik-Gerber, 2010; El Asmar et al., 2013). The study concluded that BIM is a tool that supports the aims of relational project deliveries. An important feature of relational projects is early involvement and integration, and, according to the study, BIM supports early integration either well or very well and vice versa, early integration improves the design of project.

The third article concentrated on the benefits of early integration and introduced a new tool for construction projects to enable early integration. DfX (Bralla, 1996; Möttönen et al., 2009; Lehto et al., 2011) is commonly used in manufacturing,
and the study showed that it is useful for reducing waste in construction projects as well. According to the study, major sources of waste in construction are inadequate communication and documentation, making wrong products or services, defects, people’s unused potential, and unnecessary transportation. The study showed that the fundamental requirements for early involvement and integration are relational project delivery, like IPD, and inter-organisational integration. DfX is a management method for organising the design requirements of internal tasks and outside supply chain partners.

In the fourth article, three case studies of construction projects that represented three different project delivery types revealed several challenges in construction projects’ data flow. The findings showed that the main reason for challenges on site was the lack of proper planning of stakeholders’ data needs covering the whole lifecycle; often, the needed data are missing or in the wrong format. Resistance to change is another significant challenge. For example, useful 3D data was printed on 2D pdf files because that is the way the designs have ‘always’ been handled. The efficient use of data offers opportunities for significant improvements in industry, supply chain, or business level (HM Government, 2015). Data and information are the basis of business processes and value chains, and the quality of data is essential (Godfrey, 2002). Moreover, while it is vital to identify the product data, master data, and transfer data, data governance structures are not in place in construction organisations. However, it is useful to have a clear definition of who produces, modifies, utilises, or owns the data and how these roles change in different lifecycle phases (Cohen, 2006). The correct and updated data concerning the object forms the foundation for the whole project. However, individual stakeholders require different kinds of data, which need to be delivered at the appropriate phase in the right format. Therefore, there need to be different viewpoints available on the object data, like as-planned, as-built, as-utilised, and as-maintained to serve business and supply chain needs (Silvola, 2018).

The main contribution of this study is that it identifies a need to design a project product data model in the early phases of the project, according to the information of all stakeholders. It is essential to design the project product data model latest at the beginning of the design phase. There are several BIM execution plan-templates available, but like the case studies show they have not improved the data flow in practice in infra construction projects. General templates seem to be insufficient. Instead, the project product data model is better to design specially for each unique project that matches the capability level of the project team, available data, software and hardware, project delivery type, and team motivation. Early involvement and
integration can enhance data utilisation in the construction projects’ lifecycles. This study verifies early integration benefits in construction projects (Baiden et al., 2006; Ballard, 2008; Lahdenperä, 2012; Aapaoja et al., 2013). One master data enables data sharing with different applications. Furthermore, while it is essential to identify the product data, master data, and transfer data the data governance structures also need to be in place in construction projects. However, it is useful to have a clear definition of who produces, modifies, utilises, or owns the data and how these roles change in different lifecycle phases (Cohen, 2006). Design for X (DfX) can be used for early integration. The client is responsible that the project delivery agreements support the well-organised use of data and information flow throughout the project’s lifecycle. This study also highlights the importance of considering a project team's capability level in BIM so that the team can effectively use the designed data and applications (Succar, 2009, 2010). The most significant barrier for achieving the benefits of BIM is that the data needs and the overall process of BIM utilisation are not planned proactively. The data needs for all stakeholders in all project phases need to be designed in the early phases of a construction project. Early involvement and integration of all stakeholders are essential for succeeding.

4.2 Practical implications

This dissertation’s aim is to study data utilisation in construction project lifecycles and its enhancement through early involvement and integration. The study’s empirical section exposed barriers in the usage of BIM and challenges to data utilisation in three case study projects. The contributions highlighted in the previous section innovate several practical implications that might improve productivity in the construction sector.

Data utilisation in construction project lifecycles needs to be planned proactively. The improvement ideas outlined in these articles can be divided into these eight implications:

1. The project product data model, project delivery process and data deliveries should be planned at the beginning of the project, together with all the relevant stakeholders.
2. The project delivery method needs to enable free data flow. The client has a role in how to enable data flow. Whereas in traditional project deliveries separate agreements might hinder data flow, DfX helps to organise proper planning and agreements to aid fluent data flow.
3. It is useful to nominate a data governance organisation and train the project team in it at the beginning of the project. There must be responsible persons or teams to take care of data steward, data owner, data manager, and data user roles in the project.

4. Data can be shared efficiently using cloud technology, and all relevant data should be available to the whole project team.

5. The capability level of the project team needs to be measured, and data delivery adjusted to support the team’s skills in using different kinds of data and software applications. If the project team’s capability is, for example, at level one (Succar, 2010), then the project cannot use collaborative BIM without taking technology, process, and policy steps.

6. The software used should be assessed in each lifecycle phase. Is the software suitable for the agreed capability level and lifecycle phase? For example, design software is not always the best tool for finalising constructible models for automated machinery.

7. There are several innovations to digitise and improve maintenance operations, like the use of IoT. The planning of the digital maintenance process is essential at the beginning of the project.

8. The efficient maintenance of structures needs digital information of the structure’s geometry and detailed information of all the material and equipment installed in the facility.

The planning of the project delivery process and data deliveries at the beginning of the project, together with all relevant stakeholders, is essential. The design of data deliveries should be sufficiently detailed; it is essential to have precise requirements from the receiving stakeholder regarding what data, at what accuracy level, and in which format the data is delivered. Well-documented open BIM transfer files (IFC, LandXML) are a good starting point for data deliveries. Sometimes these open standards do not cover all the transfer needs, and the format must be agreed separately. Integrated project delivery models make it possible for stakeholders to design data deliveries and formats early in the project in cooperation with other stakeholders. In traditional project deliveries, the client plays a crucial role in arranging the planning of data organisation and data deliveries from relevant stakeholders at the beginning of the project. The client must find a way to facilitate cooperation between all the lifecycle phases, although design, construction, and maintenance operators have separate agreements. However, the DfX concept provides a useful guideline for how to provide data needs from different stakeholders. In DfX, X can
refer to designing, construction, maintenance, or operation. After the data deliveries are planned, the actual data sharing in projects is efficient to do using internet-based cloud technology.

In other industries, the data governance organisations and tasks are clearly delineated, which should also be possible in construction projects. Table 12 suggests possible data governance roles in a construction project. According to Cohen (2006), data stewards take care of data governance policy and advise data owners and data managers how to apply those rules. Data stewards develop, monitor, and control policies for data, serving as overall coordinators for enterprise data delivery efforts. The data steward can be one person or a stewardship committee. Data owners, who are data stewards’ co-workers, are primarily responsible for defining enterprise information requirements. Every business function has a data owner, who develops standards for the storage, retention, and disposal of corporate information. Data owners ensure information quality and availability, continually improving the data flow and measuring the performance. Data managers, also known as custodians, carry out the data delivery function. They work closely with the data stewards and data owners to implement data governance policies. There are several data managers in an organisation; they work with users to help them with current applications and technology and are responsible for gathering process improvement ideas. On the technical side, data managers follow the policies defined by data owners, and they capture, store, retain, and dispose the enterprise’s information. They also design the technical infrastructure according to data owners’ information requirements. Though data users are not part of the official data governance organisation, they are an essential part of the system because all the policies, requirements, delivery mechanisms, and technical architecture designs are made for them. Without users, there would not be a need for data governance; the desires of the user community drive the need for data governance (Cohen, 2006).
Table 12. A suggestion for data governance roles in construction projects.

<table>
<thead>
<tr>
<th>Project Phase / Role</th>
<th>Preliminary Planning</th>
<th>Design</th>
<th>Construction</th>
<th>Operation</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Steward</td>
<td>Client's BIM-consult</td>
<td>Client's BIM-consult</td>
<td>IT Manager / Development Manager / BIM-consult</td>
<td>Owner's IT Manager</td>
<td>Owner's IT Manager</td>
</tr>
<tr>
<td>Data Owner</td>
<td>Client's Department Leader</td>
<td>Designer's Department Leader</td>
<td>Principal Designer / Data Model Coordinator / Client's Project Manager / Contractor's Project manager</td>
<td>Owner</td>
<td>Owner</td>
</tr>
<tr>
<td>Data Manager</td>
<td>Principal Designer of Preliminary Planning / Project Manager</td>
<td>Principal Designer / Project Manager</td>
<td>Measurement Foreman / Site Engineer</td>
<td>Owner's Traffic Manager</td>
<td>Maintenance Foreman</td>
</tr>
<tr>
<td>Data User</td>
<td>Pre-engineer Designer</td>
<td>Foreman / Site Foreman</td>
<td>Traffic Contractor</td>
<td>Maintenance Workers</td>
<td></td>
</tr>
</tbody>
</table>

The capability level of the project team needs to be measured and data delivery adjusted to support the team’s skills in using different kinds of data and software applications. For example, to use BIM on level two (Succar, 2010) sets strict requirements regarding technology, process and policies. It requires that all design disciplines are modelled so that it is possible to produce one collaborative model and that proprietary software is used to locate clashes and other design mistakes and produce 3D models and 4D simulations. It is critical to validate and properly choose the software that each stakeholder uses in each phase of the project. The software needs to be suitable for the specific lifecycle phase on the agreed capability level. For example, basic design software is not always the best tool for finalising constructible models for automated machinery. The project team needs to be trained in the required process, technology in use, and project policies.

Several innovations exist to digitise and improve maintenance operations, like IoT. The planning of the digital maintenance process is essential at the beginning of the project so that the implementation and replacement of sensors (for humidity, pressure, temperature, etc.) is planned optimally and the construction stakeholders have instructions for the implementation and documentation. The efficient digital maintenance of structures requires digital information of structure’s geometry and detailed information about all relevant material and equipment (structures that need
maintenance) that are installed in the facility. Information about the organisation responsible for the installation, how to order spare parts, and maintenance is essential. A digital model of the build object a ‘digital twin’ can help to monitor the sensors’ information and maintain the facility.

4.3 Reliability and validity

This dissertation discusses BIM, product data, early involvement, and integration to create a model of how to plan and enhance data utilisation in a construction project’s lifecycle. The history of BIM started in the 1970s, though data modelling started in the 1960s. Many earlier studies discuss the theoretical framework of this study. The new information offered in this dissertation, which contributed to enhancing data utilisation, is based on qualitative studies. Saunders et al. (2009, p. 603) describes validity as “(1) the extent to which data collection method or methods accurately measure what they were intended to measure. (2) The extent to which research findings are really about what they profess to be about”. Saunders et al. (2009, p. 600) defined reliability as “the extent to which data collection technique or techniques will yield consistent findings, similar observations would be made or conclusions reached by other researchers or there is transparency in how sense was made from the raw data”. Lancaster (2005) explains validity in a similar way as the level at which data collection and research methods define what they are intended to define. The researcher must measure to the range at which a method of the data collection will yield data that are valid. However, validity is a versatile concept, and there are many types of validity, including: ‘content validity’, ‘predictive validity’, ‘concurrent validity’, ‘construct validity’, ‘face validity’, ‘internal and external validity’, and ‘statistical validity’. Lancaster (2005) states that reliability is valid when a specific data collection method will deliver the same results on different occasions. A precondition is that there are no real changes in the target measured or in the conditions of such measurement. Discussing trustworthiness, Gunawan (2015) maintains that research is trustworthy only if the reader decides it to be so and that validity in qualitative studies cannot be linked to truth or value as they are for positivists. According to Gunawan (2015) trustworthiness can be divided into four categories: credibility, which matches roughly with the positivist concept of internal validity; dependability, which is closer to reliability; transferability, which is an instance of external validity; and confirmability, which is mostly an issue of presentation. Shenton (2004) also discusses the trustworthiness of qualitative research, stating that it is often questioned by positivists perhaps because
their ideas of validity and reliability cannot be met in the same ways as in naturalistic work. However, qualitative researchers can incorporate measures to mediate these issues. Yet many naturalistic researchers have favoured using different terminology to distance themselves from the positivist paradigm.

In this study, we evaluate reliability and validity using Bryman & Bell (2003) approach. According to Bryman & Bell (2003), the reliability and validity of qualitative research can be assessed by answering these four questions:

1. What is the trustworthiness of the results?
2. Are the results valid in a different environment?
3. What is the repeatability of the observations?
4. What was the impact of the researcher’s values on the results?

When discussing the trustworthiness of the study results, we can say that the results correspond to the real world. The study consisted of several case studies and followed the theory of qualitative research methods. Several interviews were also conducted. First, empirical research was based on expert focus group sessions using Ishikawa diagrams. Other interviews were made using semi-structured methods, allowing fluent interaction between the researcher and interviewee and leaving opportunities for the interviewee to clarify the topics in his or her own words. In this study, the results corresponded with the literature review theories, providing new insight into aspects of construction project processes.

The validity in the case study interviews was planned to be as high as possible, and the interviewees were self-selected to provide the best insight into the studied phenomena. The non-probability sampling approach was chosen (Saunders et al., 2009). In the focus group interview, the interviewees each represented a different phase of the construction lifecycle, having different roles as well. The aim was to better understand the barriers that prevented the BIM benefits described in the literature from being gained in practice. The interviewees’ experience indicated that the researcher could expect to have correct information about real-life projects. In the semi-structured interviews concerning project data flow, project managers with extensive experience of the construction projects were selected. The project managers’ experience was only from Finland, which must be considered, especially if applying these results to other countries. The project managers had experience of various project delivery types, which improved the validity of the results.

The methods used can be repeated and the results collected in the same way. While the studies can be repeated, the case studies’ results may vary depending on
the specific interviewee’s opinions. The interviewees in this study had strong experience in construction, and another interview with a specialist with the same long experience may produce similar results. However, it is important to realise that conditions are different in each country. Digitalisation rates, the use of legacy applications, and work procedures with different legislation concerning commercial model project delivery systems in construction may affect the results.

The researcher conducted the interviews. As Ishikawa diagrams are well structured, they provide little space for research influence. In semi-structured interviews, the interviewees checked the transcribed interview documents, which allowed little room for the interviewer’s own thoughts. The researcher tried conscientiously to avoid influencing the interviewees’ opinions. The interviewees asked questions about the topic, and, therefore, the researcher could influence the results, but the risk is quite small. The interviewees were mostly selected as experienced professionals with well-developed thoughts on the topic, which improved the value of the results.

4.4 Recommendations for further research

The outcomes of this study generate ideas for further research. The research project can be categorised under topics such as project product data design, delivery systems, BIM capability level, data governance organisation and tasks, data sharing technology and guidelines, and, finally, clarification of the digital twin concept.

It is essential to design the project product data model latest at the beginning of the design phase. Future research could investigate how the design is organised in different project delivery types. Traditional DBB is most challenging because all project phases’ stakeholders are not yet agreed. There are several BIM execution plan -templates available, but like the case studies show they have not improved the data flow in practice in infra construction projects. General templates seem to be insufficient. Instead, the project product data model is better to design specially for each unique project that matches the capability level of the project team, available data, software and hardware, project delivery type, and team motivation.

Future research could further explore the development of project delivery types. Traditional project delivery types, like DBB, are currently the most common delivery type, but they have many shortcomings related to liability issues and enabling early involvement and integration. However, there are success stories of the usage of alliancing and IPD, which perfectly allow collaboration, early involvement, and free data flow. If integrated project delivery models cannot be used in all projects,
including in small projects, it would be profitable to further develop the DBB project delivery system. The shortcomings could be overcome by, for instance, combining DfX features and the bidding process.

According to Succar (2010), it is essential to understand the project team’s BIM capability. If the project management is expecting benefits from the collaborative use of BIM, the team’s skill level should be at the required level. Otherwise, the expected results cannot be obtained. Capability levels consist of technology, process, and policy aspects. One reason for unsatisfactory results in using BIM might be that the project team’s skill levels are not at required level. A future research project could suggest capability requirements for each capability level and procedures for how to measure capability and maturity stages and to train teams to advance in capability levels.

It is critical that in BIM-based construction projects, data organisation is in place. Data steward, data manager, data owner, and data user roles should be specified. A future research project could clarify the tasks of these roles in detail for construction project contexts and suggestion how these roles are nominated.

Another research project could clarify data sharing process in construction projects. Data management procedures should be developed from databases and document data banks to cloud-based technology for product data sharing.

Digital maintenance systems are based on a digital model of the build object. This model is often called a digital twin of the facility. It would help to plan the data deliveries during construction lifecycle so that all the relevant digital information, including sensors, is available when the maintenance and operation phase starts. The expression digital twin is often used in connection with construction digitalisation, and clarification of what it means in construction would be beneficial. For example, in buildings, it would be useful to have recommendations what the digital twin is of a building. In infrastructure construction, a schematic model for the digital twin for highway, street, tunnel, bridge, and intersection would ease the stakeholders’ data utilisation planning when the final goal is determined at a general level.
5 Summary

Project productivity has not developed as well in construction as in other sectors. One factor contributing to this low productivity is the weak digitalisation intensity of the construction sector. Studies have shown that companies that have digitalised their operations and succeeded in transformational projects have increased revenue, profitability, and market value (Westerman et al., 2012). The construction industry is ripe for change. Major projects take, on average, 20% longer than planned and costs are often exceeded by 80% (Agarwal et al., 2016). The implementation of construction projects is fragmented, and the objectives of individual project stakeholders may conflict with those of the whole project (Aapaoja & Haapasalo, 2014). Significant attention has been paid to the use of BIM in the construction industry, which is seen as an essential element in connecting fragmented stakeholders, addressing gaps in information management, improving quality, and streamlining processes (Ashcraft, 2008; Eastman et al., 2008; Succar, 2009; Becerik-Gerber & Rice, 2010). The purpose of this dissertation is to investigate how early the involvement of different stakeholders and the integration of stakeholder activities can improve project data utilisation. This study is a qualitative case study consisting of a literature review, focus group interviews, survey, and interviews.

The theoretical groundwork of this dissertation is founded on these main concepts: BIM, product data, DfX, early involvement, and integration. These concepts are applied to form an accurate and adequate understanding of data utilisation, how early involvement and integration affect it, and what mechanisms enable early integration in construction projects. Eastman et al. (2008) observe that BIM generates new opportunities for relations and roles in projects. If it is applied correctly, BIM allows for more integrated design and construction tasks, resulting in shorter schedules, better quality, and fewer costs.

In general, the abbreviation BIM is understood to refer to modelling technology with processes to analyse, communicate, and develop building models. The proper use of BIM brings several benefits to construction projects, including the facilitation of efficient collaboration, the use of Alliance/IPD, lower CO2 emission, more sustainable construction, better construction procedures, improved data and information flow, better quality, cost savings, shorter project timelines, efficient model-based maintenance, and faster commissioning (AGC, 2006; Ashcraft, 2008; Azhar et al., 2008; Succar, 2009; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Arayici et al., 2011; Eastman et al., 2011; Khosrowshahi & Arayici, 2012; Vähä et al., 2013; Wong & Fan, 2013; Attarzadeh et al., 2015; Nath et al., 2016).
BIM can be understood to mean model, tool, or process. According to Azhar et al. (2008), BIM models can be used as a tool for facilities management, forensic analysis, 3D visualisation, fabrication/shop drawings, code reviews, cost estimating, and construction sequencing, as well as conflict interference and collision detection. BIM can also facilitate the use of IPD (Ashcraft, 2008; Sacks et al., 2010; Eastman et al., 2011). According to Succar (2009, 2010), the implementation of BIM can be divided into capability stages: pre-BIM, object-based modelling, model-based collaboration, network-based integration, and post-BIM stage. An organisation can proceed in capability stages only by taking technology, process and policy steps. The user gains benefits when BIM is in collaborative use in projects (Ashcraft, 2008; Grilo & Jardim-Goncalves, 2010; Sacks et al., 2010; Eastman et al., 2011). All parties involved in the project should use BIM, and there should be a plan, with clearly assigned roles, on how to create and maintain the BIM model of the project, covering all lifecycle phases. Product data, master data, and product data lifecycle management are also essential for the construction industry to improve data and information management. The construction industry should also adopt data governance organisation. The basis in data management is the object that is first created and then altered in different lifecycle phases. The process, composed of different lifecycle phases, should handle the same information throughout the lifecycle. In the product data management, the master data term is essential. The master data defines business objects and how they are characterised in various ICT systems (McKeen & Smith, 2007).

DfX is a set of tools that can involve main stakeholders in the initial phase of a project. In the DfX concept the design is considered from different aspects (X) like lifecycle phase, or a specific stakeholder (Bralla, 1996; Möttönen et al., 2009; Lehto et al., 2011). DfX assists with functional integration, creates competence, and obtains the best capability for the project (Ulrich & Eppinger, 2008). Early involvement of all the stakeholders in the design phase improves the likelihood of a more effective design, enhanced construction operations, and less scrap (Dowlatabadi, 1998; Valkenburg et al., 2008). Moreover, early involvement empowers the exchange of ideas and enables innovative results. Project integration guarantees that the numerous actions within a project are properly coordinated (Kirsilä et al., 2007).

According to the results of this study, the most significant barriers to using BIM are organisational and related to common process. The second largest barrier is resistance to change. To answer this study’s second research question, BIM effectively supports early involvement and integration. However, in the design of data
management, it is critical that the data needs and deliveries in the project lifecycle are planned in the early phase of the project in collaboration with all relevant stakeholders. Overall, this dissertation demonstrates that data utilisation can be improved by planning the project information management process in the early stages of the project, together with all relevant stakeholders. The project delivery type should support the efficient use of data and information throughout the project's lifecycle. Where necessary, early involvement can be encouraged. The client can require the planning of the data needs for all the lifecycle phases early in the project. At the same time, when planning the project's information needs and its implementation, the project team's level of expertise must be considered. Effective digital project maintenance requires that during the design and construction phases, the relevant digital information is collected according to the maintenance stakeholders’ requests.
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