Master Thesis – Master Sustainable Business and Innovation

Facilitating the Digital Transformation of Building Design and Engineering Companies by Transferring Knowledge across Projects

A new approach to implementing 'Building Information Modeling' (BIM)

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List of Acronyms

AECO	Architecture, Engineering, Construction and Operations
BIM	Building Information Modeling
DT	Digital Transformation
KBS	Knowledge-Based System
KM	Knowledge Management

Abstract

Digital technologies provide new opportunities for building design and engineering companies which have a fundamental need to change toward *Digital Transformation* (DT). Many experts and industry practitioners consider *Building Information Modeling* (BIM) to be a key technology to catalyze this transformation. BIM is a shared knowledge resource and a digital representation of all the physical and functional characteristics of a building. However, the way how companies integrated BIM to stimulate significant change has not been sufficient. In order to facilitate the DT of building design and engineering firms, a new approach to implementing BIM is needed.

A fundamental shortcoming of the industry is that the knowledge acquired during a project is not used in other projects or other contexts. As each new project is started, there is a tendency to solve many problems once again and make mistakes that have been made previously, rather than learn from the experiences of other projects. This paper argues that BIM has the potential to facilitate the DT of building design through its opportunities for knowledge transfer across projects.

Insights from industry practitioners in the Netherlands are used to develop a novel approach for BIM-based knowledge management. Therefore, the operating principles of an intelligent computer program – a *Knowledge-Based System* (KBS) – are developed. The system allows users to effectively transfer and access the knowledge gained throughout other projects and has been captured in the BIM models and (re)use it in future projects.

Keywords: Digital Transformation, Building Information Modeling (BIM), Building Design, Knowledge Transfer, Knowledge-Based System.

Executive Summary

The *Digital Transformation* (DT) is a key concern for Arcadis in order to become a digital frontrunner of the *Architecture, Engineering, Construction and Operations* (AECO) industry. Many experts and industry practitioners consider *Building Information Modeling* (BIM) to be a key technology to catalyze this transformation. BIM is a shared knowledge resource and a digital representation of all the physical and functional characteristics of a building. Therefore, Arcadis is committed to achieving 100% BIM on all relevant projects. Nowadays in the Netherlands, BIM is applied in most new projects of the company. Nevertheless, significant change in internal processes and external relationships, enabling innovation and creativity has remained limited; hence, the company has not undergone DT, yet. Thus, to facilitate the DT of the building design and engineering firm, a new approach to implementing BIM is needed.

A fundamental shortcoming of the industry is that the knowledge acquired during a project is not used in other projects. At the same time, not all for other project teams potentially useful data, information and knowledge (*project knowledge*) are stored digitally in BIM models. As each new project is started, there is a tendency to solve many problems once again and to repeat previously made mistakes, rather than learn from the experiences of other projects. This study argues that BIM has the potential to facilitate the DT of building design through its opportunities for knowledge transfer across projects. Hence, this research was conducted to provide recommendations on how BIM can enable this cross-project knowledge transfer in order to facilitate the Digital Transformation of Arcadis.

Only a few scientists have attempted an integrated analysis of BIM in the realm of *Knowledge Management* (KM). Moreover, whether the BIM-based transfer of knowledge across projects actually facilitates the Digital Transformation of building design and engineering companies has not been studied in particular. Hence, this research compares the opinions of industry practitioners working on projects that are applying BIM. This study suggests addressing the knowledge demands during the design process through a *Knowledge-Based System* (KBS) – a computer program which combines knowledge, makes it accessible in a comprehensive manner, and reusable in an easy way.

Research was done between December 2018 and July 2019. The subject matter was analyzed with the help of sixteen interviews with employees of the focal firm, and a focus group of two 'BIM managers'. The similarities and differences between the various interview answers were compared to derive (a) to what extent the knowledge stored in BIM models is useful for other projects, (b) how an ideal Knowledge-Based System would function in order to make knowledge stored in BIM accessible and (re)usable, and (c) in which ways BIM-based Knowledge Management could imply DT of a building design and engineering firm.

By comparing the findings from the interviews and the focus group with insights from BIM research, KM and organizational studies, this thesis provides important recommendations to Arcadis as to how the company can enable the cross-project knowledge transfer, and in turn, facilitate the DT of the company.

Recommendations

A KBS forms one of the three basic components for successful KM – the (technology) infrastructure for knowledge sharing. The findings, however, make clear that a KBS for transferring knowledge across projects cannot exist without the other two components – first, an organizational culture of awareness, and second, organizational processes to capture success and failure – being fulfilled simultaneously.

In a company in which the first component is fulfilled, the awareness for KM and BIM is high and an organizational culture of talking about failures in a positive way is embraced. To achieve this, the findings suggest that the benefits of BIM and the Digital Transformation are communicated within and outside of the company. In doing so, connected fears of employees about the entailing changes are addressed.

In an organization which fulfills the second component, organizational processes (workflows and automated procedures) to capture *project knowledge* are put in place. To some extent, these processes were already present at the focal firm. However, the findings show that a substantial amount of useful *project knowledge* was not captured; hence, for the proposed KBS to be successful, it is advised to adapt current processes. Also, for fulfilling the second component, subjects like scheduling and cost calculation are linked to BIM models. After all, the aspiration of BIM is it to link the 3D model of a building to a relational database that (in theory) captures everything known about the asset. Thus, ultimately, all data generated throughout a project is stored in one place and added to or linked to the project's BIM model in the KBS database.

Already at the start of a project, key parameters could be added to make the project's new knowledge accessible to all employees as soon as possible. Over the course of a project, new project specific knowledge is added and kept up to date. To facilitate the maintenance and updating of information in the KBS, it is advisable to automate as much of this process as possible, so employees do not have to add and update information manually. For example, the history of an element with name and contact of the originator could be saved by the design and modeling program automatically.

As discussed in this research, standards define what *project knowledge* is captured and its minimal level of detail required. Organizational processes are adapted accordingly. Moreover, new business models are developed to collect information on the operations of finished buildings as this is useful information for future projects; thus, it is suggested to make this information accessible via the KBS.

The ideas described in this research can be implemented as follows:

1. Raise awareness for KM and BIM and embrace an organizational culture of talking about failures in a positive way. This measure continues throughout the whole process.
2. Agree on a standard for what project and element specific knowledge is captured and at what level of detail.
3. Adapt organizational processes to capture (and validate) useful *project knowledge*.
4. Secure funding and human resources to develop the proposed KBS. For the initial setup, at least two people – one for programming and one for communicating the KBS inside the company – are deemed adequate.
5. Develop and implement the KBS in all company locations in the Netherlands.
6. Raise awareness for the developed KBS and provide trainings if necessary.
7. After this, the knowledge generated in all projects is accessible to all employees in the Dutch part of the organization.
8. Implement the KBS in the company's offices in other countries.
9. Continue developing the KBS (and new business models) to be able to include further useful *project knowledge* and extend the KBS with design assistance functionality to stay ahead of competitors.

Conclusion

The international building design and engineering firm Arcadis has much potential for achieving effective Knowledge Management, and in turn, facilitate the Digital Transformation of the firm. Arcadis faces some challenges regarding the implementation of the proposed KBS. By creating a core team which is concerned with Knowledge Management and connected issues and is supported by the higher management of the firm, more concrete results can be obtained. It is important to set specific goals and discuss the various perspectives of participating stakeholders both within and outside of the organization. There is a large potential for Arcadis to make a profound impact and to become a digital frontrunner of the AECO industry. By enabling the transfer of knowledge across projects, the company is one step closer to achieving DT.

1 Introduction

"The strength of digital technologies ... doesn't lie in the technologies individually. Instead, it stems from how companies integrate them to transform their businesses and how they work."

Gerald C. Kane, professor of information systems at Boston College, July 14, 2015.

1.1 Background of the Research and Problem Description

The exploitation and integration of digital technologies can affect large parts of a company, by impacting products, business processes, sales channels, and supply chains (Matt *et al.*, 2015). According to Knobel (2008), *Digital Transformation* (DT) is achieved when digital technologies enable innovation and creativity and stimulate significant change within the professional or knowledge domain. Likewise, there have been major innovations in the past, like the steam engine in the 18th century, which dramatically transformed economies and societies. Yet, it is still unclear whether DT is a brand-new phenomenon and/or whether existing assumptions made in extant research still hold true (Lanzolla *et al.*, 2018).

As evoked by the steam engine, entire business models can be reshaped or replaced as industry sectors are undergoing drastic change processes through DT (Downes & Nunes, 2013). The *Architecture, Engineering, Construction and Operations* (AECO) industry is exemplary for an industry that has been reluctant to change to DT in the past (McKinsey, 2016). This was due to its old-established market structures in which different stakeholders are highly dependent on each other at project-based collaboration (McKinsey, 2016). Compared to other industries, AECO has not seen a rise in productivity because of its slow DT adoption (Frost & Sullivan, 2018).

However, in recent years, the AECO industry has gained momentum for the change toward DT. Many experts and industry practitioners consider *Building Information Modeling* (BIM) to be a key technology to catalyze this transformation (Vilutiene *et al.*, 2018; Bernstein, 2005). The National Institute of Building Sciences defines BIM as "a digital representation of [all the] physical and functional characteristics of a facility", and it is a "shared knowledge resource" for the facility's related lifecycle information, "forming a reliable basis for decisions … from earliest conception to demolition" (NIBS, 2019). It extends *Computer-Aided Design* (CAD) technologies by linking the 3D built asset model to a relational database that (in theory) captures everything known about the asset, a platform for different project members and stakeholders to communicate, generate, exchange and manage information (Waterhouse, 2013; Liu *et al.*, 2013). At its full realization, BIM is an integrated collaborative tool supporting both data interoperability and lifecycle management (Davies *et al.*, 2015).

Therefore, BIM forms the foundation for the much needed innovation (e.g. virtual reality applications) and improved business performance the industry requires (Kivits & Furneaux, 2013; Chinowsky *et al.*, 2007; Yang *et al.*, 2012) and thus, can bring about important economic and societal advantages (Agustí-Juan *et al.*, 2019). Building designers and engineers in particular use the analytical abilities of BIM to assess e.g. environmental impacts, and increase resource and energy efficiency. Hence, BIM can lead to the direct improvement of sustainability on different levels: from materials to production, from project planning and conceptual design to communication between different projects and stakeholders (Agustí-Juan *et al.*, 2019). This means that BIM can contribute to a low-carbon transformation and a revitalization of the building sector (Agustí-Juan *et al.*, 2019; Klotz *et al.*, 2009), which are key components of the EU Roadmap 2050. Given these benefits, a number of governments, including those in Great Britain, the Netherlands, Finland, and Singapore, mandate the use of BIM for public infrastructure projects (McKinsey, 2016).

Building design companies all over the world are involved in construction projects from the beginning on and, on behalf of the building owner, often supervise projects until the finished building is handed over. As the first link in the chain, steps towards DT in the AECO industry typically affect the design process first. Accordingly, design firms were the introducers and first users of BIM. Therefore, studying such a company provides best insights on DT of the AECO industry. BIM has been prevailing since the early 2000s; however, the way how building design companies integrated BIM to transform their businesses and how they work has not been sufficient for Digital Transformation. In most projects, BIM is solely used as a replacement for CAD software. For a short time, though, the new technology is used to support collaboration in first projects. However, this is still far from BIM's full realization as an integrated collaborative tool linking all the knowledge about a building to its 3D model and supporting all phases of a building's lifecycle – beyond the design and construction phase. Nevertheless, the knowledge stored in BIM models has covered more and more knowledge aspects (e.g. costs and time scheduling) over the last years, and BIM models are already forming a reliable basis for decisions until project completions.

To facilitate the DT of building design and engineering firms, BIM as a centralized and shared knowledge resource could be leveraged for the acquisition and the management of important knowledge obtained in a firm's diverse projects (Deshpande *et al.*, 2014). This unprecedented opportunity may lead to major changes in the internal processes of building design companies, their external relationships and their capability to innovate and be creative, thus, it could facilitate their DT.

Problem Description

The knowledge generated throughout the lifecycle of a project is one of the most important assets of a building design and engineering firm. Effective capture, storage, dissemination, design on and reuse of this knowledge are critical for the successful execution of projects and are thus vital for the competitive advantage and survival of building design and engineering firms (Tserng & Lin, 2004). Nevertheless, achieving effective *Knowledge Management* (KM) is challenging for those firms for several reasons.

New knowledge is usually created by temporary teams and stakeholder constellations that come together for a project. For decisions on projects, feedback from other team members, departments or stakeholders is required, resulting in inefficiencies and delays. At the same time, every project generates specific hands-on experience, problem solving capabilities, understanding of various means and methods and highly contextualized solutions (Lin *et al.*, 2005). When the project-team is dissolved after the completion of the project, the knowledge gained collectively is scattered across teams and organizations (Fong, 2005). Likewise, the data generated through the project are typically stored fragmented and scattered across departments in multiple file formats, making it difficult to capture, catalog and disseminate knowledge effectively (Deshpande *et al.*, 2014). Therefore, knowledge acquired during a project is not used in other projects or other contexts. As each new project is started, there is a tendency to solve many problems once again and make mistakes that have been made previously, rather than learn from the experiences of other projects (Prusak, 1997; Ho *et al.*, 2013). The KM challenges for AECO organizations to transfer knowledge across different projects may be similar to those for other business organizations. However, since the business of those companies is usually in response to a client's request for a facility, KM needs to focus on increasing the organization's ability to bid for, and win contracts, as well as make a profit after the completion of the project (Kamara *et al.*, 2002).

BIM models are assumed to be effective in communicating and preserving knowledge across different projects (Dave & Koskela, 2009). They can be effective in this regard because they span and evolve throughout the entire lifecycle of a project. Therefore, knowledge which is created once could be reused many times. Moreover, BIM models can provide a platform to integrate the dispersed construction information with the data rich three dimensional representation of facilities (Goedert & Meadati, 2008).

1.2 Knowledge Gap

This research helps to fill at least two knowledge gaps. First after a literature review, it gave a general definition of DT and provides a better understanding of DT in a building design and engineering company. Second, it was extensively researched how the DT of such a company can be facilitated by transferring the knowledge stored in BIM models across projects. KM has received significant attention from the AECO industry and the construction research community world-wide over the last two decades (e.g. Carrillo *et al.*, 2003). However, perhaps because of the complex interdependencies in the project-based industry, only a few scientists have attempted an integrated analysis of KM. Generally, previous studies assume that digital technologies, if used in con-junction with KM, have the capability of positively influencing project performance (Yang *et al.*, 2012). Though, the abilities of BIM-based Knowledge Management to digitally transform building design and engineering companies have not been studied in particular. Hence, this research compares the opinions of industry practitioners working on projects which are applying BIM on advanced levels compared to the current industry standard. In order to realize the DT of a building design and engineering firm the requirements to utilize BIM as a collection of the knowledge of all projects of the company should be evaluated. This study suggests addressing the knowledge demands during the design process through a *Knowledge-Based System* (KBS) – a computer program which combines knowledge, makes it accessible in a comprehensive manner, and reusable in an easy way.

1.3 Research Aim and Scope

From the outset, this paper argues that BIM has the potential to facilitate the DT of a building design and engineering firm through its opportunities for knowledge transfer between projects. For this reason, this thesis proposes a novel approach for BIM-based Knowledge Management. Thus, the secondary aim of the study is to develop the operating principles of a Knowledge-Based System which allows to effectively transfer and access knowledge from other projects which has been captured in the BIM models and reuse it in future projects. According to a project's particular characteristics, users can get an overview over designs and solutions developed in previous projects. They can then (re)use this knowledge and understand the setup and/or process from their own professional perspective.

To achieve the goals of this study, interviews were conducted in a large Dutch building design and engineering firm. Interviewees were both, employees in managing positions and employees in more technical roles. Thereby, the requirements to effectively transfer and access the knowledge stored in BIM models were identified. Therefore, an overview of the knowledge needs of employees of the firm is provided. Subsequently derived from the interviews, the operating principles of a BIM-based Knowledge-Based System were constructed and expected digitally transforming effects were addressed. Those operating principles and expected effects were validated through a focus group with BIM strategy experts. This research draws on findings from BIM research, KM and organizational studies which are combined into an integrated conceptual framework.

Scope

This study is conducted in combination with an internship at Arcadis, an international building design and engineering firm with Dutch headquarters. Data will be collected at different company locations throughout the Netherlands with the 'company' as a unit of analysis. Therefore, this study is geographically delineated to this one country which represents the most advanced markets in terms of BIM implementation. BIM maturity of projects in the Netherlands is globally leading (Hall, 2018).

1.4 Research Question

In order to tackle the identified problem and achieve the research aim, the following main research question has to be answered:

> ***How can BIM enable the transfer of knowledge across projects to facilitate the Digital Transformation of a building design and engineering firm?***

Three sub-questions are posed and provide necessary building blocks that help to answer the main research question.

a) *To what extent is the knowledge stored in BIM models useful for other projects?*
b) *How would an ideal Knowledge-Based System function in order to make knowledge stored in BIM accessible and (re)usable?*
c) *In which ways could BIM-based Knowledge Management imply DT of a building design and engineering firm?*

2 Theoretical Framework

This chapter concerns the theoretical foundations of this research. Firstly, in Chapter 2.1 the background of Digital Transformation is presented. Subsequently, Chapter 2.2 compiles the scientific understanding of Knowledge Management and establishes an integrated conceptual framework.

2.1 Digital Transformation

In the recent past, companies in many industries have explored new digital technologies and conducted a number of initiatives to exploit their benefits. Digital technologies rely on microprocessors, hence, computers and applications that are dependent on computers such as the internet, as well as other devices such as mobile devices (Salmons & Wilson, 2008). The introduction of new digital technologies commonly involves transformations of key business operations, as well as organizational structures and management strategies (Matt *et al.*, 2015).

2.1.1 Delineation of Digital Transformation

The academic literature comprises multiple definitions for the transition of companies and industries through digital technologies, commonly known as DT (Schallmo, 2016). There is no generally accepted definition of DT, although definitions overlap to a large extent. Moreover, terms like digitalization, the digital age or industry 4.0 are often used interchangeably. However, some noteworthy differences are touched upon, in order to clarify the more narrowly defined application of DT.

As baseline, Knobel (2008) points out the transformative character of DT. According to the author, DT is achieved when the digital usages which have been developed enable innovation and creativity and stimulate significant change within the professional or knowledge domain, rather than simply enhance and support traditional methods. Likewise, PwC (2013) defines DT as the transformation of the corporate world through the establishment of new technologies based on the internet, with implications for society as a whole. Here, the use of new technologies is paramount. In contrast, Bowersox *et al.* (2005) use the term 'Digital Business Transformation' and refer to it as the process of redefining a business by digitizing processes and extending relationships across multiple value-adding levels. It can also impact company structures, the culture, the portfolio of products and services, management, decision making, in short the overall existence of a firm or how the firm used to work. Thus, here, the focus is on the individual firm. Similarly, Westerman *et al.* (2011) introduce DT as the use of technology to increase the performance or reach of companies. Also, Mazzone (2014) defines DT as the conscious and ongoing digital evolution of a business, a business model, an idea, a process, or a method, which can be strategic as well as tactical. Boueé & Schaible (2015) go even further as they refer to DT as the interlinking of all economic sectors and as the adaptation of the actors to the new conditions of the digital economy. In doing so, they require decisions in interconnected systems that include data exchange and analysis, calculation and evaluation of options, as well as, initiation of actions and consequences. Here, the importance of KM becomes evident.

In the context of DT, the networking of actors across all stages of the value chain (Bowersox *et al.*, 2005; Boueé & Schaible, 2015) and new technologies (PwC, 2013; Westerman *et al.*, 2011) are key components. Building on this, DT requires KM skills that involve extracting and sharing data and analyzing and transforming it into information. This information should be used to make decisions (Boueé & Schaible, 2015). In theory, DT can be achieved for companies, business models, processes, relationships, products, etc. (Bowersox *et al.*, 2005; Mazzone, 2014) to increase the performance and reach of a business (Westerman *et al.*, 2011). For the sake of this study, however, the focus lies on DT of a company. Concluding, this study's working definition of DT is as follows:

DT is the transformation of a company through digital technologies which stimulate significant change in internal processes and external relationships, enabling innovation and creativity.

2.1.2 Digital Transformation through BIM

Over time, the value chain of project delivery is getting transformed. BIM drives this change because the BIM model is a central information resource throughout a building's entire lifecycle (Kivits & Furneaux, 2013), naturally leading to intensive communication, joint decision making and interdependence that blur the boundaries between parties. Succar (2009) divides the lifecycle of construction projects into three main phases. During the design phase, the client's requirements are converted into an appropriate design. In the construction phase, the design is transformed into a facility which is used by the client during the phase of operations. Figure 1 shows a simplified model of the lifecycle phases including the knowledge flows to and from the BIM model where all data about the project is stored.

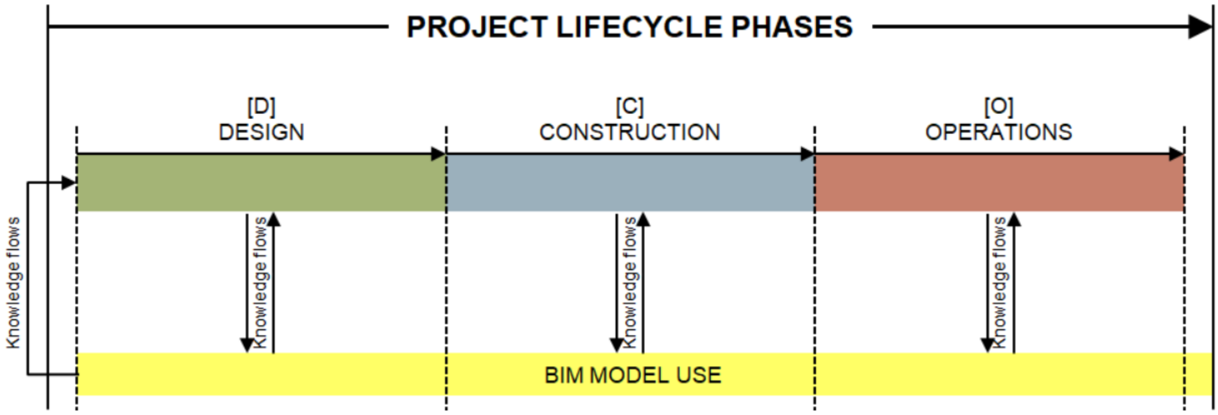

Figure 1*: Simplified model of the construction process (based on Succar, 2009) with knowledge flows to and from the BIM model throughout all lifecycle phases (based on Kamara et al., 2002).*

Lin (2014) compiles the many benefits of BIM stated by previous authors: BIM supports decisions and improves processes throughout the project lifecycle (e.g. Eastman *et al.*, 2011; Shen & Issa, 2010; Manning & Messner, 2008). For the design phase, positive effects include parametric modeling, identification and analysis of design conflicts, green design, design simulation, accurate cost estimation, and precise geometric representation of all facilities (e.g. Ding *et al.*, 2006; Li *et al.*, 2006; Lee *et al.*, 2012a, b, c). In today's advanced BIM projects, the collaboration between the designing and the constructing party is much closer and starts earlier in the process (Hartman & Fischer, 2008; Succar, 2009). Therefore, during the construction phase, benefits include less rework, reduction in requests for information, customer satisfaction through visualization, improved scheduling, and faster and more effective construction management (e.g. Eastman *et al.*, 2011; Hardin, 2009; Azhar, 2011). In case the end users of buildings utilize BIM in the operations phase, benefits during this phase potentially include the control of more effective facility management, integrated lifecycle data, and live and accurate information on activities (e.g. Eastman *et al.*, 2011; Staub-French & Khanzode, 2007; Rezgui *et al.*, 2013).

The effects through BIM described in literature seem promising. However, on the one hand, many of those effects are theoretical and, in the industry practice, could not be experienced regardless of BIM usage. On the other hand, it remains unclear whether these effects can actually be attributed to DT. Even though a number of new software solutions have been developed for the AECO industry and building design and engineering in particular, according to a study by McKinsey (2016), the industry is still among the least digitalized with only agriculture and hunting ranking lower. As the effects implied through digital technologies have not been sufficient for DT, a new approach to implementing those technologies is needed. Utilizing BIM for KM purposes could entail the needed implications for the DT of building design and engineering companies.

BIM-Enabled Knowledge Transfer across Projects

For sharing knowledge between projects, construction professionals traditionally use techniques ranging from annual meetings to face-to-face interviews (Reuss & Tatum, 1993). Furthermore, they predominantly exchange text-based information, with less focus on virtual illustration and sharing (Ho *et al.*, 2013). BIM-based KM bridges the world in which knowledge gained throughout projects is mainly shared with surrounding colleagues in large time intervals or in incomprehensible texts with the world in which innovative technologies leverage the capture of and give access to knowledge augmented with building objects in the 3D building model (Fruchter, 2009). This could involve a new way of working because many expert feedback loops become redundant. However, much of the potential for BIM has yet to be realized due to the current level of development (Kivits & Furneaux, 2013). Figure 2 gives a succinct summary of how BIM can facilitate DT as it enables knowledge management across projects.

Figure 2*: BIM as the foundation to DT.*

BIM forms the basis for effective KM in an AECO company as BIM enables the transfer of knowledge across projects (Deshpande *et al.*, 2014). As derived in Chapter 2.1.1, DT is the transformation of a company through digital technologies which stimulate significant change in internal processes and external relationships, enabling innovation and creativity. In the case of this study, the digital technology is BIM. Accordingly, the DT of a building design and engineering company is achieved when BIM-based KM does entail significant change in the three domains: company internal processes, company external relationships, and innovation and creativity.

Only a few previous studies have dealt with BIM-based KM for transferring knowledge across projects, let alone described the effects this will have on companies. Liu *et al.* (2013) stated that the BIM-based transfer of knowledge between projects offers the opportunity to reduce redundant and unnecessary rework by fully utilizing expert knowledge. Wong & Fan (2013) continue that uncertainty and the likelihood of errors are decreased. Moreover, Fruchter (2009) mentions that this will reduce the time wasted searching for information. Therefore, working efficiency and productivity are greatly increased (Liu *et al.*, 2013), the barriers of communication across disciplines are lowered (Fruchter, 2009), and faster and more reliable decisions are made possible (Fruchter, 2009; Liu *et al.*, 2013).

None of the previous studies examined those effects in-depth nor did they focus particularly on the implications on DT of companies. Again, it is debatable whether the effects described in previous studies stimulate significant change within the professional or knowledge domain. Therefore, this study aims to research this matter in detail.

2.2 Knowledge Management

This research analyzes DT from the firm perspective and its effects on knowledge flows. The fundamental theory that combines these views is the knowledge-based view (Grant, 1996). The knowledge-based view considers knowledge as "the most strategic resource of the firm", which enables the firm to develop competences and capabilities which ultimately improve the firm's performance or competitive advantage (Daud, 2012, p. 4224). According to Stewart (1998), knowledge has become the most important resource and asset for companies in the modern economy.

The aim of KM is to improve the organization's knowledge assets and production efficiency (King, 2007). As the flow of timely, actionable, and decision promoting knowledge is critical for success (Leeb, 2014), the actual practice of KM reflects the experience and intentions of individual organizations (*context*), and the understanding of the meaning of knowledge (*content*) (Scarbrough *et al.*, 1999). The understanding of *content* and *context* has a bearing on the KM strategy adopted (Kamara *et al.*, 2002).

Kandadi (2017) states that in today's knowledge economy companies need to continuously innovate to remain competitive. To innovate on a continual basis, thus create new knowledge, it is necessary to collaborate and share existing knowledge. For knowledge creation, focus does not lie on research and development but rather on ways to interact with customers, solve problems, and identify new market patterns. Kandadi (2017) highlights three components for successful KM: (1) Firstly, an organizational culture of awareness which supports informal knowledge sharing and talking about encountered problems. Therefore, a supportive leadership needs to create a save environment to talk about failures in a positive way. (2) Secondly, organizational processes to capture success and failure have to be in place.

(3) Thirdly and lastly, companies need to provide the infrastructure for knowledge sharing. This includes physical infrastructure like an office design that supports trans-departmental encounters, technology infrastructure like computer programs and other kinds of facilitating infrastructure.

Digital technologies are the backbone of KM because they are essential for collaboration and innovation in the modern economy (Kandadi, 2017). Knowledge moves freely and fast today because of digital technologies.

Knowledge-Based Systems

The significance of well-designed technological solutions, so called *Knowledge-Based Systems* (KBS) has been fully recognized for effective KM (Carrillo *et al.*, 2000; Anumba *et al.*, 2000; Egbu, 2000; Tan *et al.*, 2010; Elgobbi, 2010). A KBS is a computer system that utilizes a knowledge base to help its users solve complex problems (Amuna *et al.*, 2017). Users obtain the knowledge they need through a user interface (Berrais, 1997). KBSs complement human skills so that the combination of KBS and user produces something which is far more powerful than the sum of the parts (Miles & Moore, 1994).

2.2.1 Specification of Knowledge

Knowledge can be an ambiguous term. Hence, its meaning in relation to this study is derived below. To begin with, the concepts of data, information and knowledge are closely related (Kock *et al.*, 1997), and it is commonly known that knowledge has a higher level than information, and information has a higher level than data (Tuomi, 1999).

Fruchter *et al.* (2009) describe data as ‘raw facts’. Information emerges as data, is getting structured and meaning is added through a process of contextualization and synthesis (Aamodt & Nygård 1995; Davenport & Prusak 1998). Fruchter *et al.* (2009) state that knowledge is created through dialogue within or among people as they use their past experiences and knowledge in a specific context to create alternative solutions. Through this cognitive effort knowledge is created as connections, comparisons, combinations, and their consequences are explored. Hence, knowledge is the application of data and information (Ackoff, 1990) and contains judgment (Tuomi, 1999). Kock *et al.* (1997) conclude that data is a carrier and storage of information and knowledge, and a media for information exchange and knowledge transfer.

Organizations play an active role in creating knowledge as well as in transferring knowledge and sources of new knowledge (Kogut & Zander, 1992; Spender, 1996; Chiva & Alegre, 2005). Knowledge can be tacit or explicit. Tacit knowledge is personal result of learning and experience, rooted in action and a specific context, which makes its transmission difficult (Polanyi, 1957; Nonaka, 1994; Afiouni, 2007). Explicit knowledge is formal and can be found in manuals, databases and books, making it easily stored and shared via digital technology (Nonaka, 1994; Gorman, 2002). In an intangible value chain, value creation is the result of the tacit or explicit transfer of knowledge between individuals and lies in the conversion of different types of knowledge (Nonaka, 1994; Sveiby, 2001). Through social interaction and the exchange of knowledge within the firm and with external organizations, new knowledge is created (Valentim *et al.*, 2015).

Knowledge transfer in building design involves reusing knowledge gained during the completion of previous projects to maximize the achievement of future project objectives (Reuss & Tatum, 1993). El-Diraby & Kashif (2005) present six major concepts to classify construction knowledge: project, process, products, actor, resource, and technical topics (boundary conditions). The focus of this study is on all those concepts in relation to particular projects, in the following referred to as '*project knowledge*'. Hence, the term includes all explicit data, explicit information and explicit knowledge from other (previous and ongoing) projects.

2.2.2 Influences on Cross-Project Knowledge Transfer

The AECO industry is a project-based industry which utilizes a variety of separate firms in a temporary multidisciplinary organization – the project – to produce custom built investment goods (Kamara *et al.*, 2002). *Project knowledge* is only useful for other projects if it is transferred to them. Hence, the implementation of KM in project-based organizations should enable knowledge transfer across different projects, as well as capturing and storing knowledge in an efficient way (Kamara *et al.*, 2002).

Newell *et al.* (2006) define three basic prerequisites for cross-project knowledge transfer: First, there must be some knowledge actually created at the project team level. Second, the team must be knowledgeable enough to realize that there is indeed knowledge that exists beyond the confines of the project that could be a useful tool to help to improve progress on their project. Third, the knowledge that exists in an explicit form must actually be useful to others as a tool of knowing.

A project is a temporary endeavor undertaken to create a unique product (Project Management Institute, 2004). The more a project is perceived as unique the less likely are teams to try and learn from others (Moud & Abbasnejad, 2012). Nevertheless, it is not unusual to find several projects of a very similar nature in the process of project implementation (Newell *et al.*, 2006). In a project-based organization, projects are generally similar in work tasks, operations, technologies (Darr & Kurtzberg, 2000) and organizational structures (Zheng *et al.*, 2010). Based on this, some scholars have discussed the impact of similarity on knowledge transfer. Project similarity refers to the degree of tasks with something in common between projects or the similarity in the work flows and implementation methods embedded in executing the project tasks (Ren *et al.*, 2018). It is the requirement for successful knowledge transfer across projects (Zhao *et al.*, 2015). Lewis *et al.*'s (2005) empirical study suggests that project similarity can support knowledge transfer between projects, because the more one project has in common with another, the more likely its lessons and examples will be useful for the other project (Darr & Kurtzberg, 2000). But Zhao *et al.*'s (2015) research is inconsistent with the research above; they find that the effect of project similarity on knowledge transfer is contingent on types of knowledge being transferred cross-project. When the to-be-transferred knowledge was related to the client, such as knowledge of business processes and operations, the similarity between the source and recipient projects became a significant predictor of cross-project knowledge transfer. By contrast, when the to-be-transferred knowledge was technology-oriented, such as knowledge of hardware, software or implementation methodology, then the influence of the project similarity diminished. Furthermore, the analysis by Newell *et al.* (2006) indicates that the capture and sharing of knowledge about the processes that the team had deployed to achieve goals and the reasoning for their success or failure would be more useful than the sharing of knowledge about actual achievements in relation to the stated goals.

Other influencing factors on knowledge transfer discussed in literature are geographic distance and time pressure. Geographic separation of sites and projects reduces the communication and social networks, thus, impedes knowledge transfer (Haldin-Herrgard, 2000; Moud & Abbasnejad, 2012; Ho & Liu, 2011; Wiewiora *et al.*, 2009). Moreover, time pressure can raise difficulties for sharing knowledge in organizations. On the one hand, time urgency of a project motivates a project team to seek knowledge from other project teams (Newell *et al.*, 2006). On the other hand, under restrict deadlines and a tight schedule there is no free time to allocate for communication or to capture learnings (Zhao *et al.*, 2015; Loo, 2002; Moud & Abbasnejad, 2012). Different from aforementioned authors, time constraints had no significant effect on knowledge sharing in Connelly *et al.'s* (2009) two experimental studies. Hence, time might actually not impact the transfer of knowledge across projects. The authors call for further research to clarify the impact of time pressure on knowledge sharing.

2.2.3 Knowledge Management in AECO Companies

Because KM is linked to *content* as well as *context*, universal solutions to KM problems are unlikely to be successful (Dixon, 2000). Thus, KM strategies for AECO organizations should reflect the *context* of that industry, with respect to the way business is conducted, and the types of knowledge (*content*) that are critical for its success (Kamara *et al.*, 2002).

Different studies have worked on the implementation of KM practices and systems to capture the knowledge of construction projects (Carrillo *et al.*, 2003; Cheung *et al.*, 2003; Tupenaite *et al.*, 2008). Kanapeckiene *et al.* (2010) present an integrated model which showcases the influence of external factors on KM. In their integrated model, the authors distinguish four important KM stages: knowledge gathering, knowledge acquisition, best practice knowledge data base contribution, and knowledge-based decision support. Tan *et al.* (2010) summarize four processes: knowledge capture, knowledge sharing, knowledge reuse, and knowledge maintenance. Knowledge capture includes to identify and store knowledge, and evaluate information captured; knowledge sharing means to exchange and transfer knowledge to a person or an organization through some media like documents, phone, and the internet; knowledge reuse entails to re-apply knowledge stored for innovation; and knowledge maintenance implies to archive and refine knowledge in the repository, and keep the necessary information up-to-date. According to the authors, these stages or processes are an essential condition for effective KM.

Ribeiro (2009) analyzes KM effort based on case studies and provided recommendations and insights for enhancing KM in construction firms. For effective knowledge storage, refinement, and transfer within the organization, the author recommends the establishment of knowledge repository systems, such as databases and knowledge bases. KM effort should involve the entire organization through the integration of internal and external knowledge and capabilities. Hereby, digital technologies can help to enhance collaborative teamwork to provide cooperative network systems available to all knowledge workers. The author reasons that effective implementation of KM activities includes a clear view of what knowledge constitutes for the firm, what knowledge needs to be achieved, and what are the key enablers and barriers for internal knowledge creation and cross-functional knowledge sharing. Furthermore, he highlights the role of decentralized knowledge communities as a valuable source of new knowledge that can contribute to the transmission of tacit knowledge in the firm. Following this, Chen & Mohamed (2010) provide empirical evidence for the stronger strategic role of tacit KM in comparison to explicit KM.

Kivrak *et al.* (2008) used a survey to find out how tacit and explicit knowledge are captured, stored, shared, and used in forthcoming projects and to identify major drivers and barriers in knowledge management. The results show that knowledge gained in past projects has not been used very often in forthcoming projects. The respondents stated that they rely mostly on the experience of individuals in problem solving and reuse knowledge gained in previous projects only in emergency conditions. The main reason for that is noted as the difficulties in finding the relevant knowledge whenever required. Hence, they prefer using experts' and engineers' knowledge instead of trying to find the knowledge, which has been considered as a time consuming process. The overall finding of the survey is the inefficiency of KM within AECO firms, especially due to lack of a deliberate strategy and a systematic way of managing knowledge.

Chen *et al.* (2012) presented a knowledge-sharing model to determine whether risk mitigation based on the use of derivatives would be beneficial to the companies. Building on past experience, construction material suppliers are supported to select the most similar cases. Forcada *et al.* (2013) presented a survey of perceptions of KM implementation in the Spanish construction sector and compares the results obtained from design and construction firms. Their results indicate that construction and design companies understand the knowledge management concept differently. Design firms are more technology oriented and recognize KM as a digital system for the management of intellectual assets while construction companies also understand KM as a methodology for the identification, optimization and active management of intellectual assets. For design companies, the organizational strategies to increase knowledge sharing can be oriented to promote face-to-face communication between designers and improve digital technology tools such as communities of practices or BIM to share visual information among all design partners. Likewise, Hartmann & Fischer (2007) describe how project teams can use visuals efficiently to support the communication of knowledge during the constructability review on construction projects.

2.2.4 BIM Application for Knowledge Management

Although numerous knowledge management systems have been developed for the application of construction KM, such systems typically exist for knowledge sharing using only text-based illustrations (Ho *et al.*, 2013; Lin, 2014). Likewise, a great deal of previous research pertains to BIM issues in construction. A large amount of information is exchanged and potential lessons learned are generated in BIM activities. However, current KM practice is an independent process, and few systematic approaches or procedures have been established to transfer and reuse the knowledge captured in BIM.

Fruchter *et al.* (2009) present a working software environment that demonstrates how BIM can be expanded to become a rich multimedia 'building knowledge model' in order to assist project teams and companies to capitalize on the core competence by capturing, sharing and reusing knowledge in addition to data and information. The authors indicate that a successful ‘building knowledge model’ can help keep the organization ahead among other competitors, and provide training resource for new employees.

Following up on this, the paper by Liu *et al.* (2013) intends to develop a new ‘building knowledge modeling’ approach. A plugin for the widely used BIM software Autodesk Revit for designers and engineers is proposed to connect BIM application and KBS to expand BIM. Users capture lessons learned from BIM activities through the plugin which sends them to the KBS so that they will be validated by related team members or experts, and stored in the KM repository. Meanwhile, the plugin is also used to retrieve previous knowledge from the KBS to facilitate design and collaboration processes on the BIM platform.

Ho *et al.* (2013) propose the BIM-based animated illustration of knowledge to keep and explain information in a digital format and to facilitate the updating and transfer of knowledge in the BIM environment. The model is constructed from variables that can be decomposed into objects of a BIM model and can then store the identified knowledge (problems and solutions). The authors classify the shared information into saved as ‘activity’, ‘object’, or ‘issue’ for collection and management. Knowledge saved in the ‘issue’ category includes both tacit and explicit knowledge. With respect to explicit knowledge, BIM-related information normally includes original comments, reports, drawings, documents, and comments submitted by jobsite engineers. In contrast, tacit knowledge may include process records, problems faced, problems solved, expert suggestions, know-how, innovations, and notes on experience. Information that relates to the whole project that cannot be easily classified into issue components is saved under the ‘project’ category.

Deshpande *et al.* (2014) present a framework of the knowledge capture from BIM as knowledge is generated throughout the design and construction phases. Focus of the study was on the implementation of BIM-based KM processes. It is explained that firms can develop shared parameters in a BIM model strategically and deploy them to allow users to enter information as soon as they learn something new. Previous KM processes for the industry have focused on extracting knowledge at the end of the construction process which creates a significant lag between knowledge generation and its dissemination. Instead, Deshpande *et al.* (2014) suggest companies to set milestones during the design and construction processes when the knowledge generated and stored in the model can be extracted to a database. The database can contain information about the project team, lessons learned and a link to the location of the BIM file. This would allow for a shorter lag in dissemination of knowledge and spur continuous improvement.

Previous papers add steps to the workflow of designers and engineers to actively add, share and update knowledge and rely on the manual filtering or complex queries. Thereby, they do not take into account the already growing amount of knowledge stored in BIM. The actual knowledge demands from employees in both managing and technical positions should be in alignment with the knowledge stored and made accessible. The opportunities of making this knowledge easily accessible for building design companies, and therefore, utilizing latest technical developments like big data and machine learning remain to be investigated. Therefore, an integrated approach for BIM-based KM which takes advantage of a KBS is needed, so that the knowledge stored in the BIM models can be transferred to and (re)used in other projects.

2.2.5 Integrated BIM-Based Knowledge Management

The analysis of published articles shows that only a few studies attempt an integrated analysis of BIM applications for KM in construction. The transformative effects through BIM are addressed but conclusions for the implications on DT of a company are rarely drawn. In order to enhance designers' and engineers' ability to share and acquire *project knowledge* linked within a 3D environment, this study proposes a novel BIM-based KBS for building design and engineering companies. The implications of such a KBS on the Digital Transformation of those companies are subject of the research. The integrated conceptual framework of BIM-enabled DT developed in this study is shown in Figure 3. This framework combines the theory discussed above.

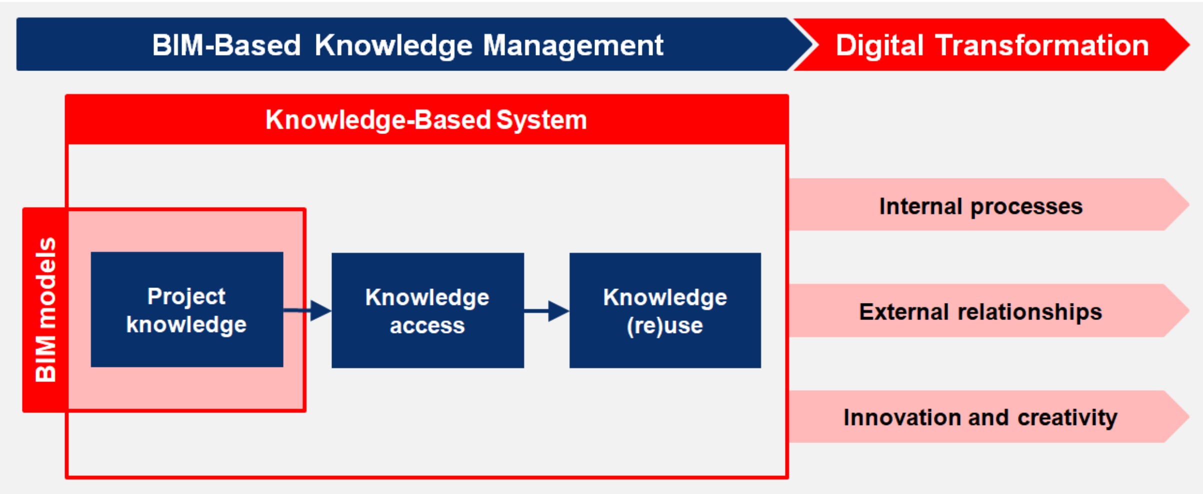

***Figure 3**: Integrated conceptual framework of BIM-enabled DT.*

Through BIM, project teams transform their tacit into explicit knowledge in the form of 3D information and databases attached to them. However, the DT of a company is not caused by the digital technology – BIM – individually. Instead, the right integration into design companies' KM transforms their business and how they work.

BIM-based KM can utilize the knowledge stored in BIM models, and thus, enables the transfer of knowledge across projects. Therefore, a KBS is introduced to give employees access to the *project knowledge* stored in the BIM models. This supports knowledge-based decisions and knowledge can be reused. The implementation of BIM-based KM stimulates significant change in internal processes, as steps in the design process are altered, in external relationships, as interactions with clients and external stakeholders change, and enables innovation and creativity, by making new services, business models and unprecedented design opportunities possible. Thus, BIM-based Knowledge Management facilitates the Digital Transformation of a company.

3 Methodology

To understand the process of DT in a building design and engineering company, the ‘company’ is the units of analysis. This chapter presents the research design and gives insights into the methodological choices that have been made in the research process. The research strategy comprises a qualitative analysis with data derived from interviews and a focus group.

3.1 Research Strategy

To achieve the primary and secondary research aims (facilitate the DT of building design companies and define the operating principles of a KBS for the BIM-based transfer of knowledge across projects), a qualitative analysis was conducted. Qualitative research methods enable a profound scrutiny of the researched topic which is not possible in quantitative research. The questions stated in this study require to be answered from the individual perspective of participants – given their personal experience and interpretation of meaning. Understanding the context and environment a practitioner is in is crucial in this study for two reasons: First, because the similarities and uniqueness between the various AECO projects influences cross-project knowledge transfer (see Chapter 2.2.2); and second, because of the general relevance of *context* and *content* for KM in organizations (see Chapter 2.2). Moreover, qualitative research methods can capture the needs practitioners have and cannot articulate and the difficulties they have in finding information or in using a KBS.

To research how BIM can be utilized for KM and in turn facilitate the DT of a building design and engineering company, semi-structured interviews were conducted with an equal number of participants in managing and in technical positions. For validating the results derived from the interviews, a focus group with BIM strategy experts took place. To answer the research question, the analysis of the collected data was divided into three steps: identification, definition and implication. In Figure 4, the research design is presented.

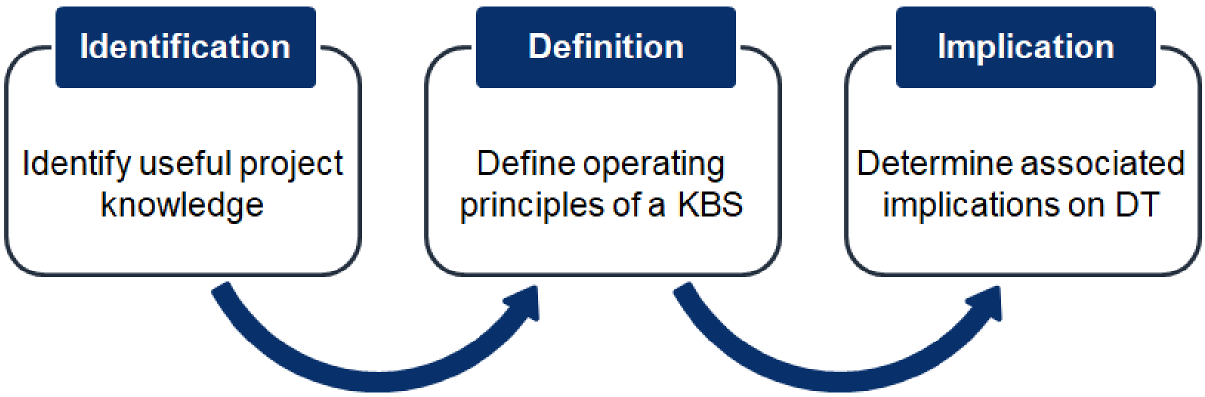

Figure 4*: Research Design.*

The interviews were assessed to identify what knowledge created and stored (in BIM) during projects, namely '*project knowledge*', could be useful for practitioners. As defined in Chapter 2.2.1, the term includes all data, information and knowledge from other (previous and ongoing) projects that are deemed useful. In the next step, the operating principles of a KBS were defined which makes this knowledge accessible and (re)usable within the company and connected concerns were addressed. The functioning of the KBS was visualized in a conceptual interface design. Building on that, the implications of such a KBS on the Digital Transformation of a building design and engineering company were determined.

Rather than identifying an existing theory on KM and DT, this research began by collecting data from a group of industry practitioners to understand what knowledge they find useful, how they would define a KBS, and what implications for DT they expect. This research design asks for an inductive approach. Induction implies that data – in the case of this study in the form of interviews – was collected prior to the analysis and the development of theories on basis of those data.

The study proposes the operating principles of a KBS that is meant to enable cross-project knowledge transfer and consequently improves the insufficient DT of building design and engineering companies. Therefore, the research strategy is comparative. As such, the research entails a descriptive part to define concepts from the interviews, and a comparative part to systematically compare different features of the phenomenon under investigation to find an answer to the posed research question.

3.2 Data Analysis

To derive clear answers to the research question from the collected data, a number of steps had to be taken, which altogether constitute the data analysis. In Figure 5, the general process of data analysis is presented.

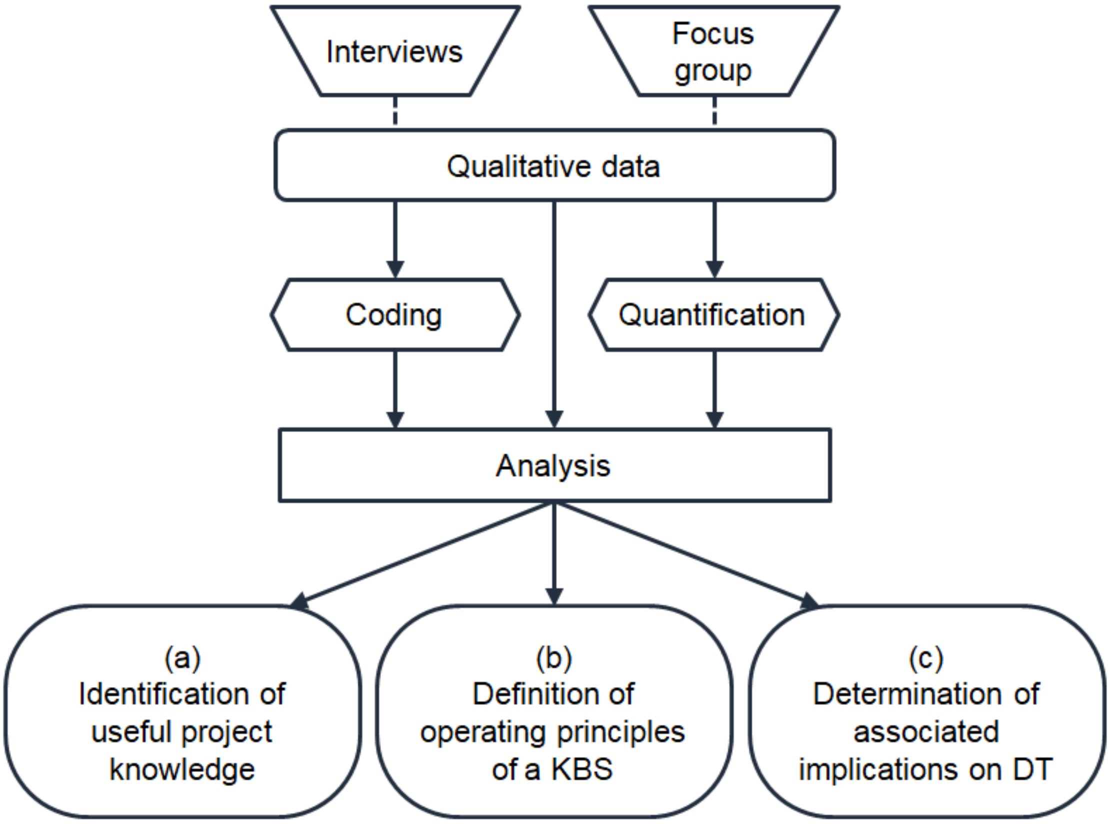

Figure 5*: Data analysis. The different processes and tools that will lead to the results.*

To gain a first understanding of the organizational structure and the general strategy in the *context* of the company, desk research on the intranet was done and employees of the firm were consulted. Through this, the guidelines for the population and the choice of interviewees were determined as described in Chapter 3.3. The interviews were recorded and transcribed afterwards.

From the interview transcripts, the qualitative data set for further analysis was compiled through a thematic analysis. Therefore, as explained by Saldaña (2015), the interviews were coded in three steps: First, by *open coding* – breaking data down into smaller components and labeling those. These labels summarize the primary topic of the respective excerpt (*descriptive coding*). The *open coding* was based on predefined codes, three for each step of the research design, which have been derived from literature (key themes in Table 1). Those starting codes were subdivided and further specified during the coding process. Second, by *axial coding* – comparing data with data, case with case, code with code to identify relationships among codes to understand and explain variation in the data. Third, codes were eventually combined and related to one another. At this stage they were more abstract and were referred to as concepts. Concepts were allocated to themes, which, in turn, were associated to structural codes. The research structure predefines the structural codes as: (1) useful *project knowledge*, (2) operating principles of a Knowledge-Based System, and (3) Digital Transformation through the Knowledge-Based System. Further on, the conceptual framework is operationalized by the investigation of key themes which have been derived from literature (Table 1).

***Table 1**: Operationalization.*

Research step	Structural code	Key themes
Identification	Useful project knowledge	• Currently reused project knowledge, • Generally stored project knowledge, • Generally not stored project knowledge.
Definition	Operating principles of a Knowledge-Based System	• KBS prerequisites, • KBS functioning, • Barriers.
Implication	Digital Transformation through the Knowledge-Based System	• Effects on internal processes, • Effects on external relationships, • Effects on innovation and creativity.

The coding was begun as soon as possible, and continued in parallel with data collection. Coding was done manually in Microsoft Word and Excel (see Supplementary Files). Hereby, the three coding laps were iterated with every new interview. To begin the coding process, the six key themes were used as the first codes. As required, they were divided and, steadily, concepts were subordinated. In the end, twelve themes and 101 concepts were derived from 375 coded statements. An overview over the identified concepts and themes was visualized in the form of a code tree (see Appendix D). Based on the number of mentions and emphasis of interviewees, conclusions were drawn for the results. The analysis of each of the three structural codes is needed to answer the connected sub-question.

After the analysis of the interviews, a focus group with BIM strategy experts took place to check the derived outcomes. A focus group is a special type of group interview that is structured to gather detailed opinions and knowledge about a particular topic from selected participants (Bader & Rossi, 2002). According to Morgan (1997), a basic use of focus groups is as a supplementary source of data in studies that rely on some other primary method, interviews in the case of this study. The focus group served as a source of follow-up data to assist the primary method. The focus group was divided into two parts. During the first part, notes were taken for later evaluation (see Appendix F.1). For the second part, participants jointly evaluated statements by ranking them on a scale for subsequent analysis (see Appendix F.2); hence, quantification takes place to some extent. For further description see Chapter 3.3.3. Literature has shown that a focus group helps to extract knowledge and information which cannot be extracted by a survey (Bader & Rossi, 2002). This extracted knowledge is necessary to answer the research question because it allows for a qualitative evaluation of the findings.

3.3 Data Collection

Data was collected in the Netherlands from April until July of 2019. Therefore, this study is geographically delineated to this one country which represents the most advanced markets in terms of BIM implementation. BIM maturity of projects in the Netherlands is globally leading (Hall, 2018). In particular the study of a design company can be insightful because it is involved in construction projects from the beginning on and it is dependent on knowledge gained throughout the entire lifecycle of buildings. Also, steps towards the DT in the AECO industry typically affect the design companies first. Therefore, studying such a company provides best insights on the most advanced group of companies in terms of DT in the AECO industry. This study is conducted with Arcadis, an international building design and engineering company for natural and built assets with Dutch headquarters. Globally, the company is committed to achieving 100% BIM at a minimum of BIM level 2 (see Appendix A.1 for the different BIM levels) on all relevant projects (Arcadis, 2019). Nowadays in the Netherlands, BIM is applied in most new projects of the company (Arcadis, 2019). Data will be collected from employees working on various projects and at different company locations throughout the Netherlands with the 'company' as a unit of analysis.

The population accessible in the firm in the given time was limited and interviews offer an opportunity to acquire a richness of information from each respondent. For the project-based industry, contextual and relational aspects were seen as significant, thus, semi-structured interviews allow seeking the personal views on the focused topic. An equal number of participants in managing and technical positions were interviewed as those are the two roles generally involved in and necessary for the delivery of a building design project. The choice of interviewees is further specified in Chapter 3.3.2. The goal of any qualitative research interview is to see the research topic from the perspective of the interviewee and to understand how and why they came to have this particular perspective (Cassell & Symon, 2004).

Since the industry is organized around projects, the projects determine the *context* and at the same time the viewpoint of each participant. Hence, the general conditions for the projects of interest were defined and determined the population. Generally, BIM (level 1 at a minimum) was applied in all projects, which was the fundamental requirement. To cover the widest possible range of projects and participants, there were no boundaries set on the type of building, building category or industry. In order to ensure the comparability of the projects, thus, interviewees chosen, the company had to be involved in the projects' design and engineering in at least one discipline (e.g. structural engineering, architecture, mechanical, electrical and plumbing etc.). Besides, the design as the first phase of the construction process (see Figure 1) can be divided into different sub-phases (see Appendix A.2). Depending on the design sub-phase the interviewees were in with their focus project, it was assumed that their perspective on the questions would differ. To cover a wide spectrum of perspectives, the projects were chosen as evenly distributed as possible according to the projects' design sub-phases. As most of the projects were already in the final sub-phase, the execution phase, the number of projects investigated per sub-phase was limited to a maximum of three.

The projects were determined through an excerpt of all the projects in the company's SAP system. To ensure the highest possible involvement of participants in their projects, the projects with the highest gross revenue in the system (more than €200,000) determined the population. Therefore, a typical project covered one up to all involved design and engineering disciplines and was priced at an average of €140 million total development costs, meaning all costs incurred from initiation to implementation of a project (HUD, 2014). An average project had five employees of the company working on it full-time. However, one project (project 3) was extraordinary large with 55 employees involved. Over the course of a project, the company was collaborating with the project's one or two clients as well as one main contractor and sometimes multiple sub-contractors.

The heads of the market groups were stated in the project list extracted from SAP and were contacted to get to the responsible person of the project (managing positions) – the project managers, assistant project managers or project directors. For the formation of the focus group, see Chapter 3.3.3.

3.3.1 Sample

Eventually, it was possible to find out who a responsible employee in the managing position of all projects was and to contact them. At the end of the interviews with people in managing positions, each of them suggested an employee working in a technical position in their project for the next interview. In case no technical employee was involved in their project, a technical employee from another project was recommended and interviewed.

- 34 projects' responsible employee in a managing position was contacted;
- 22 projects' responsible employee in a managing position did reply;
- 12 projects had stopped, finished or were secret;
- 10 projects' responsible employee in a managing position was open for an interview;
- 8 projects' responsible employee in a managing position was interviewed;
- 8 employees in technical positions were interviewed.

Following the data collection principles, as most projects available for interviews were in the final design sub-phase (UO), two projects in that phase were excluded from the interviews. An overview over the interviewees working on each design sub-phase is presented in Figure 6.

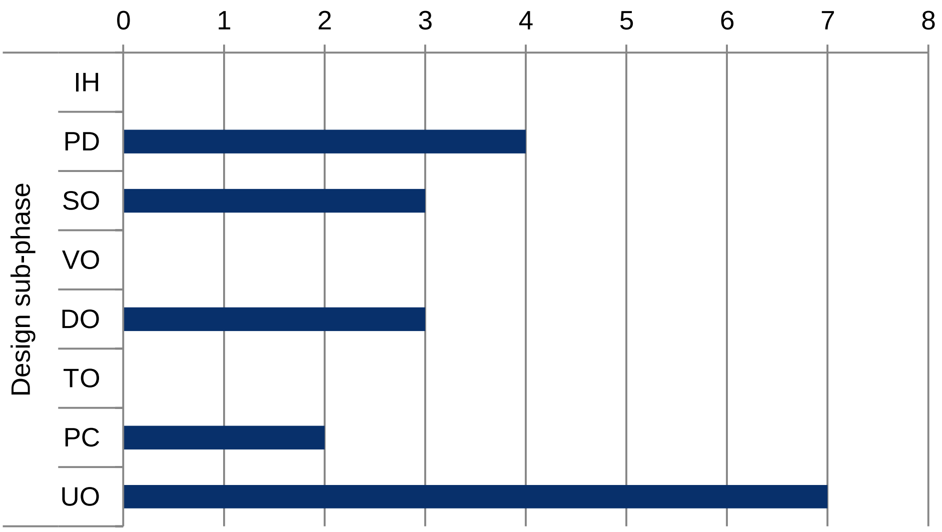

Figure 6*: Number of interviewees working on each design sub-phase. IH is the first and UO is the last sub-phase in the design process.*

An overview over the number of interviewees working on each BIM-level is shown in Figure 7. The BIM-level which was applied in those projects was mostly level 1 (10 out of 16 interviewees). Characteristic of this level is the application of clear objects to which information can be linked (BIR, 2016). The '+' indicates that some criteria of the next level were applied as well, but the next level was not reached yet. The rest of the projects had BIM-level 2 implemented (6 out of 16 interviewees). Main characteristic of this level is the collaboration of different disciplines inside the company through BIM software (BIR, 2016). So far, no project did work on level 3, in a fully integrated way.

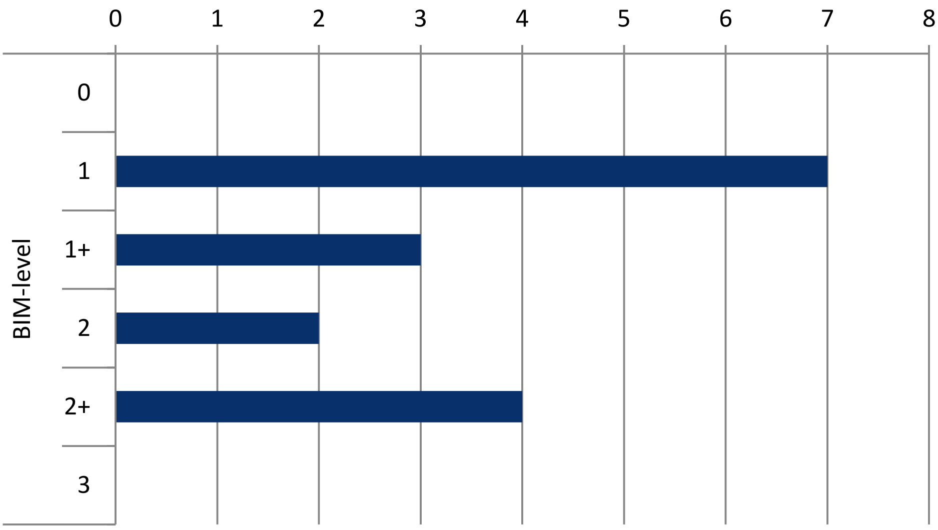

***Figure 7**: Number of interviewees working on each BIM-level. In level 0, BIM is not applied; level 3 is the most advanced BIM application.*

All the projects had BIM implemented, but not all of the participants used BIM software. Although most interviewees were working with BIM software on a daily basis, participants in high managing positions with a very low level of complexity were less likely to use such software. Four of the sixteen interviewees "don't know it yet" [1] or said they "wouldn't know how to handle it" [4]. All of them were in high managing positions. However, there is a growing trend (company strategy) towards the use of BIM software in managing positions [1, 7], "now we are changing to BIM 360" [7].

The projects' most interviewees were working on new buildings (13 out of 16 interviewees). Moreover, three interviewees were working on an extension project. In addition, six of the interviewees' projects included the refurbishment of an existing building. Furthermore, the so called 'building category' of the interviewees' projects was broadly mixed: commercial (6), residential (3), mixed use (3), industrial (2), and governmental (2).

3.3.2 Interviews

An interview guide (see Appendix B) was designed to get the most insights in the key topics. Its structure was adjusted to allow for on average 45 minutes long interviews and got tested in a test interview with an assistant project manager outside of the population. That employee was outside of the population solely due to the fact that her project was a smaller one (less than €200,000 gross revenue). Therefore, her perception on and response to the questions was still seen as adequate for testing the interview guide.

Half of the interviews were conducted with employees in a managing position of the projects, generally the project managers. The project manager was usually the first person that could be found in connection to a project. Employees in managing roles had an overview over different aspects of the project, were in direct contact with clients and stakeholders and had a planning and organizing function. At the end of the interviews, the participants in managing positions were asked to name one person in a leading technical position of the project to interview next. If the project was in an early stage, there were no technical employees involved yet. In those cases, any technical person could be named. A person in a technical role, generally a building designer or engineer, was working on specific details and was concerned with technical issues. Interviews were conducted with an equal number of participants in managing and in technical positions. Those are the two general roles involved in and necessary for the delivery of a building design project.

In total, sixteen interviews were conducted with participants working on eight different projects. The interviews were done from April until May of 2019, if possible in person. When time and distance did not allow for a personal interview, the interview was done via Skype. As two of the participants in managing positions were working in an early phase with no involvement of technical people, a technical employee from another project was recommended by each of those project managers. Coincidentally, those recommended technical people were working on projects already interviewed. Hence, the total number of projects is still eight. The interviews lasted 31 to 71 minutes (45 min on average). The interviewees were numbered consecutively from interviewee one [1] to interviewee sixteen [16]. An overview over the interviewees is shown in Table 2, a more extensive version can be found in Appendix C.

***Table 2**: Interviewees.*

No.	Position	Focus project	Date	Duration	Technique
1	Project manager	Project 1	11-04-2019	42 min	Skype
2	Project leader architecture	Project 2	18-04-2019	44 min	Personal
3	Modeler MEP	Project 1	24-04-2019	53 min	Skype
4	Project director	Project 3	29-04-2019	49 min	Skype
5	Architectural designer	Project 2	30-04-2019	34 min	Skype
6	Project manager	Project 4	06-05-2019	35 min	Skype
7	Project manager, advisor	Project 5	07-05-2019	71 min	Personal
8	Assistant project manager	Project 6	13-05-2019	37 min	Personal
9	BIM coordinator, designer	Project 3	14-05-2019	51 min	Personal
10	Project manager	Project 7	15-05-2019	56 min	Personal
11	Designer	Project 4	15-05-2019	45 min	Personal
12	BIM coordinator, designer	Project 4	22-05-2019	32 min	Skype
13	Technical advisor	Project 5	23-05-2019	45 min	Personal
14	Project manager	Project 8	24-05-2019	50 min	Personal
15	Designer, digital innovation engineer	Project 3	24-05-2019	39 min	Personal
16	BIM coordinator, designer	Project 8	24-05-2019	42 min	Skype

All interviews were conducted in English, recorded and the recording was subsequently transcribed, initially by hand. To reduce the transcription workload, the auto-transcription service ‘Otter’ by AISense was used. Otter is an Android app that uses speech recognition technologies and artificial intelligence. The generated transcripts, however, were not perfect and required extensive editing. Nevertheless, it did speed up the over-all transcription speed compared to the initial method.

3.3.3 Focus Group

A guide for the focus group (see Appendix E) was designed to get the most insights in the key topics. Its structure was adjusted to ensure a sufficient amount of time for discussion within the 60 minutes long session. The focus group was conducted in English language at 9 July 2019 in the company's office in Amersfoort.

The focus group constituted of two 'BIM managers'. People in this role are responsible for initiating, policy-making and the creation of framework conditions within the organization for implementing projects with BIM. Therefore, they could best assess the realizability of the proposed KBS and could best estimate the implications such a system would have. The participants for the focus group were found over 'PeopleFinder', the company's system on the intranet to look up information on employees, and were contacted via email. The number of participants was two for both practical and methodological reasons. On the one hand, in the Netherlands the company had only three employees in that position, out of which two were available in the timeframe of this study. On the other hand, as the participants had much expertise on the research topic of implementing such systems and experience with the involved effects, the group size should be kept small (Krueger & Casey, 2009).

The focus group was divided into two main parts. After a short introduction, in the first part, the defined KBS was presented and discussed. A preliminary concept design of the system interface was presented via PowerPoint slides and it was explained how the system functions. The verbal feedback was recorded on the basis of brief handwritten notes to allow for a quick analysis thereof. Previous to the focus group, the through the interviews 22 identified concepts on the effects such a KBS would have had been formulated into 22 exemplary statements. In the second part of the focus group, the participants were instructed to make joint decisions on how likely each proposed statement would occur. Therefore, the statements were listed on a poster on which the participants made a corresponding mark on a scale from one – 'unlikely to occur' – to five – 'likely to occur'.

Those two parts of the focus group cover the second and third step of the research design. The first step – the useful *project knowledge* identified – was not validated during the focus group. The knowledge deemed useful is very individual as it is based on an employee's position, experience and the *context* of his or her current project(s). Hence, the knowledge deemed useful by one interviewee might not be useful for the participants of the more homogenous focus group nor would their perspective diminish the actual usefulness for another persona. For this reason, validating the personal viewpoints of previous interviewees during the focus group was not considered reasonable to add to the previous findings.

3.4 Research Quality

This section assesses the quality of the research methods around different issues. Therefore, as set forth by Golafshani (2003), validity and reliability are elaborated below in the context of this qualitative study.

3.4.1 Validity

A major drawback of this research is that big construction projects often take multiple years to be completed. An investigation over the whole construction process would have been more valid; however the short time period in which this research is carried out does not allow that. Moreover, besides the collected data – via interviews and the focus group – no additional materials on the researched subject were available in the company.

The chosen research design is well-suited to make generalizable claims, if the sample cases are broadly representative for the industry. Therefore, case selection will be quite randomly done, on the basis of screening for suitable projects but is dependent on the accessibility of team members. Moreover, generalizability is dependent on sample size (Yin, 2013). The sample size in this research is quite low, while the research subject is quite broad. This negatively affects the generalizability of the results. To improve generalizability, either more cases could have been selected, or a simpler conceptual model could have been constructed.

3.4.2 Reliability

Two important ways to increase a qualitative study's reliability are providing a detailed description of the methodological steps. This is done in Chapter 3.1 and 3.2. A second strategy is to use more than one method to show the result's similarities. With the interviews and a focus group, this study uses two methods. Using further methods could have made the findings of this study more reliable, however, the projects researched are in different locations throughout the whole Netherlands, which may provide internal consistency of a measure across companies and locations.

4 Findings

The DT of a company is not caused by the digital technology – BIM – individually. Much of the potential for BIM has yet to be realized due to the way it is currently implemented in building design and engineering companies (Kivits & Furneaux, 2013). This study argues that the right integration of BIM into building design and engineering companies' KM transforms their business and how they work; hence, facilitates the DT of those companies.

The findings were structured according to the research design. Before presenting those findings in the following sub-chapters, a link to the theory is made for each sub-chapter. First, the *project knowledge* deemed useful will be presented (Chapter 4.1). Second, the stated operating principles of a Knowledge-Based System are set out (Chapter 4.2). Third, the expected implications of the KBS on the company's DT will be described (Chapter 4.3).

4.1 Useful Project Knowledge

According to Stewart (1998), knowledge has become the most important resource and asset for companies in the modern economy. The implementation of KM in project-based organizations should enable knowledge transfer across different projects, as well as capturing and storing knowledge in an efficient way (Kamara *et al.*, 2002). BIM forms the basis for this cross-project knowledge transfer and can provide a platform to integrate all relevant *project knowledge* with the data rich three dimensional representation of facilities (Goedert & Meadati, 2008; Deshpande *et al.*, 2014). In theory, all important knowledge obtained in a firm's many different projects can be stored in BIM and its linked databases. However, not all useful *project knowledge* is by default stored in a standardized digital and explicit form.

Ribeiro (2009) reasons that effective implementation of KM in AECO firms includes a clear view of what knowledge constitutes for the firm and what knowledge needs to be achieved. Similarly, Kamara *et al.* (2002) emphasize the *content* and *context* of knowledge. Respecting the *context* of a building design and engineering company, the *content* is discussed in the following.

4.1.1 Currently Reused Project Knowledge – Theme 1

Some interviewees did reuse knowledge from other projects in some form. Knowledge from other projects that was reused was primarily working methods and standards (5 out of 16 interviewees). In particular, those were "the standards you are using to describe the specifications" [7], the use of software, e.g. "BIM 360 platform and how to use it with external users" [14], and the methodology for "setting up the program of requirements" [13]. 3D elements (families) for design and modeling software were also reused (4 out of 16 interviewees). "We have a library and old projects are also in the library" [12]. This company-wide "library which expands" [9] made those 3D elements designed in previous projects available for reusing them in current ones [9, 12]. Furthermore, technical calculations (3 out of 16 interviewees), costs from previous projects with the same client [4, 5], scripts for the modeling software [8] and drawings [6] were reused.

4.1.2 Generally Stored Project Knowledge – Theme 2

A lot of knowledge and information that was getting stored in BIM models or relational databases could be useful for future projects. However, this *project knowledge* was not accessible or not findable (5 out of 16 interviewees) because it was unclear where to search for the information [16] or because "I don't have access to those models" [6] as the rights were not granted. Figure 8 gives an overview over the stored knowledge and information which was considered useful by the interviewees.

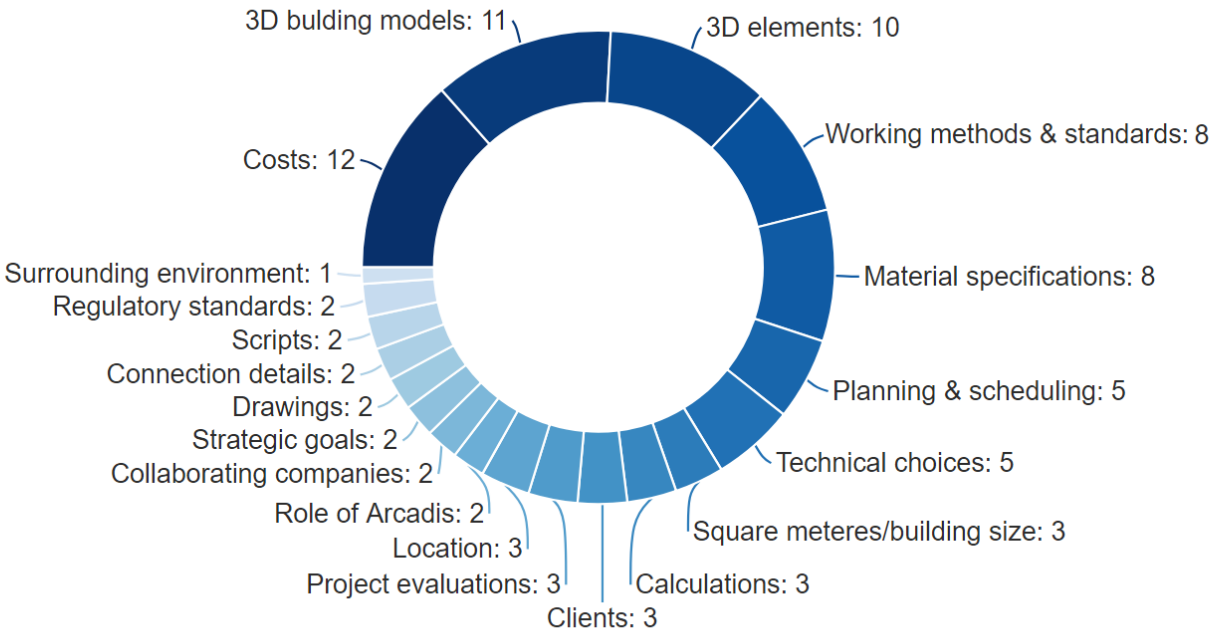

***Figure 8**: Generally in BIM models and databases stored project knowledge.*

Costs were considered the most interesting (12 out of 16 interviewees). "Reusing that data [of previous projects] to make a new cost calculation, that's really useful" [2]. Disagreements have come up about the level of detail at which price information should be captured – the whole building [2], "per supplier" [8] or "attached the price to [all] the elements" [12]. The designs in the forms of 3D building models were also deemed useful (11 out of 16 interviewees). Although, reusing elements on a larger scale was sometimes seen as problematic, "reusing big geometry, ... I've never really seen that" [9], still, some interviewees saw potential "when the kind of the building is the same ... and then the depths and then divide are almost similar ... [to] literally make a copy" [7]. An increased reuse of building blocks, "that's a tangible, small 3D model in our BIM models that can be transported from one project to another" [3] (e.g. a laboratory) was seen as an opportunity. In general, the 3D models of previous buildings could help to give inspiration to designers and clients and can help clients to make decisions [9].

The usefulness of 3D elements for the modeling software was repeatedly highlighted (10 out of 16 interviewees). A big library with "the definitions of objects" [15], "families in the BIM models" [13], "the identifier of an element" and "placeholder with the identifier" [9] would benefit building designers and engineers the most. Working methods and working standards are already exchanged on a small basis (see Chapter 4.1.3) but the actual need goes beyond the current state (8 out of 16 interviewees). Project workflows [4, 13] and the usage of new software [12, 16] were mentioned repeatedly. Furthermore, material specifications were considered useful information (8 out of 16 interviewees). That was because, on the one hand, solutions were needed for specific material circumstances like "using wood outside or metal outside" [10], and because on the other hand, "you can reuse that information to determine which choices are the best for a new situation" [2]. For the reasons behind the other available *project knowledge* which were considered useful see the supplementary files.

4.1.3 Generally Not Stored Project Knowledge – Theme 3

There was multiple information that would be useful but that are not stored anywhere at this moment. Figure 9 gives an overview over the knowledge and information which is not stored normally but which would be useful for the interviewees. The participants meant this information should be added to BIM models.

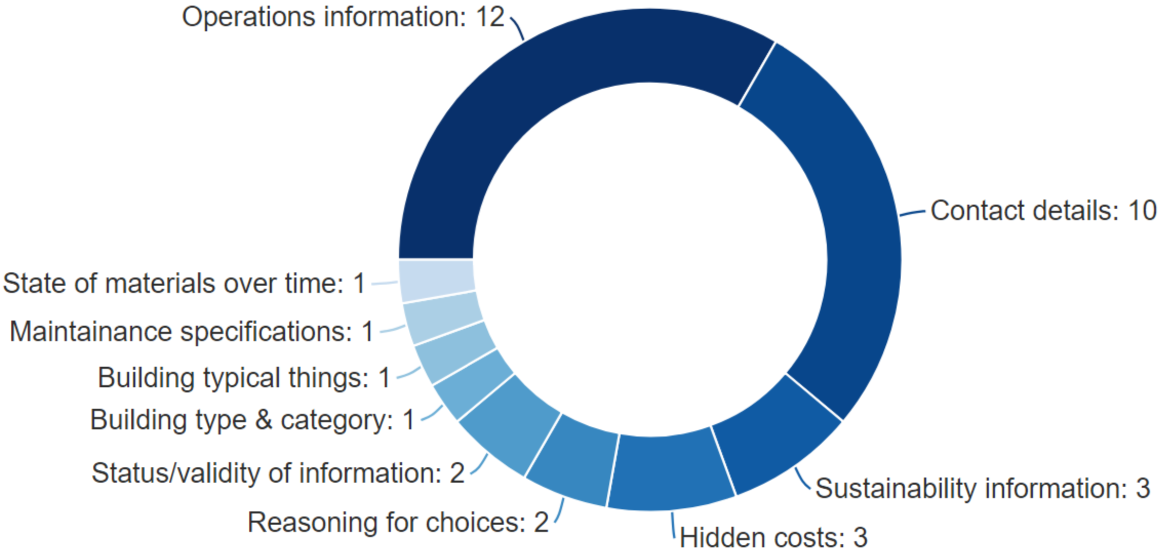

Figure 9*: Generally not stored project knowledge which should be added to BIM models.*

The potential value of information about the operations of buildings was pointed out the most (12 out of 16 interviewees). This data would be collected via sensors in the assets. Having this feedback for how well the designs and solutions developed functioned in practice, "I think that would be the best thing to validate your design during the operate and maintain phase" [8] which, in turn, would be "very interesting going back into the design process" [15]. At the same time, "we could be able to give a better advice" [14] to improve the performance of the assets of current clients. Also, contact details including the roles of people who worked on projects were considered very helpful for clearing questions about 3D elements, project decisions and experiences (10 out of 16 interviewees). At the moment, "it's very difficult to find the right person within Arcadis to start a dialogue to get a better understanding" [10]. Nevertheless, five interviewees considered contact details as unnecessary because, "when [the] design is complete enough, you can see what happens and the 'why'" [13] and "everyone knows how this was created or what were the principles" [3]. Despite this, in case questions remained, "we already know, who can be useful for a detail" [16] because "after a few years, you have a pretty good view of who you have to speak on which problems" [14].

Furthermore, sustainability information was highlighted (3 out of 16 interviewees). Given the fact that “there are some strict new regulations that are coming to the Netherlands” [7], “what we can add to our services is different types of sustainability advice” [14]. To give adequate sustainability advice in the future, information about sustainability measures that were taken in previous projects will be needed [14]. ‘Hidden’ costs were also brought forward as something that was not covered (3 out of 16 interviewees). Those costs are important for correct cost estimations and include “all things you don’t physically build” [2] like personnel and machinery costs to e.g. “making a hole in the ground” [2]. Another example that was mentioned was that, regardless of the material costs, “if the element is higher in the building, it will be more expensive” [12]. Moreover, as “the ‘why’ is very important” [13], a possibility to save the reasoning for choices was considered useful (2 out of 16 interviewees). Besides, the status of the validity of information was referred to as crucial to base future decisions on it (2 out of 16 interviewees). Therefore, it should be transparent how old the information is [13] and whether it is a conceptual solution or final and approved [6]. Apart from that, project information about the type and category of buildings [1], highlighting “these kinds of typical things for the ... building” [1], maintenance and security specifications about elements [7], being able to include the state of materials and elements over time, e.g. “we place a certain force on it [the beam] like a concrete floor and then it will be straight” [12], were considered important to be saved in BIM by individual participants.

4.2 Operating Principles of a Knowledge-Based System

Well-designed Knowledge-Based Systems are the backbone of effective KM (Carrillo *et al.*, 2000; Anumba *et al.*, 2000; Egbu, 2000; Tan *et al.*, 2010; Elgobbi, 2010). At the studied company, “there is nothing like a data storage, or I don’t think there is even a sort of a platform where we can store the information and make it reusable” [8]. For this reason, the operating principles of a KBS are researched, so that the knowledge stored in the BIM models can be transferred to and (re)used in other projects.

4.2.1 System Prerequisites – Theme 4

The KBS which is needed to make the knowledge mentioned in the previous chapter accessible and (re)usable would have to function easy and user friendly (6 out of 16 interviewees) – “otherwise, people won’t use it” [14]. Therefore, it was mentioned that the interface should not entail “just plain numbers, and really dry tables” [3] but should rather be visual and make it possible to “enter the models very easily” [6].

In terms of how to access the KBS, the opinions of interviewees were divers. The majority of those who furnished particulars (8 out of 16 interviewees) considered a web-based access point the favorable solution. This was deemed the best way to make all information available for everyone, also on “the phone or any computer you have internet” [14]. Besides, “a Revit plug-in can be very useful ... [because] a lot of people open Revit in the morning and close it in the evening” [11]. Revit by Autodesk is the company’s primarily used BIM software. Other participants “wouldn’t really focus on a Revit model personally” [3] for the reason that “it sort of limits usage ... because a lot of people don’t have Revit or access to Revit” [6]. Regardless, the plug-in could be run next to the web-based KBS and “it should have the same functionality" [3]. In addition, the plug-in could also provide useful design assistance, and therefore, would focus on the needs of building designers and engineers [2].

The need to combine a number of software and "some kind of business intelligence" in the background was highlighted [15]. Yet, the opinions on what platform the KBS should be based on and on which the BIM models should be stored on were divided. Two options were mentioned: using BIM 360 and realizing an own platform on SharePoint. BIM 360 is a cloud-based online platform for the management of construction projects and it is already used by the company. According to interviewees and focus group participants, some models are stored on BIM 360 already, why it was mentioned as an easy solution by some interviewees [1, 6]. During the focus group, the biggest advantage of BIM 360 was deemed the use of Revit files. Revit as the company's primary BIM software is used by all designers and engineers. Thereby, the BIM model of a building constitutes of the different disciplines' separate aspect models. Revit and BIM 360 are provided by the same company (Autodesk) and extend each other. Revit files contain all data of the elements, including detail sheets with 2D drawings, measurements and calculations behind them etc.; hence, they enable the search for those details. The KBS could link to BIM 360 to show those details. Others, however, stated that "the functionality [of BIM 360] is not as we wish, ... they have a lot of times a crash" [11]. Also, in BIM 360, "all the other projects I cannot review or look into" [11] "because in BIM 360 we are denying access and you have to ask for it" [16]. This was also the biggest critique point discussed during the focus group as an overall access to projects is not granted.

Given the downsides of BIM 360 and Revit, one interviewee [13] put forward "we have to realize our own platform to do that". Therefore, during focus group, SharePoint was discussed as a reasonable alternative to BIM 360. SharePoint is a web-based collaborative platform from Microsoft. The KBS which would be implemented on SharePoint would be based on the open BIM standard IFC (Industry Foundation Classes). The benefit would be a greater flexibility as "it doesn't matter if we want to change from Autodesk to Bentley tomorrow, that it's still a possibility" [8]. Compared to BIM 360, all employees would have access if BIM models were stored on SharePoint. Nevertheless, it was mentioned during the focus group that some accessibility problems would remain, and also, other than BIM 360, the system would have to be built from scratch. The main flaw, however, was that through the export from Revit to IFC, all detail sheets are lost. At the same time, the different aspect models from Revit are combined into one single model. Still, the kinds of details saved in the parameters of the exported IFC model might be enough for the KBS. Besides, as a workaround it was mentioned that the details could be kept separate and get linked to the IFC model. Yet, it remained unclear how this could be done.

4.2.2 Project Filtering and Displayed Results – Themes 5 and 6

Before being presented a pre-selection of projects, all projects of the company should be filtered based on some general criteria (10 out of 16 interviewees). After, the users could look into a specific project or search for more specific information in the BIM models. For filtering the projects, different building typological selectors were mentioned multiple times (7 out of 16 interviewees). These include "the type of building" [1] (new, existing, extension), building category (commercial, residential, mixed use, industrial, governmental)

[14], the intended “purpose ... for the building” [15] (e.g. office, education, health-care, sport), and the industry the building was built to serve [2]. Also, the external stakeholders involved were an important criteria to filter on (5 out of 16 interviewees) because different projects were done with those same stakeholders over a long period of time. Especially “all experience from specific clients” [10] but also “which contractors built a project” [14] were seen as crucial to base the project selection on. Furthermore, “you have to add materials [which were used]” [12], as well as “you can add laws and standards as the actual laws in text could be a filter” [9] (both 3 out of 16 interviewees). Equally essential was the buildings’ size, “with around this many square meters and then do a query” [2] (3 out of 16 interviewees). Another project filter mentioned was the surrounding environment (2 out of 16 interviewees), “so you say to urban area, you sort of filter your portfolio” [8] or “search for sea conditions” [10]. Moreover, the consideration of investment costs [2, 16] was highlighted. Besides, the strategic goals which were later translated into technical specifications [7, 15] were seen as an important selector before presenting a pre-selection of projects.

Half of the interviewees (8 out of 16) wanted the results of this filtering to prioritize successful projects, often referred to as ‘best practices’ [9, 15]. They mentioned, “it would be nice to have a tool which quickly enables the required person to get an overview of possible solutions, previous solutions, successful solutions” [4]. “So you can make a copy of the good examples” [7]. “I think only the results of evaluations, which lead to a good result are important for [us]” [10]. A lot less of them (2 out of 16 interviewees) meant, “it’s good to have bad results as well” [10] because “you learn much more from failure” [14]. For the selection of projects, there should be “the image and the description” [14] and “how many elements per square meter, so, everything would be averaged out to how many square meters per function” [3]. It was brought forward by some (3 out of 16 interviewees) that the KBS should “consider what kind of discipline” [1] the user has. For example, for a structural engineer, “it would be most helpful to have sort of details, to have access to the connection [technical] details” and a project manager “would search for specific project management things like risk management” [10]. During the focus group, however, it was stated that details like connection details were not specified as such in BIM models; thus, they would not be searchable in a KBS. Instead, it could be searched for types of 3D elements (families in Revit) and this way, the details could be found. For finding elements, it was suggested to use the codes assigned to each element according to the Dutch standard (NL-SfB).

An additional system feature which was deemed useful by participants of the focus group was the option to share the information about a project found in the KBS with clients digitally. For them, an online access point to view project information would be useful. Moreover, in case BIM 360 was the platform of the KBS, it was considered to provide the opportunity to specify the type of aspect model in which the KBS should search for information.

4.2.3 Design Assistance – Theme 7

Besides the by building designers and engineers often mentioned library of 3D elements (10 out of 16 interviewees), other design and modeling support functions were considered. Automation with the help of machine learning was one of those mentions (3 out of 16 interviewees). The system would get to a point at which it could interpret previous BIM models in such a way that it could design automatically, “you say created and it’s being created" [9]. Only key parameters would have to be provided to the system to perform such tasks [8]. Another idea was to expand the use of flexible building blocks, "developed through a few projects and now the same building block is already much better" [3]. Moreover, it was considered to combine this approach with machine learning and augmented reality. Based on previous projects, "the BIM modeling software would transparently position a project or a typical installation or layout of a building block for me. ... This optimized building block would fit in that volume and then you could say place it and I would do the fine tuning" [3]. Furthermore, "the suggestion part would be really interesting to help the modelers in making the right decisions. ... I analyze like ten earlier projects automatically and let the computer give me a suggestion for which material or which wall I should place" [2]. Another approach to this was, "I designed something in a in a specific phase and I would say analyze this and compare it to the previous design based on the key values ... [to see if I] meet the requirements" [3].

4.2.4 Entailing Problems – Theme 8

A number of issues have to be addressed to make the KBS work. First of all, new business models regarding the operations phase were deemed necessary (10 out of 16 interviewees). Those new business models would enable the collection of valuable usage data to enable the evaluation of designs and solutions developed in order to make better decisions for future projects [8]. At the moment, "our collection of information stops at this point that the building is finished" [1]. Nevertheless, clients had already started to ask, "What else can we do with the model? What other opportunities can you offer?" [3]. However, it was not clear yet, "how much money you can save or can be earned through this kind of model" [6].

At the same time, the difficulty remained to combine the very different projects on one system (8 out of 16 interviewees). The work and the projects that were done were perceived as very unique because "the type of buildings that we are working with is quite specific for this part of the Netherlands" [4], because of unique requirements and technical specifications [7], building size [7] or industry [14]. "And also, not all projects have BIM at the end. At Arcadis, there are also projects on energy advice or [on] advice for municipalities" [15].

Furthermore, it was indicated that a new standard for the information that would have to be added to BIM models would be required for the KBS to work (9 out of 16 interviewees). Subjects like scheduling were usually kept unlinked to the BIM models and useful parameters and details were not added [2]. Thus, everybody would have to be "willing to do a little bit more to deliver a model that's also suitable to reuse data from" [2].

"But all data has, everything has a price. So we have to look at value for money – what brings it for us and for the client" [14]. Therefore, usually, "we do not allow any other smart solutions because it then becomes too costly" [4]. Moreover, a high level of details "gives a heavy load to the model" [13], hence, the program runs slower (4 out of 16 interviewees). A technical solution for the KBS to function with such large models would have to be found [13].

Similarly, it was deemed complex to resolve the fundamental issue of dealing with a vast amount of data (3 out of 16 interviewees). "How do you organize it? How do you filter other relevant information for you? How do you share? And how do you make sure that information reaches the relevant people?" [3] "And most of times you're interested in details because the big parts are well known for everybody. And the details make the success. And how can you find them in such a lot of information?" [13].

Generally, the maintenance of such a system over time was queried, "Because people always struggle with maintenance, struggle with updating" [9] and "I'm not sure if this is possible to do this with all families from all projects" [15]. Also, "you really have to be sure that all your data is reliable or really see it as rough data and also approach it that way" [2] (3 out of 16 interviewees). But, "it's sometimes less easy to check if the information there is correct" [6]. Therefore, an easy way to check the accuracy of the information in the KBS would be needed. The issue of making sure that data in the KBS is correct was also highlighted during the focus group. Therefore, for each Revit family, a responsible person would have to be appointed who checked and made sure that all information was correct. Moreover, it was mentioned that many projects do not make it to the level of detail design. Linking to this topic, nowadays, the fast obsolescence of information might make it difficult to base decisions on the information in the KBS. This accounts true for the fast "development with innovation" in general [11] and also for price information for materials and products which are changing frequently [13].

To be able to use the KBS adequately, two interviewees (out of 16) had the opinion that "you have to have some knowledge to be able to analyze it [knowledge in the KBS]" [7]. Otherwise, "people are applying solutions to a situation which they cannot fully oversee and judge" [4], why "you'll have to be more a specialist" [7]. Likewise, "it can be very different what people expect or want from this kind of tool – not only from different people but also from different disciplines. So, that might make it difficult to make one general thing for everybody." [1].

Another concern that was mentioned concerned the automation through machine learning, "it could be like an algorithm wall" [8]. This development might reach a point at which employees cannot comprehend the recommendations of the system anymore, nor can they understand what the algorithm, "sort of what your core business is doing" [8].

4.2.5 Non-Technical Barriers – Theme 9

The interviews have shown that there are many non-technical barriers which would have to be overcome. Only then, the company would be able to implement a BIM-based KBS and could realize its DT.

It seemed like many people in the company still had difficulties in understanding DT and the capabilities of BIM as a digital technology (6 out of 16 interviewees). "Many people have difficulties or they say, 'okay, bring down I can't follow'" [3]. For this reason, "Arcadis is struggling now with defining the proper policy" [7]. A fundamental issue was the reluctance of people to change (4 out of 16 interviewees). DT, "it's not really on the top of the priorities" [8] as departments hold on to obsolete procedures and outdated technologies [12].

Furthermore, some people were expected not to be willing to share their knowledge as they held onto it as their intellectual result [9, 10]. "I think some people will think 'it's my intellectual result; I don't want to use it for another [project]'" [10]. Another reason mentioned why people could reject a KBS which makes their projects visible for everyone in the company was the fear of denunciation of their bad results [10]. Through this, colleagues might speak badly about them and value their work less. “Then they could say, ‘Hey, Ben has a bad result, what did he do there or is it just a joke’” [10]. Similarly, it was stated that some people saw a threat in the KBS because it could lessen the importance of their expertise, thus weaken their status in the company (3 out of 16 interviewees). Hence, “if you give your experience to another, that could be dangerous for some people” [10]. Besides all those barriers, some knowledge is “protected by privacy settings or laws, so you can’t reuse it” [9]. For example, “we can’t show our model to another supplier of the same product” [14].

It was claimed that employees and clients have to be convinced by the benefits of BIM and the proposed KBS (5 out of 16 interviewees). “So you really got to sort of engage people and proof that this is the best solution” [8]. This has to happen company internally, but also “we have to convince the client what we can do with BIM, what BIM stands for” [16]. Therefore, “awareness is the most important thing, otherwise there will be resistance to use different software or work in a different way” [11]. Only then, people could change their mentality and behavior and transform to a new company culture (4 out of 16 interviewees). “So people have to get more open to questions and try to help other people” [15]. “For some people it would be also a sort of a cultural change because they have to use some new software [and] also get acquainted with or getting used to that everything is centrally stored in the cloud ... [instead of using] ... their own little archives” [6]. Besides, “we as engineers should have much more focus on soft skills” [3].

4.3 Digital Transformation through the Knowledge-Based System

With knowledge being the most important resource and asset of a company (Stewart, 1998), and a BIM-based KBS enabling to access this knowledge (Deshpande *et al.*, 2014), this study argues that BIM-based KBS, in turn, facilitates the Digital Transformation of building design and engineering companies. As derived in Chapter 2.1.1, DT is the transformation of a company through digital technologies which stimulate significant change in internal processes and external relationships, enabling innovation and creativity. In the case of this study, the digital technology is BIM. The DT of a building design and engineering company is achieved when and if the proposed BIM-based KBS does entail significant change in: 4.4.1 Company Internal Processes, 4.4.2 Company External Relationships, and 4.4.3 Innovation and Creativity. The kind of change such a KBS implies in those three DT domains is object of this study.

4.3.1 Company Internal Processes – Theme 10

During the interviews, eleven different possibilities could be distinguished on how the BIM-based KBS could affect company internal processes. Figure 10 shows an overview over the likelihood of those possibilities to occur as expected by the follow-up focus group.

Figure 10: *Ranking of effects on company internal processes on their likelihood to occur ('0' – unlikely, '4' – likely).*

The general opinion was that the proposed KBS would improve communication and the spread of experience (10 out of 16 interviewees). Firstly, "people are easier to find and to ask questions about certain projects they've done" [15]. Secondly, the spread of experiences would, not only include a single department or country but the whole company worldwide. "Maybe it's possible that you start contacting somebody that is in France who created something that you're using. ... The contact between you and that person would be good for Arcadis and for the development of your own personality" [9]. Thirdly, "if you have accurate information digitally available to everyone, it also makes communication easier" [6]. Ideally, any information needed could be found as explicit knowledge in the system. Therefore, the dependence on other colleagues like a "manager or people who have generally been longer within the company and are always busy" [15] is reduced. However, this might have the counter effect that people would speak less with each other; even though, "every conversation can give you some [valuable] information or trigger some creativity" [8]. The focus group confirmed the relevance all of these interviewees' expectations.

Nowadays, "I talk to you, you forward me to the next person, [and] they forward me to next one" [8]. The KBS would allow users to "get faster to the information from colleagues" [1] than on the traditional way (13 out of 16 interviewees). This would "save time, so you have more time for the creative part" [3], it would "speed up the whole schedule" [7] and "you will not have to do all rework" [8], thus, work "can be more efficient and quicker" [4]. "So the productivity will improve" [8]. At the same time, "you don't make the same mistakes" [12]. Participants of the focus group were more critical on this point as users would still make mistakes. Actually, they saw a risk that wrong things could be copied as the information in the KBS could not be right all the time. As interviewees expected less mistakes, "you can improve the quality of your work" [15] (3 out of 16 interviewees). "So when it's shorter in time and then the quality remains high, it definitely is a victory" [7]. The focus group was similarly critical on that point but seized the opportunity for this. Another possible positive effect through the KBS to "create more acceptance and respect for each other" [9] was seen as unlikely by the focus group participants.

Some interviewees were convinced that new workflows would be required (5 out of 16). Also, the focus group rated this aspect with the highest likelihood. The reasons stated were ranging from the new need to work "in a very structural way" [13], having to add "an extra step or some extra actions" [15], to a fundamental change in the digital environment because "3D modeling times are over" [3]. Apart from that, the KBS was seen as a new way of setting up project teams with the right expertise (3 out of 16 interviewees). The system would make it "easier to filter out which persons you want to work with within a project" [15], "like PeopleFinder but for designs" [9]. PeopleFinder was the company's system on the intranet to look up information on employees. The focus group acknowledged a limited likelihood for the KBS to be used for this purpose as people from last projects are not necessarily most suited for next similar ones. Furthermore, the KBS would enable it to "make more reliable decisions earlier ... so, you don't need really the highly specialized people from week one on but you can use that information to make high level decisions" [2] (3 out of 16 interviewees). Therefore, experts would be needed only later in the process for more detailed decisions. Furthermore, an expert's task could be "delegated to a junior who doesn't have the experience, but has the ability to look into a data source with the experience" [15]. The focus group considered this implication through the KBS; however, participants saw a small likelihood for it. Concurrently, within the company, "we will need some more digital talent" [8]. An increased "digital savviness" was assumed necessary to make the KBS work as well as with respect to the needed digital endeavors of the company [8].

4.3.2 Company External Relationships – Theme 11

The interviewees mentioned four main possibilities on how the BIM-based KBS could affect company internal processes. As derived from the focus group, Figure 11 shows an overview over the likelihood of those possibilities to occur.

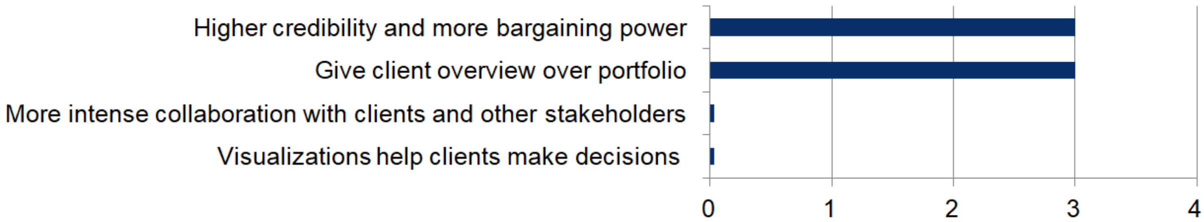

***Figure 11**: Ranking of effects on company external relationships on their likelihood to occur ('0' – unlikely, '4' – likely).*

The effect on external relationships, especially with clients, was rated throughout very positively during the interviews (15 out of 16 interviewees). Visual models and visualizations of previously applied solutions could help clients to make better decisions (10 out of 16 interviewees). "It's a big advantage for them to see what in a design what they are going to get ... and it's also easier for a client to make a design decision then" [6]. Considering the big differences between projects, the focus group rated this aspect as unlikely. Nevertheless, using the KBS, "we can show them how useful BIM can be. That's sometimes what we miss. You know, we have to convince that client: What is BIM, what can you do with it" [16].

Similarly, clients could be given an overview over the portfolio with the company's experience relevant to them (3 out of 16 interviewees). "To show what was done before can be very convincing for clients and it can help us to get more projects" [11]. The focus group saw this as similarly useful. Through the widely collected and evaluated data, the KBS would help to precise estimations, "because you have a better reference of previous projects then this helps the client in getting the estimations better" [15]. "It also helps to build a good relationship and trust if you can show what was done and have numbers for the success" [11]. Reliable and convincing data would also give the company a higher credibility and more bargaining power in debates. "Right now, it's just opinions – it's your opinion to my opinion. But if I can explore what's going on with the data, 'look, we've measured this on 50 buildings, so, we know what we're doing.' I think that gives you a better position during debates" [8]. The participants of the focus group considered this as quite likely.

Moreover, a more intense collaboration with clients and other stakeholders should be pursued (4 out of 16 interviewees). Thereby, companies could "help each other to be more productive and more innovative with the whole business" [2]. "And hopefully this will make sure that clients get what they want" [9] and "in the long term it can help the whole industry" [2]. However, the focus group found this to be a unlikely implication through the KBS.

4.3.3 Innovation and Creativity – Theme 12

During the interviews, seven different options could be differentiated on how the BIM-based KBS could affect innovation and creativity. Figure 12 shows an overview over the likelihood of those options to occur as expected by the follow-up focus group.

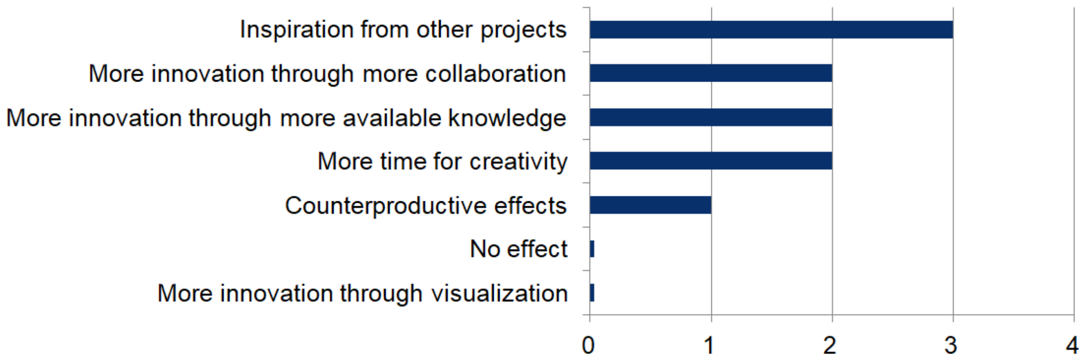

***Figure 12**: Ranking of effects on innovation and creativity on their likelihood to occur ('0' – unlikely, '4' – likely).*

The view on the enabling of innovation and creativity through the proposed KBS was ambiguous. Most interviewees mentioned positive effects (11 out of 16 interviewees). As the KBS saves its users time, "you have more time then to accelerate on this knowledge and use your creativity to do new things" [15] (3 out of 16 interviewees). The newly available time can be used "for the creative part of the design aspect" [3] and more value could be added to projects, "if I can come up with a smart way to automate it, I have more time to think about the installation concept or making, for example, a virtual reality tour for the client" [3]. All of these creative tasks require creativity and innovativeness and would otherwise not be pursued. Through the KBS, trying "a different approach doesn't need to be that costly because the machine does most of the work" [4].

In addition, the KBS would enable the sharing and utilization of more knowledge. More knowledge would lead to more innovation (3 out of 16 interviewees), in particular in connection with digital technologies [8]. As put by one participant, "I think it brings knowledge. You can use knowledge for innovation, [and] combine it with other digital solutions" [14]. Furthermore, "it might also get you to new ideas if you look around a little bit" [1]. Likewise, "you can really help each other to be more productive and more innovative with the whole business" [2]. Thus, more collaboration – with "other disciplines" [6] and with "the whole industry" [2] – would help to spur innovation (3 out of 16 interviewees). Through collaboration, "people start to put their own knowledge together ... and then we start to innovate because we can make combinations of things" [7]. The focus group considered some likelihood for all aforementioned implications of the KBS on innovation and creativity. Furthermore, an interviewee deemed, "if the design is more readable through 3D digitization, through looking at it from the same perspective, it can be also easy to have more creative solutions because more parties involved can give their ideas" [6]. This, however, was seen as unlikely by the focus group participants.

At the same time, three arguments were given for counterproductive effects on innovation and creativity (3 of 16 interviewees). Firstly, "if you want to be creative, you won't be influenced too much by a result of old projects" [10]. Secondly, "a bigger amount of data about how it has always been forces you within a direction it has always been and keeps the innovation apart. Because you know what's working and actually, the things you've done two or three times become the new standard and keeps it centered because they're easier to look back into" [15]. Thirdly, as already mentioned, if all information were available digitally, employees would have to speak to less or to even no people at all to get the information they need. However, "every conversation can give you some information or trigger some creativity" [8]. The participants of the focus group considered a limited likelihood for these counterproductive effects to occur.

Besides all this, some interviewees (5 out of 16) do not expect any effect on innovation and creativity. As one interviewee put it, "I don't think it's within the system, the innovation, I think, is still within the people" [15]. As the focus group expected effects on innovation and creativity to occur, the participants rated no effects through the KBS as unlikely.

4.4 Summary

Figure 13 shows an overview over the results. The KBS transfers the *project knowledge* stored in BIM models to building designers and engineers of the focal firm. This has an effect on internal processes, e.g. through higher efficiency and performance, improved communication and new workflows. Furthermore, external relationships are effected, e.g. through higher credibility and bargaining power, more intense collaboration and helping the clients to make decisions. At the same time, the KBS affects innovation and creativity of the company directly through, e.g. inspiration from other projects, and indirectly through the increased collaboration with external stakeholders.

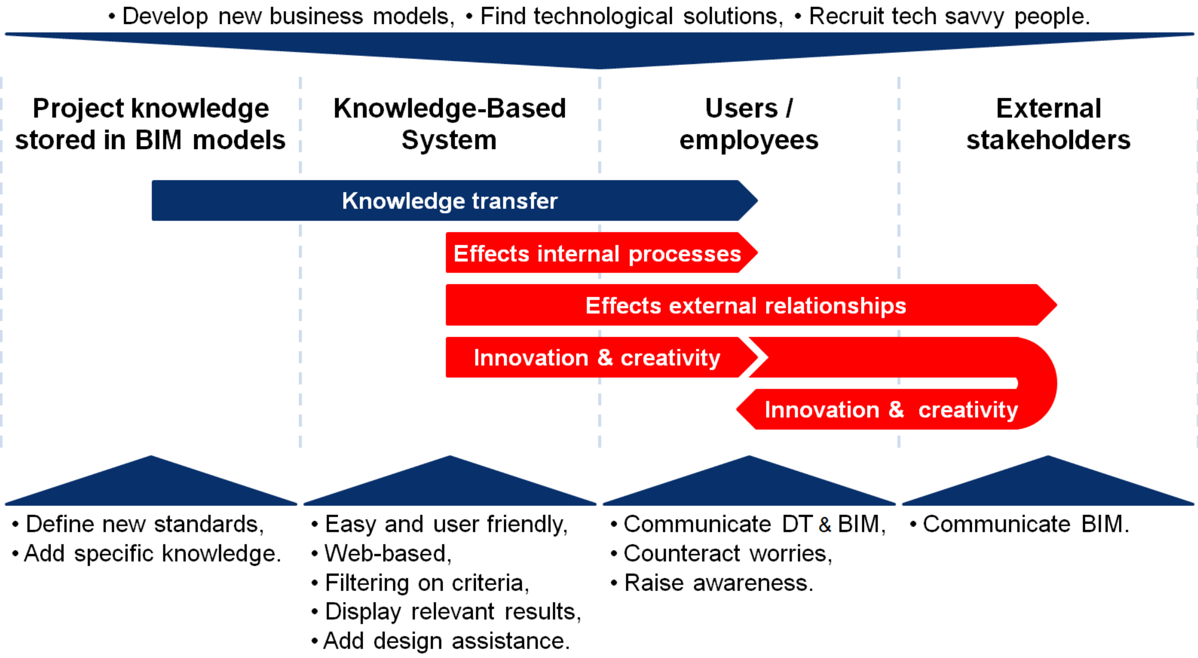

Figure 13*: Overview over the results.*

For the knowledge transfer to function and for the described effects to happen, a number of criteria have to be fulfilled. Firstly, to the *project knowledge* stored in BIM models, further specific knowledge has to be added and therefore a new standard has to be defined for what and how knowledge is getting stored. Secondly, the KBS has to function easily and user-friendly, it should be web-based, enable the filtering based on specific criteria, display relevant results and provide additional design assistance to designers and engineers. Thirdly, to the users of the system, thus the employees of the firm, the benefits of DT and BIM have to be communicated, worries connected to DT and the introduction of the KBS have to be counteracted, and awareness for KM and the KBS have to be created. Fourthly, like the employees inside the firm, the external stakeholders, hence clients, contractors and sub-contractors, have to be convinced of BIM by putting the benefits of the technology across. Lastly, on the company level, new business models concerning the operations phase have to be developed and implemented, technical solutions have to be found for e.g. dealing with a vast amount of data and with intelligent algorithms, and more tech savvy people have to be recruited to be able to cope with these issues.

5 Discussion

This chapter compares the findings to previous research in order to expand on the theoretical level of the integrated conceptual framework of BIM-enabled DT (Figure 3), thus, increases its explanatory power (Chapter 5.1). Afterwards, it discusses the limitations of the present research (Chapter 5.2), and subsequently, the posed avenues for future research (Chapter 5.3). Lastly, it elaborates on the implications of the study, both theoretical and practical, on the DT of building design and engineering companies (Chapter 5.4).

5.1 Enriching the Theoretical Framework

Firstly, it will be discussed what useful *project knowledge* constitutes and what factors influence the cross-project transfer thereof. Secondly, the operating principles for a KBS which can, in turn, make this knowledge accessible, are defined. Therefore, the functioning of the KBS is discussed and visualized in a conceptual interface design. Lastly, the implications of the proposed KBS on the DT of a building design and engineering company are discussed.

5.1.1 Useful Project Knowledge

Following Ribeiro (2009) and Kamara *et al.* (2002), this study aims to identify knowledge what constitutes for building design and engineering companies. With respect to the opportunities through BIM, it is critical to define the *content*, thus the useful *project knowledge*, for the given *context* of those firms. Therefore, the actual knowledge demands from employees in both managing and technical positions should be in alignment with the knowledge stored and made accessible to them.

Actually, much of the *project knowledge* deemed useful were either information on the project as a whole or on the specific elements. Elements are the virtual equivalents of actual three-dimensional building components. They include walls, columns, beams, roofs, and slabs amongst others. In that sense, neither the classification by El-Diraby & Kashif (2005) – into project, process, products, actor, resource, and technical topics – nor the classification by Ho *et al.* (2013) – into activity, object and issue – suit the needs for KM in a building design and engineering company. As an alternative, this study proposes the classification into two main concepts of *project knowledge*: ‘project specific’ and ‘element specific’. Project specific knowledge is general information about a project as a whole. Most of those particulars are well known by all team members and can be added without substantially increasing efforts (and costs). In contrast, element specific knowledge is information on the different elements of a building’s BIM model. Depending on the point of view, some knowledge can be assigned to both concepts, for example costs for the whole project and costs for each element. In Table 3, the identified types of knowledge were allocated to those two concepts. Types of *project knowledge* in the middle column were assigned to both concepts.

***Table 3**: Allocation of identified types of project knowledge to the introduced concepts.*

Project specific	Element and/or project specific	Element specific
3D building models (design),	Costs,	3D elements,
Working methods & standards,	Material specifications,	Calculations,
Planning & scheduling,	Sustainability information,	Connection details,
Square meters/building size,	Drawings,	Scripts,
Clients,	Operations information,	State of materials over time,
Project evaluations,	Contact details,	Maintenance specifications.
Location,	Hidden costs,	
Role of Arcadis,	Reasoning for choices,	
Collaborating companies,	Technical choices,	
Strategic goals,	Status/validity of information.	
Regulatory standards,		
Surrounding environment,		
Building type & category,		
Building typical things.		

In accordance with Nonaka (1994) and Sveiby (2001), through BIM, project teams transform their tacit into explicit knowledge in the form of 3D information and databases attached to them. Project specific *project knowledge* can be added to projects' BIM models without much effort, increasing the usefulness of those models for the future. Equally, knowledge types assigned to both concepts can be stored on the project dimension. However, digitally storing element specific knowledge at a high level of detail is connected to difficulties such as higher efforts, time and costs. Currently, the level of detail saved in BIM models varies greatly between projects [1, 13]. On the one hand, details of other projects are most wanted and determine the success of a project [13]. Hence, the highest possible level of detail in a model should be aimed at during projects. On the other hand, "all data has, everything has a price" [14]. To balance knowledge availability for future (re)use and costs, a compromise has to be found and defined as a reasonable standard for the minimum level of detail at which *project knowledge* should be stored. This concerns element specific knowledge in particular as its level of detail, in theory, could be exorbitantly high.

Role of Tacit Knowledge

Hence, tacit knowledge exchange could help to bridge the gap between the stored explicit *project knowledge* and the not stored knowledge on details. Previous literature commonly highlights the importance of social interaction and dialogue among people to create new knowledge (Fruchter *et al.*, 2009; Valentim *et al.*, 2015; Chen & Mohamed, 2010; Forcada *et al.*, 2013). The findings of this study, however, challenge the importance of tacit knowledge exchange. On the one hand, the majority of interviewees saw benefits in knowing the contact details to connect with creators and decision-makers of other projects to clear questions. In this sense, the KBS could facilitate explicit and tacit knowledge exchange alike. On the other hand, two interviewees stated that when the models would have the highest level of detail, it would be sufficient for all designers and engineers to understand the underlying reasoning for the choices made and know how elements were created. Hence, contacting people would be obsolete if one could find all the needed information in the KBS.

However, this is unlikely to be sufficient in every case. Even though most choices for element details might be comprehensible from the BIM model solely, this is probably not always the case. In fact, Newell *et al.* (2006) indicate that the knowledge about the deployed processes to achieve goals and the reasoning for their success or failure would be more useful than the sharing of knowledge about actual achievements in relation to the stated goals. Strategic choices taken throughout the process are saved in project evaluations; still, not everything can be expected to be saved in them. On the one hand, this would increase the needed effort for a project, and on the other hand, as evaluations are usually written down at the end of a project, reasons behind decisions during the project lifecycle are likely getting lost. Therefore, and looking back at the required high level of detail for element specific knowledge, tacit knowledge exchange can give access to otherwise unavailable knowledge. Until technologies reach an economically viable point at which reliable information is stored with the highest levels of detail, providing contact details for facilitating tacit knowledge exchange is the best practice to supplement the transfer of explicit knowledge.

Influences on Cross-Project Knowledge Transfer

This study supports the findings of Kivrak *et al.* (2008). *Project knowledge* of other projects often was not findable and not accessible [8]. Hence, indeed, KM within the firm was not sufficient as there was no general strategy and no systematic way of managing knowledge across project borders. Moreover, as brought forward by several authors (Haldin-Herrgard, 2000; Moud & Abbasnejad, 2012; Ho & Liu, 2011; Wiewiora *et al.*, 2009), geographic separation impedes the transfer of useful *project knowledge*. Generally, this holds true for the studied firm as the exchange of knowledge with a person outside of the Netherlands was seen as extraordinary, "good for Arcadis and for the development of your own personality" [9]. Furthermore, the findings of this study confirm Newell *et al.* (2006) because it project teams have used knowledge from other projects to save time [9, 13]. Concurrently, as stated by Zhao *et al.* (2015), Loo (2002) and Moud & Abbasnejad (2012), the required time effort to capture learnings was seen as a barrier for the cross-project transfer of knowledge [2]. Hence, this study does not support Connelly *et al.* (2009) because under the given circumstances of the focal firm, time actually had an impact on knowledge transfer.

Moreover, as discovered by Moud & Abbasnejad (2012), the findings confirm that the more a project is perceived as unique, the less likely participants try to learn from others. Continuing Lewis *et al.* (2005) and Darr & Kurtzberg (2000), project similarity was the determining factor for knowledge transfer. In general, the participants indicated that the more a project had in common with their own, the more likely the knowledge gained in the other project would be useful for their project. At the same time, the findings support Zhao *et al.'s* (2015) conclusions on the diminishing influence of project similarity on the transferred knowledge when the to-be-transferred knowledge was technology-oriented. Currently, as it was hardly possible to find out what projects are similar to one's own and to access the related knowledge, non-project specific knowledge in the form of working methods and standards for the use of software were the most accessible, thus, most reused kind of knowledge. In those cases, the settings of the projects had subordinate importance.

5.1.2 Operating Principles of a Knowledge-Based System

A KBS forms one of the three basic components for successful KM highlighted by Kandadi (2017) – the (technology) infrastructure for knowledge sharing. Unlike Liu *et al.* (2013), the results show that the proposed KBS should not rely on a plug-in for the BIM software Autodesk Revit primarily. To make the stored *project knowledge* available to all employees, a web service is the preferred option. Still, a shortcut to the web-based KBS could get implemented in Revit. Besides, during the focus group, central topic of the discussion was the platform on which the KBS should be based on and on which the BIM models should be stored on. As described in Chapter 4.2.1, two options are possible: using BIM 360 and realizing a platform on SharePoint based on the open standard IFC. Appendix G.1 compares both platforms and pursues an approach to combine them.

Search Principles

To access the *project knowledge* stored in the KBS, previous authors such as Liu *et al.* (2013) refer to complex queries to search for the needed knowledge in the database. However, this is contrary to the general demand for an 'easy' system. Hence, this study proposes two successive search steps: First, searching for the project(s) about which information is wanted and finding its/their project specific knowledge; and second, searching for element specific knowledge needed from this/those project(s).

For the first search step, the search for projects and their project specific knowledge, users should be able to search projects on the basis of the same criteria as the project specific knowledge (see Table 3). Besides, different main filters that should always be presented were identified during the interviews (see Chapter 4.2.2). The following filters were deemed appropriate:

- Investment costs,
- Building size,
- Building type,
- Building category,
- Building function,
- Sector,
- Region,
- Status.

It was decided on these filters because they are generally available for all projects and comprehensible for technical and managerial positions alike.

Following the first search step, the search for element specific knowledge happens in a second search step. Thereby, users might either look up information on elements or they might want to find 3D elements for reuse in their current project. Hence, an option to specify on that aspect is needed. They can find elements (and view their details) via the search for keywords or through the codes assigned to each element according to the Dutch standard (NL-SfB) or another element identifier. For technical constraints on accessing specific *project knowledge*, see Appendix G.2.

Search Results

Ho *et al.* (2013) emphasize on the BIM-based illustration of knowledge to keep and explain information in a digital format. The findings support that results should be presented in a visual manner [3]. Generally, most participants would prefer to make only successful projects and solutions available via the KBS. However, according to Kandadi (2017), for successful KM, success as well as failure has to be captured (and made accessible). Only then, companies can learn from all the experiences of other projects. Moreover, whether a solution is good or bad is mainly depending on personal opinion [10]. Therefore, the proposed KBS includes all projects and solutions – successful or not. Furthermore, as suggested by Deshpande *et al.* (2014), not only finished but also ongoing projects should be available through a KBS. The authors suggest companies to set milestones when the knowledge generated and stored in the BIM models is extracted to the KBS database. Going a step further, ideally, the latest versions of projects' BIM models should be available via the KBS. This allows for an even shorter lag in dissemination of knowledge and spurs continuous improvement.

Ho *et al.* (2013) introduce variables to store tacit knowledge and make it available through a KBS. Though, according to Nonaka (1994) and Sveiby (2001), through this, tacit knowledge is converted into explicit knowledge. Hence, previous literature on BIM-based KBSs sees the KBS as a means to facilitate the transfer of knowledge in its explicit form only. However, with the importance of tacit knowledge exchange as discussed in Chapter 5.1, it is also crucial to provide the names and contacts of experts who were working on the projects and elements. Moreover, for the filtered projects, average project specific knowledge, e.g. average square meters and investment costs, were requested during the interviews.

Validation of Project Knowledge

Workflows have to get adapted to validate the *project knowledge* made available via the KBS. This is needed because "you really have to be sure that all your data is reliable" [2] and "comparable to one another" [15]. Following Liu *et al.* (2013) and Deshpande *et al.* (2014), concerning project specific knowledge, at the end of a project, it is made sure by a related team member that all project specific knowledge was added and is correct [1]. Furthermore, concerning element specific knowledge, it has to be made sure that the Revit families for reuse are correct. Therefore, while designing in Revit, there could be a checkbox or request to validate and release the family for reuse. In contrast to project specific and other element specific knowledge, only validated families should get extracted and shown in the KBS results for 3D elements for reuse [15] as those are meant for direct copying.

Interface Concept

Based on the findings and discussed aspects, a concept design of the KBS interface was developed. The following description is only exemplary (for enlarged depictions and detailed description, see Appendix H.1). For the sake of an easy to use KBS, "it should be some kind of Google, some kind of search system" [16]. Hence, the Google search along with Amazon and Bol.com served as inspiration for the KBS interface.

Characteristic for the start page of the KBS (Figure 14) is a predominant central search field, inspired by the Google search start page. Likewise, below the search field, suggested projects (websites on Google) are shown.

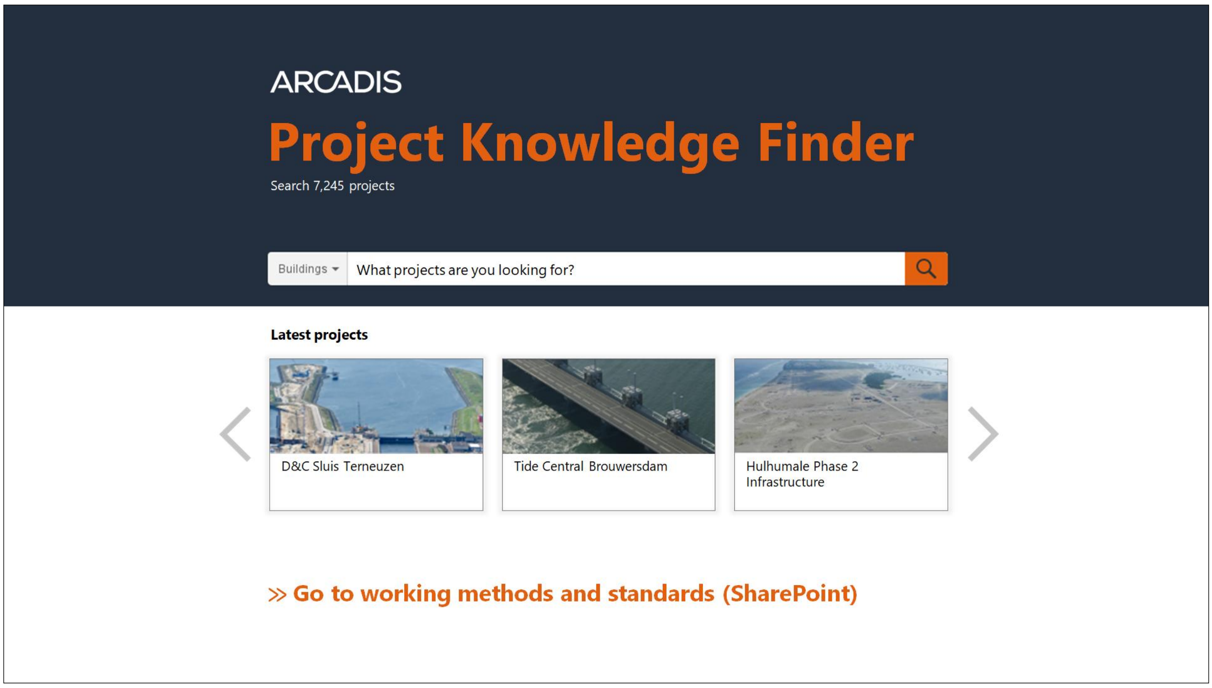

Figure 14*: KBS concept ‘Project Knowledge Finder’ – start page.*

Inspired by Amazon and Bol.com, the results for the project filtering present an overview over the different products – in this case projects – with a picture and title. Previously discussed filter options are on a left side bar. For a further element specific search in the marked project(s), a search field is provided on a right side bar. Below, the options are given to access all the project specific knowledge of the project, view the project’s BIM model as well as to directly contact the associated project manager.

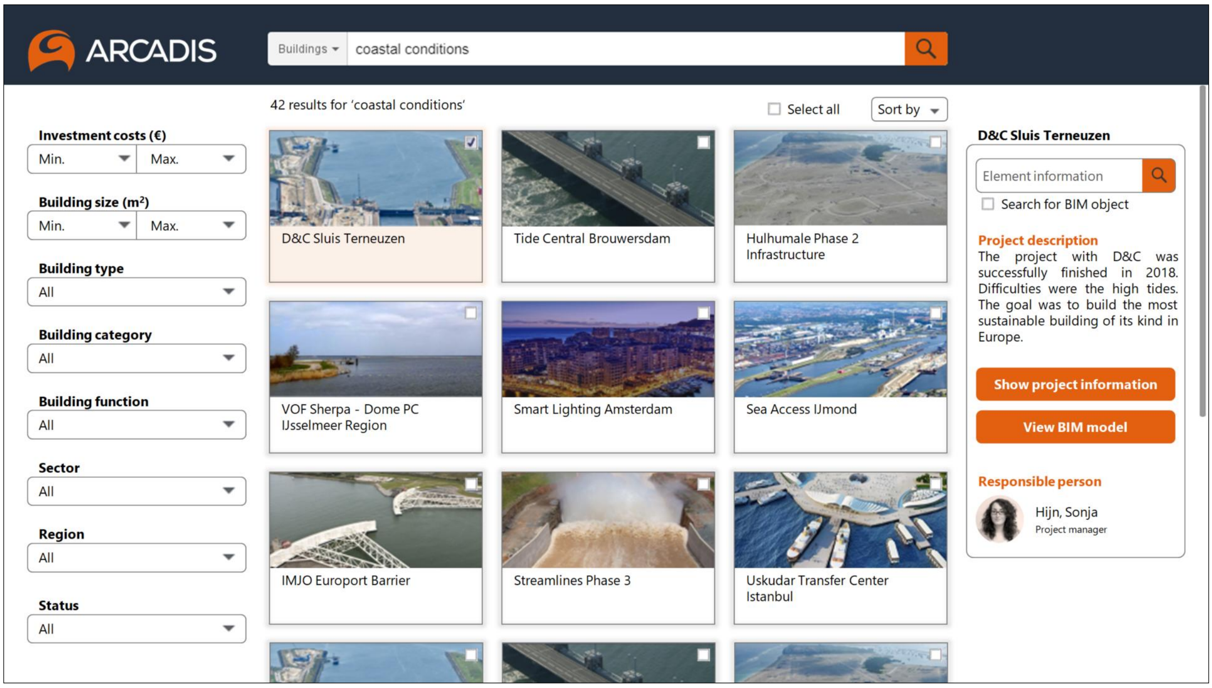

Figure 15*: KBS concept ‘Project Knowledge Finder’ – results of project search.*

The results of the search for element specific *project knowledge* (Figure 16) are presented in a similar manner than the results for the project filtering. They display a selection of all different types of the searched element integrated in the project(s).

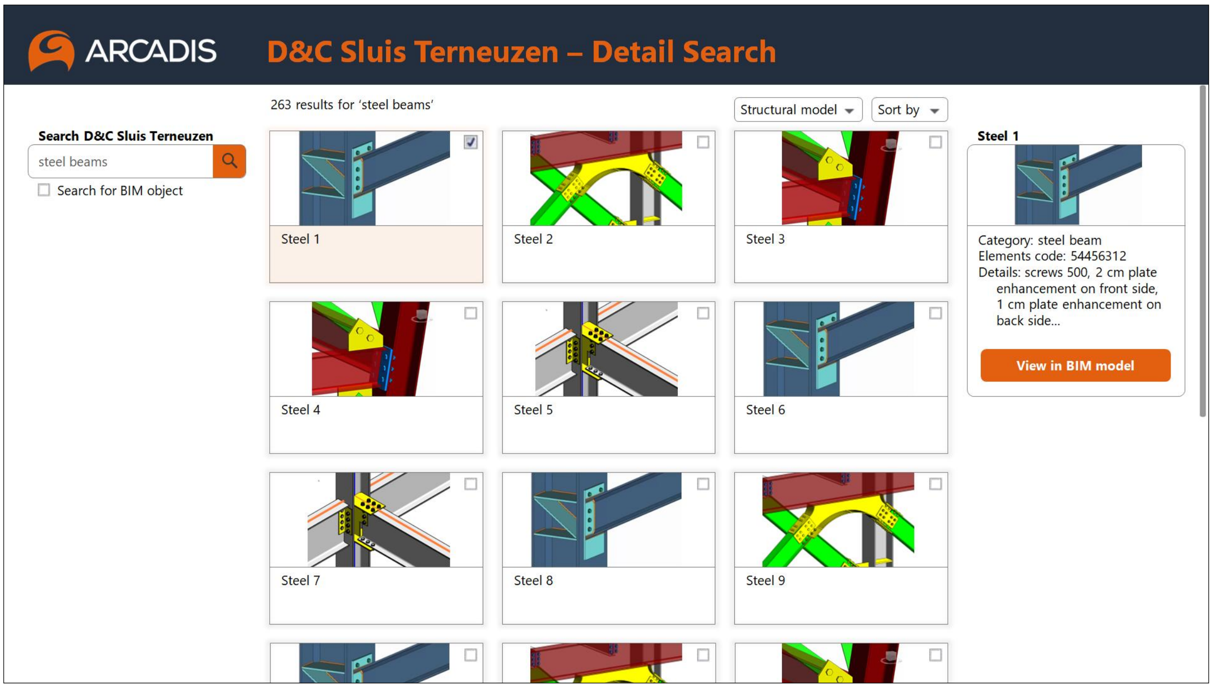

Figure 16*: KBS concept 'Project Knowledge Finder' – results for the search for elements.*

Appendix H provides a detailed description of the proposed interface concept. Furthermore, it is elaborated on possible design assistance functions which could be provided with the help of a BIM-based KBS.

5.1.3 Digital Transformation through the Knowledge-Based System

Until now, no AECO company has completed its DT – one that fully harnesses the power of digital technology to rethink every aspect of the organization. Moreover, over time, new digital technologies continue to emerge and the organization continues to transform. Therefore, it can be argued that the DT of a company is never ending. However, at the moment, the AECO industry is undergoing a complete DT for the first time through digital technologies such as BIM. Certainly, the wide-scale adoption of CAD software since the late 1980s (Osman *et al.*, 2003) had already transformed internal processes of building design and engineering companies to some extent. Still, CAD as well as the current usage of BIM had little to no effect on the way business was conducted in the old-established market structures, as often, "we are submitting our work in paper" [4]. Likewise, innovation and creativity have hardly been spurred, as the productivity of the European AECO industry has stagnated for decades (McKinsey, 2016). Concluding from Chapter 4.2.5, for the successful DT of building design and engineering companies, a fundamental shift in mindset is required from employees of the focal firm and external stakeholders alike. Figure 9 illustrates those requirements for DT. Hence, this first complete DT can be seen as the most crucial one.

Determination of Significant Change

This study aims to determine whether BIM-based KM in the form of the proposed KBS is able to facilitate the DT of a building design and engineering company. According to this study's working definition of Digital Transformation, BIM facilitates the DT of building design and engineering companies when it stimulates significant change in internal processes and external relationships, enabling innovation and creativity. Knobel (2008) points out that significant change within the professional or knowledge domain is not simply the enhancement and support of traditional methods. Thus, for company internal processes, significant change means any change involving a fundamental reorganization of processes (and possibly people) inside the company. Regarding company external relationships, the nature of those relationships changes and the upcoming of new types of stakeholders change the way which and how stakeholders interact. Moreover, unprecedented possibilities for innovation and creativity emerge.

During the interviews, many of the claims made in literature (see Chapter 2.1.2) were stated repeatedly. Concerning the effects of BIM in general (not KBS specific), many effects could already be judged on their impact in practice. BIM supported decisions and improved processes throughout the project lifecycle confirming the findings of e.g. Eastman *et al.* (2011) and Shen & Issa (2010). Positive effects that were perceived for parametric modeling, clash control, simulations and accurate geometric representations support e.g. Ding *et al.* (2006) and Li *et al.* (2006). Furthermore, Hartman & Fischer (2008) and Succar (2009) stated intensified collaborations which, in fact, could be confirmed by participants. Also, the customer satisfaction had risen through visualization and the information exchange had become easier confirming e.g. Eastman *et al.* (2011) and Azhar (2011). Benefits through the application of BIM in the operations phase were recognized by the majority of interviewees (12 out of 16 interviewees); however, BIM is barely applied by the end users of buildings until now. Regardless, the expectations of interviewees support the connected benefits for more effective facility management with an easier, rapid and accurate information exchange and integrated life-cycle data as stated by e.g. Eastman *et al.* (2011) and Rezgui *et al.* (2013). Moreover, benefits for sustainable design, as mentioned by e.g. Eastman *et al.* (2011), were expected but not realized, yet.

Beyond general effects through BIM, a couple of authors touched upon the implications of a BIM-based KBS. Their claims are endorsed in the findings of this study. The interviewees expected the saving of time, higher efficiency and better performance through the proposed KBS which supports Furcher *et al.* (2009) and Liu *et al.* (2013). Furthermore, as Furcher *et al.* (2009) mentioned, communication and the spread of experience are improved. Likewise, the avoidance of mistakes and the reduction of rework, as stated by Wong & Fan (2013) and Liu *et al.* (2013) were confirmed. Moreover, communication across disciplines is improved (Fruchter, 2009), and faster and more reliable decisions are made possible (Fruchter, 2009; Liu *et al.*, 2013). Hence, the focus of previous literature on a BIM-based KBS was primarily on company internal effects. The effects mentioned, however, rather enhance and support traditional methods than stimulate significant change within the professional or knowledge domain because they do not imply a reorganization of internal processes.

To reliably assess whether building design and engineering companies reach DT, the three domains company internal processes, company external relationships, and innovation and creativity require separate evaluation. Accordingly, Table 4 classifies the through the introduction of the proposed BIM-based KBS expected effects which were identified through the interviews. Some of those effects actually are digitally transformative because they imply significant change within the professional or knowledge domain, while others only enhance and support traditional methods.

***Table 4**: Distinction between digitally transformative effects and traditional methods enhancing and supporting effects of the proposed KBS.*

Digital Transformation fundamentals	Digitally transformative effects	Traditional methods enhancing and supporting effects
Company internal processes	• Less dependence on colleagues, • New way of setting up project teams with the right expertise, • More reliable decisions earlier without experts, • New workflows required, • More digital talent required.	• Saving of time leads to higher efficiency and performance, • Avoidance of mistakes, • Higher quality, • Improve communication and the spread of experience, • Improve respect for each other.
Company external relationships	• More intense collaboration with clients and other stakeholders, • Higher credibility and more bargaining power.	• Give client overview over portfolio, • Visualizations help clients make decisions.
Innovation and creativity	• Inspiration from other projects, • More innovation through more knowledge and digital technologies, • More innovation through more collaboration, • More innovation through visualization.	• More time for creativity.

Through the interviews, a couple of digitally transformative effects through the BIM-based KBS were determined. They were deemed as such for the following reasons:

Company Internal Processes

Four digitally transformative effects on company internal processes were identified. First, less dependence on colleagues is such an effect because the hierarchical structures of how people depend on each other and how they pass on knowledge are fundamentally altered. Second, as a new way of setting up project teams with the right expertise, the KBS does also change the way how teams are formed; thus, different teams might be formed than before. Third, more reliable decisions earlier without experts are a crucial change because when in the process and from whom decisions are taken changes. Therefore, the scopes of duties of experts and non-experts shift and overlap. Although, according to the focus group, this kind of implication through the KBS is less likely, it remains a possibility. Fourth, new workflows emerge. The replacement of old workflows with new ones is a central point of DT. Fifth and last, more digital talent is required. This reflects the new processes and tasks for which more tech savvy employees are needed who also have the soft skills to explain technical topics in an easily comprehensible way.

Company External Relationships

Concerning company external relationships, the proposed KBS implies two digitally transforming effects. First, a more intense collaboration with clients and other stakeholders is a significant change in the professional domain. Collaborations with clients become more intense as, through the KBS, the focal firm understands their needs better; thus, new services can be provided to them. Moreover, the intensity of collaboration and the roles of stakeholders in the old-established market constellations change. However, the focus group deemed a more intense external collaboration an unlikely effect through the KBS. Second, the credibility and bargaining power of the focal firm increases. This puts the company in a strong position to win tenders and convince new clients and stakeholders.

Innovation and Creativity

For principal reasons, some interviewees did not expect any effect on innovation and creativity. "I don't think it's within the system, the innovation, I think, is still within the people" [15]. Fruchter *et al.* (2009) stated that knowledge is created through dialogue within or among people as they use their past experiences and knowledge in a specific context to create alternative solutions. Hence, the KBS does not lead to innovation by itself, but as it is used as a tool to obtain new knowledge, new possibilities for users emerge to apply this knowledge to innovate and to be creative. Many possibilities for innovation and creativity which the KBS implies are unprecedented. The KBS enables creativity through inspiration from other projects, spurs innovation through the accessibility of more knowledge and digital technologies, drives innovation through more collaboration, and stimulates more innovation through comprehensible visualization made accessible through the KBS. However, although Hartmann & Fischer (2007) highlight the importance of efficient visuals to support the communication of knowledge in construction projects, the latter point was not expected to have a major effect on innovation and creativity by the focus group.

5.2 Limitations

As described in Chapter 2, the '*content*' is difficult to separate from its '*context*' when looking at the AECO industry. This calls for an intensive study. However, as this research had time constraints, the intensity of study was limited to sixteen interviews and a focus group. Through the general conditions for the choice of interviewees (Chapter 3.3), this study has tried to capture the largest possible variety of project *contexts*. Still, the participants determine the results, as one interviewee stated, "because people have experiences that are only part of the game and then they have their own view on things or their own perception" [7]. During the interviews, many points were mentioned repetitively; nevertheless, for a better understanding of the research subject, a larger sample would have been necessary to capture the full realm of predominant opinions. Moreover, an ideal setting of the study would follow the participants over the entire course of their project(s). As it was assumed that the viewpoints on what *project knowledge* was deemed useful change over the course of a project, participants should get interviewed in every sub-phase of the design process. This is also important given the fact that three out of eight sub-phases of the design process were not covered through the participants available at the time.

As stated in Chapter 4.2.5, a number of serious worries were connected to the Digital Transformation of the focal company. To avoid possible changes implied by the results of this research, consciously or subconsciously, some interviewees might have not been completely open and/or too critical about the current situation (social desirability bias). To avoid this, the purpose of the research could have been kept vague towards the participants and questions would have been worded carefully with respect to each participant.

The validity of the results is limited as only one organization was studied. Nevertheless, the chosen company is exemplary for building design and engineering firms in the Netherlands for several reasons. First, BIM has a high priority not only in the focal firm but throughout the Dutch AECO industry (Hall, 2018). Second, according to a study by NBS (2018), the company's primary BIM software by Autodesk (Revit and BIM 360) was used by 66% of all building designers and engineers in the UK in 2018. Because of the geographic proximity and a similar BIM awareness and adoption in Great Britain and the Netherlands (McKinsey, 2016), it can be assumed that Autodesk software is similarly predominant in the Netherlands. Hence, similar KM issues resulting from the restriction of *project knowledge* through the use of BIM 360 can be expected for a majority of Dutch firms. For those reasons, the generalizability of the findings for the Netherlands can be assumed. With the rising regulatory demand for BIM in many developed countries (McKinsey, 2016) and given the need for effective KM to remain competitive in the modern economy (Stewart, 1998), the general applicability of this study can be expected to continue to rise internationally.

5.3 Avenues for Future Research

To address the aforementioned limitations, a wide range of building design companies should be researched in follow-up studies. In doing so, a larger number of participants should be followed over the whole course of their project(s) and measures to counteract social desirability bias should be taken.

This study developed the operational principles for a BIM-based KBS and researched in what ways its introduction implies the DT of a building design and engineering company. Naturally, the next steps are to put the system into practice and to study whether the expected digitally transforming effects hold true. In doing so, possible risks of the KBS to adversely affect traditional knowledge transfer methods should be monitored. Interviewees and the focus group alike saw a risk in employees obtaining information from the KBS rather than from people, because the exchange of useful side information is diminished. Similarly, interviewees stated that fewer conversations could adversely affect innovation and creativity. The proposed KBS counteracts these threats through the provision of contact details to spur tacit knowledge exchange. Yet, further research needs to validate these risks and the effectiveness of counteracting measures.

Furthermore, the advanced development of a BIM-based KBS requires more research on the different identified levels of design assistance (see Appendix H.2); hence, how the KBS can be extended to allow for design assistance functions. Moreover, as described in Chapter 5.1 and 5.2, the development of new standards and workflows to capture, store and disseminate project and element specific knowledge and new business models concerning the operations phase of buildings are needed. Therefore, extensive research is necessary. At the same time, internal and external communication of DT and BIM and the changing requirements through

DT in building design and engineering companies require further studies. This is necessary to raise awareness and lower connected fears of employees about the entailing changes.

The discussed issues result in the following research questions which could not be answered by this thesis and should be addressed by future research:

- Do the through the proposed KBS expected digitally transforming effects hold true in practice?
- Does the proposed KBS adversely affect traditional methods for tacit knowledge transfer of a building design and engineering company?
- How can the proposed KBS be utilized for design assistance?
- What are suitable business models for a building design and engineering firm to collect data on buildings' operations?
- How can the benefits of Digital Transformation and BIM be communicated most effectively to employees of a building design and engineering company?
- How can the current workforce adapt to the changing requirements of a digitally transforming building design and engineering company?
- What are the drivers and barriers of different construction stakeholders to adopt BIM?
- What are suitable standards and workflows to capture currently not captured *project knowledge* of a building design and engineering company?
- At what level of detail should *project knowledge* be captured to ensure an optimal potential for later knowledge (re)use at a building design and engineering company?

5.4 Implications

This chapter elaborates on the main theoretical and practical implications of the current study. It discusses the literature gaps addressed in this thesis, including methodological limitations of previous research in the fields of BIM, the Digital Transformation and Knowledge Management in the AECO industry. Secondly, it discusses the roles of committed employees and managers of building design and engineering companies in facilitating the DT of their organization by implementing the ideas described in this research.

5.4.1 Theoretical Implications

As mentioned earlier, the current thesis addressed multiple gaps in previous literature. Most notably, it connected the three fields of BIM, Knowledge Management and Digital Transformation. Past studies mostly focus on these research domains independently. While a few studies research BIM in relation to KM, the connection of BIM-based KM with DT is not made. Accordingly, the effects of BIM-based KM are solely discussed in the realm of enhancing and supporting traditional methods. This study, in comparison, has focused particularly on the digitally transformative effects of a BIM-based KBS on a building design and engineering company. Furthermore, in previous literature, KM and DT are usually seen as separate though each other influencing entities. This study, however, has deduced a rather leveraging relationship: effective KM is the basic prerequisite for the DT of the company. Hence, without adopting measures to enable effective KM, DT cannot be realized. This thesis therefore strengthened the fields of BIM, KM and DT. By using professional insights in the context of KM (and KBS) challenges, this study developed a novel approach for implementing BIM in a building design and engineering company. Thereby, a better understanding of DT in such companies was provided.

As discussed in Chapter 2, KM strategies for AECO organizations should reflect *context* and *content* of the project-based industry (Kamara *et al.*, 2002). Therefore, Fruchter *et al.* (2009) use ethnographic observations for their research on BIM-based KM. Other authors (e.g. Ho *et al.*, 2013) look back on previous studies and, in retrospect, gathered feedback from industry practitioners. In contrast, this study takes another methodological approach by conducting interviews before deriving results as well as using a focus group to check the validity of the results. This thesis provided rich, qualitative insights both prior and after deriving findings, addressing this persistent methodological gap.

5.4.2 Practical Implications

The theoretical implications discussed above gave rise to various practical implications. This thesis showed that Knowledge Management and the digital strategy of the focal building design and engineering companies are not aligned. On the one hand, there is a driving force for implementing digital technologies, "now we are changing to BIM 360" [7]. On the other hand, "they're creating new walls between the projects, so, it becomes impossible to look in other projects for information because of this new system" [13]. Hence, the implementation of those technologies restricts access to explicit *project knowledge* rather than allows for the transfer thereof between projects. This study argues that the alignment of KM and digital strategy, in turn, facilitates the DT of a building design and engineering company. Therefore, "I think it is important to work on the implementation of this [KBS]" [11].

As building design and engineering companies implement the proposed KBS, they enable the discussed transfer of *project knowledge* across projects. This is expected to have significant effects on company internal processes, company external relationships, and innovation and creativity; thus, it will help those companies to achieve DT. The findings show that many benefits can be connected to this. Continuing Kamara *et al.* (2002), this will increase the organization's ability to bid for, and win contracts, as well as make a profit after the completion of projects. Furthermore, following up on previous authors like Kivits & Furneaux (2013) and Agustí-Juan *et al.* (2019), it can be assumed that this leads to the improved business performance the industry requires and thus, can bring about important economic and societal advantages. Through the implementation of the proposed KBS, knowledge on the efficient use of resources and energy, both for the construction of buildings and during their operations after the completion of the projects, is captured and made accessible to other project teams. This allows for constant improvements on the use of less raw materials and energy in similar buildings which contributes to the low-carbon transformation of the AECO industry.

6 Conclusions

The way how building design companies integrated BIM to transform their businesses and how they work has not been sufficient for Digital Transformation. Therefore, a new approach to implementing BIM is needed. Utilizing BIM for Knowledge Management purposes could entail those needed effects and facilitate the companies' Digital Transformation. From the outset, this paper argues that BIM has the potential to facilitate the DT of a building design and engineering firm through its opportunities for effective KM. BIM as a centralized and shared knowledge resource forms the basis for enabling the transfer of knowledge across projects (Deshpande *et al.*, 2014). Hence, the requirements to utilize BIM for the transfer of knowledge across projects and the digitally transforming effects this might entail were evaluated in this study. Therefore, sixteen interviews with employees in technical and managing positions as well as a focus group with BIM strategy experts were conducted. In the process, the main research question was as follows:

How can BIM enable the transfer of knowledge across projects to facilitate the Digital Transformation of a building design and engineering firm?

The main research question is answered by answering the sub-questions (a), (b) and (c) which is done below.

Sub-question (a): To what extent is the knowledge stored in BIM models useful for other projects?

Much of the knowledge stored in BIM models is useful for other projects. For an overview over generally in BIM models and (linked) databases stored *project knowledge*, see Figure 8. However, not all useful knowledge is getting stored in BIM models, yet. Therefore, new standards and workflows are needed.

Sub-question (b): How would an ideal Knowledge-Based System function in order to make knowledge stored in BIM accessible and (re)usable?

An ideal BIM-based KBS would be web-based and easy to use for all employees of the firm. To grant access to all projects' knowledge, it would utilize the advantages of the open standard IFC, while maintaining the same models in the Autodesk standard to be able to give access to detail sheets if needed. The KBS should have two successive search steps: First, for project(s) of interest and providing their project specific knowledge, and second for finding element specific knowledge in those projects. For the depiction and detailed description of the proposed KBS, see Appendix H.

Sub-question (c): In which ways could BIM-based Knowledge Management imply DT of a building design and engineering firm?

The DT of a building design and engineering company is facilitated when BIM-based KM stimulates significant change in internal processes, external relationships, and enables innovation and creativity. In all of those domains, digitally transformative effects occur. An overview thereof can be found in Table 4.

The research has shown that in order to enable the transfer of knowledge across projects to facilitate the Digital Transformation of building design and engineering firms, a number of issues have to be addressed on different levels. Figure 13 gives an overview of those issues. With the identified *project knowledge* and the established operational principles of a BIM-based KBS, this study represents a basic approach to facilitate the Digital Transformation of building design and engineering firms and serves as a starting point for future research in this domain.

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The past six months have been quite a journey, both in terms of academic and personal growth. At times, this journey was challenging and like an adventure – a challenge and an adventure that I have enjoyed and learned from, but also one that I could not have done by myself.

I immersed myself into three promising fields of research in the AECO industry, being BIM, the Digital Transformation and Knowledge Management. The almost endless possibilities of BIM to manage data and to create more sustainable buildings have fascinated me since I heard of it for the first time at ETH Zurich one year ago. Eventually, I was so convinced of the opportunities of BIM that I decided to cofound a start-up concerned with the subject. The gained knowledge on BIM and its application in the built environment will therefore surely help me in my future endeavors.

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Appendix A – Project Specification

A.1 BIM Levels

The BIR (2016) defines the following BIM levels:

Level 0 – Old way of working
CAD and document-based design.

Level 1 – Object-oriented 3D design
Characteristic of this level is the application of clear objects to which information can be linked. On this level there is no question of integration between different disciplines or aspects. So no coupling of the 3D model with, for example, financial calculation or planning software.

Level 2 – Merged
Collaboration is based on a collection of autonomous databases – each has its own model. All these models are combined in one view model to collaborate file-based on a project. Applications such as planning (4D) and cost calculations (5D) can also be linked to the model. The parties that share the information are usually located within one controllable or manageable organizational unit.

Level 3 – Integrated, lifecycle
Information is shared between different (un)known parties – not just within one organizational unit – via interoperable Open BIM standards. This is possible, for example, in an integrated web services environment. No more file-based exchanges, but object-based exchanges. The construction process is fully integrated in the chain. At the end of level 3, information is shared about the lifecycle in the integrated environment. There is a stronger relationship with facility management and asset management.

A.2 Sub-phases of the design process

Table A.1*: Sub-phases of the design process – Dutch standard DNR-STB 2014 (BNA, 2017).*

Label	Name	Purpose
IH	Initiative/feasibility *Initiatief/haalbaarheid*	Making an inventory and analyzing a housing requirement or market demand and investigating the feasibility of a project to meet that need or market demand.
PD	Project definition *Projectdefinitie*	Inventorying and recording the ambitions, requirements, wishes, expectations and conditions of the client and future users in such a way that a design process can be started on that basis.
SO	Sketch design *Structuurontwerp*	Development of a general representation of the project in such a way that it gives a good picture of the solutions on an urban scale and of the main form and layout of the buildings.
VO	Preliminary design *Voorontwerp*	Development of a general representation of the building in such a way that it gives a good picture of the location, the functional and spatial structure, requirements, uses, the architectural appearance and the integration of structural and installation aspects.
DO	Final design *Definitief ontwerp*	Development of a detailed representation of the building in such a way that it gives a good picture of the appearance, the internal and external structure, the use of materials, the finishing and detailing, the structural structure and nature and capacity of the installations.
TO	Technical design *Technisch ontwerp*	Elaborating and specifying the structure in all its facets in a technical sense in such a way that definitive pricing for the execution can take place on that basis.
PC	Price and contract formation *Prijs- en contractvorming*	Selecting and contracting an 'offering party' for the implementation of the project, depending on the contract form, whether or not including design, financing, maintenance and / or operation
UO	Execution *Uitvoering*	Development of the design in such a way that the production of building and installation components, as well as the actual execution and assembly can take place on the construction site on the basis thereof.

Appendix B – Interview Guide

Introduction

I study a Master in Sustainable Business and Innovation at Utrecht University. Right now I am writing my master thesis here at Arcadis. Through my research I want to facilitate the digital transformation of the company. Therefore, I focus on the transfer of information and knowledge across projects.

To be able to process the gathered information correctly, I kindly ask for your permission to record this interview. All information will be treated confidentially and your name can be anonymized upon request in my thesis. The interview will take about 45 minutes. Please answer freely and add experiences and thoughts you have spontaneously.

Generalities

Interview number:
Date and time:
Location:

Interviewee

Name:
Position:
Relative level of abstraction: *very low / low / high / very high*
Years of experience:

Focus project

Name:
Design phase: *IH / PD / SO / VO / DO / TO / PC / UO*
Building type: *new / refurbishment / extension*
Building category: *commercial / residential / mixed use / industrial / governmental*
Total development costs (estimate):

I. What are your general responsibilities?
II. Can you shortly describe the usage and involvement of BIM in the project (BIM level)?
III. What program do you personally use in connection with BIM?

Main Part

Are you using information or knowledge from other projects in which you were not involved in?

1. **Why? Why not?**
2. **What (other) knowledge of other projects could be useful?**

For my research, I am especially interested in the knowledge and information stored in the BIM models of other projects.

3. **Describe an ideal project. In general, which information stored in its BIM model could be useful to you?**

3.1. To what extent are designs of other (similar) projects useful?

3.2. To what extent are contact details of other (similar) projects useful?

3.3. To what extent are specifications like cost estimations, suppliers, constructability, time scheduling and planning of other (similar) projects useful?

3.4. To what extent would data collected during the operation (via sensors) and updating the BIM model be useful for future projects?

4. **Do you think BIM models are generally missing useful information that should be added?**

I want to develop operating principles of a knowledge system which allows to access and use the knowledge and information stored in the BIM models of previous and ongoing projects.

5. **How would an ideal knowledge system look like for you?**

I imagine the system in a way that you can filter all projects of Arcadis based on general requirements (type of building, type of development, client etc.) which leaves you with a limited number of projects and information about them (location, people involved etc.) and shows average information (costs, square meters, rooms etc.). Users can ask the system for average or specific information or look into a specific project's 3D model and can contact the people involved.

5.1. What do you think about this functionality?

5.2. How should it integrate into your workflow and the software you use?

6. **What do you think in which way the tasks or workflow during a project would change?**
7. **What do you think in which way the interaction with colleagues and departments within Arcadis would change?**
8. **What do you think in which way the interaction with clients and external stakeholders would change?**
9. **What do you think in which way this would enable new innovation and creativity?**
10. **What do you think are non-technical difficulties for integrating such a BIM-based knowledge system?**

Closing

11. **[Who is a leading designer or engineer of the project I could interview?]**
12. **Is there anything else you would like to add to this interview?**

Thank you for your time and in helping me with my research. If you are interested in my results, I can provide them to you. Also, I will give a lunch presentation on the topic in Amersfoort at the end of July.

Appendix C – Interviewees

Table C.1*: Interviews. Personal data about the interviewees were complemented through the search system 'PeopleFinder' on the intranet. Project information was gathered through the consultation of the company supervisor and during the interviews.*

Interviewee						Focus Project						Interview			
No.	Name	Role	Position	Years experi-ence	Use of BIM software	Focus project	Design sub-phase	Building type*	Building category**	Total develop-ment costs (million €)***	BIM-level ****	Date and time	Duration (min)	Technique	Location interviewee
1	Dieneke Grimmelius	managing	Project manager	22	no	Project 1	UO	new	commercial	41	2+	11-04-2019, 14:00	42	Skype	Rotterdam
2	Matthijs van de Riet	managing	Project leader architecture	3	yes	Project 2	PD	new	industrial	120	2+	18-04-2019, 16:00	44	Personal	Den Bosch
3	Gergely Horváth	technical	Modeler MEP	13	yes	Project 1	UO	new	commercial	41	2+	24-04-2019, 10:00	53	Skype	Amersfoort
4	Erik Loovers	managing	Project director	26	no	Project 3	DO, SO	new, refurbishment	residential	> 300	1+	29-04-2019, 14:00	49	Skype	Den Bosch
5	Pascal Gulikers	technical	Architectural designer	22	yes	Project 2	PD	new	industrial	120	2+	30-04-2019, 11:00	34	Skype	Maastricht
6	Meint Smith	managing	Project manager	12	yes	Project 4	UO	extension, refurbishment	commercial	12	1	06-05-2019, 11:00	35	Skype	Rotterdam
7	Henri Verploegh	managing	Project manager, advisor	36	yes	Project 5	UO	new	governmental	270	1	07-05-2019, 14:00	71	Personal	Amersfoort
8	Miguel Verweij	managing	Assistant project manager	3	yes	Project 6	PD	new	mixed use	300	1	13-05-2019, 13:00	37	Personal	Amersfoort
9	Michel Fiscalini	technical	BIM coordinator, designer	12	yes	Project 3	DO, SO	new, refurbishment	residential	> 300	1+	14-05-2019, 13:00	51	Personal	Amersfoort

Interviewee						Focus project						Interview			
No.	Name	Role	Position	Years experi-ence	Use of BIM software	Focus project	Design sub-phase	Building type*	Building category**	Total develop-ment cost (million €)***	BIM-level ****	Date and time	Duration (min)	Technique	Location interviewee
10	Ben Roest	managing	Project manager	29	no	Project 7	PD	new	commercial	50	1	15-05-2019, 11:00	56	Personal	Amersfoort
11	Pascal Robben	technical	Designer	25	yes	Project 4	UO	extension, refurbishment	commercial	12	1	15-05-2019, 14:00	45	Personal	Amersfoort
12	Pascal de Leeuw	technical	BIM coordinator, designer	23	yes	Project 4	UO	extension, refurbishment	commercial	12	1	22-05-2019, 13:00	32	Skype	Rotterdam
13	Peter Loggere	technical	Technical advisor	27	no	Project 5	UO	new	governmental	270	1	23-05-2019, 10:30	45	Personal	Amersfoort
14	Bram van Gurp	managing	Project manager	20	yes	Project 8	PC	new	mixed use	30	2	24-05-2019, 09:30	50	Personal	Amersfoort
15	Joop Zuur	technical	Designer, digital innovation eng.	9	yes	Project 3	DO, SO	new, refurbishment	residential	> 300	1+	24-05-2019, 11:00	39	Personal	Amersfoort
16	Tijs Struijk	technical	BIM coordinator, designer	19	yes	Project 8	PC	new	mixed use	30	2	24-05-2019, 14:00	42	Skype	Maastricht

* Building type: Specifies whether a building is newly built, refurbished or extended.

** Building category: Specifies whether a building is commercial, residential, mixed use, industrial, or governmental.

*** Total development costs: Total of all costs incurred from initiation to implementation of a project. This includes all costs for site acquisition, relocation, demolition, construction and equipment, interest, and carrying charges (HUD, 2014).

**** BIM level: The ‘+’ indicates that at least one requirement of the next BIM level as described in Appendix A.1 was fulfilled.

Appendix D – Coding Tree

Structural Code: Useful project knowledge

For reasons of space, the coding tree was divided into three trees for the structural codes. They are presented in the following three figures (D.1, D.2 and D.3).

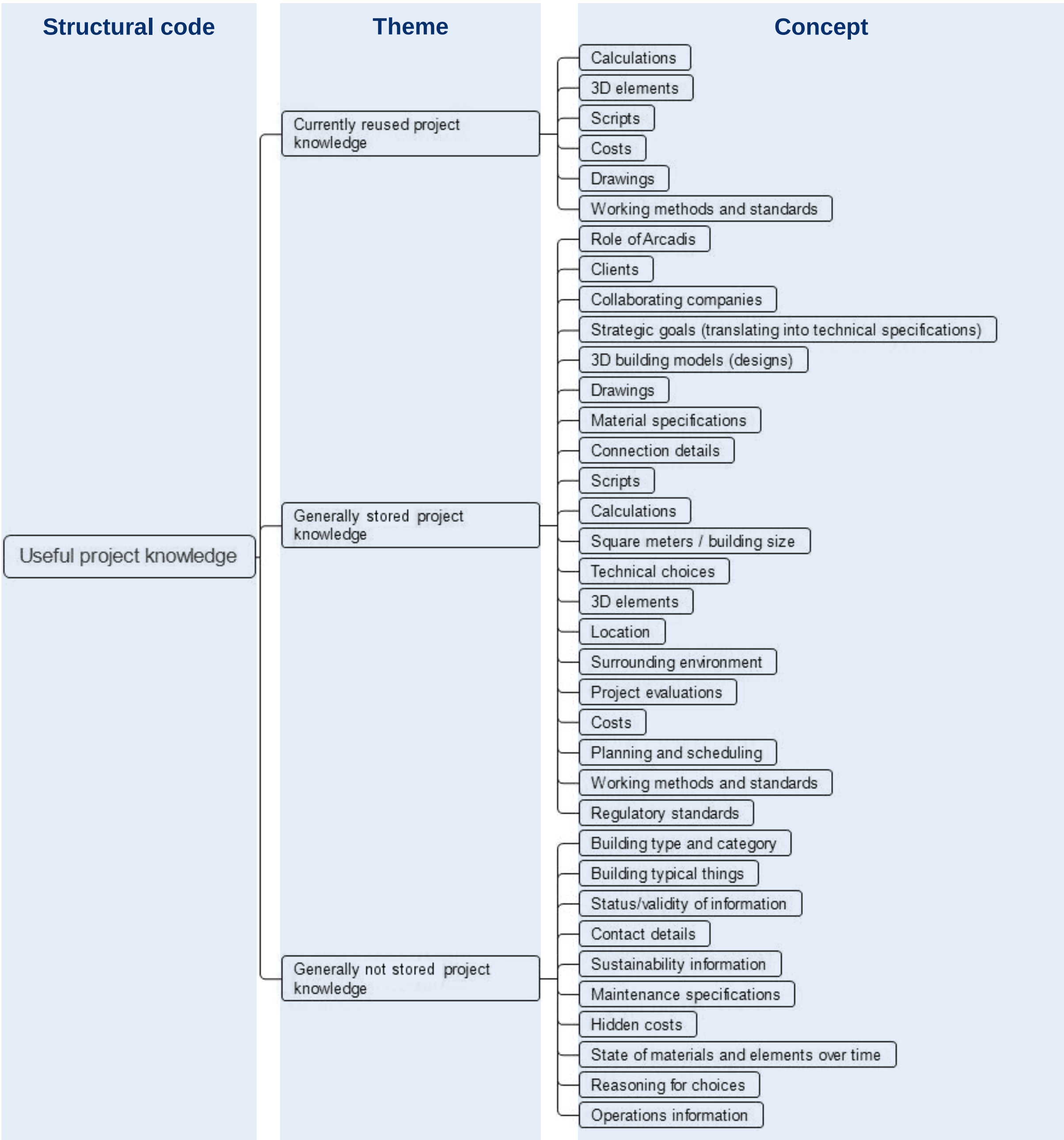


***Figure D.1**: Coding tree for structural code 'useful project knowledge'.*

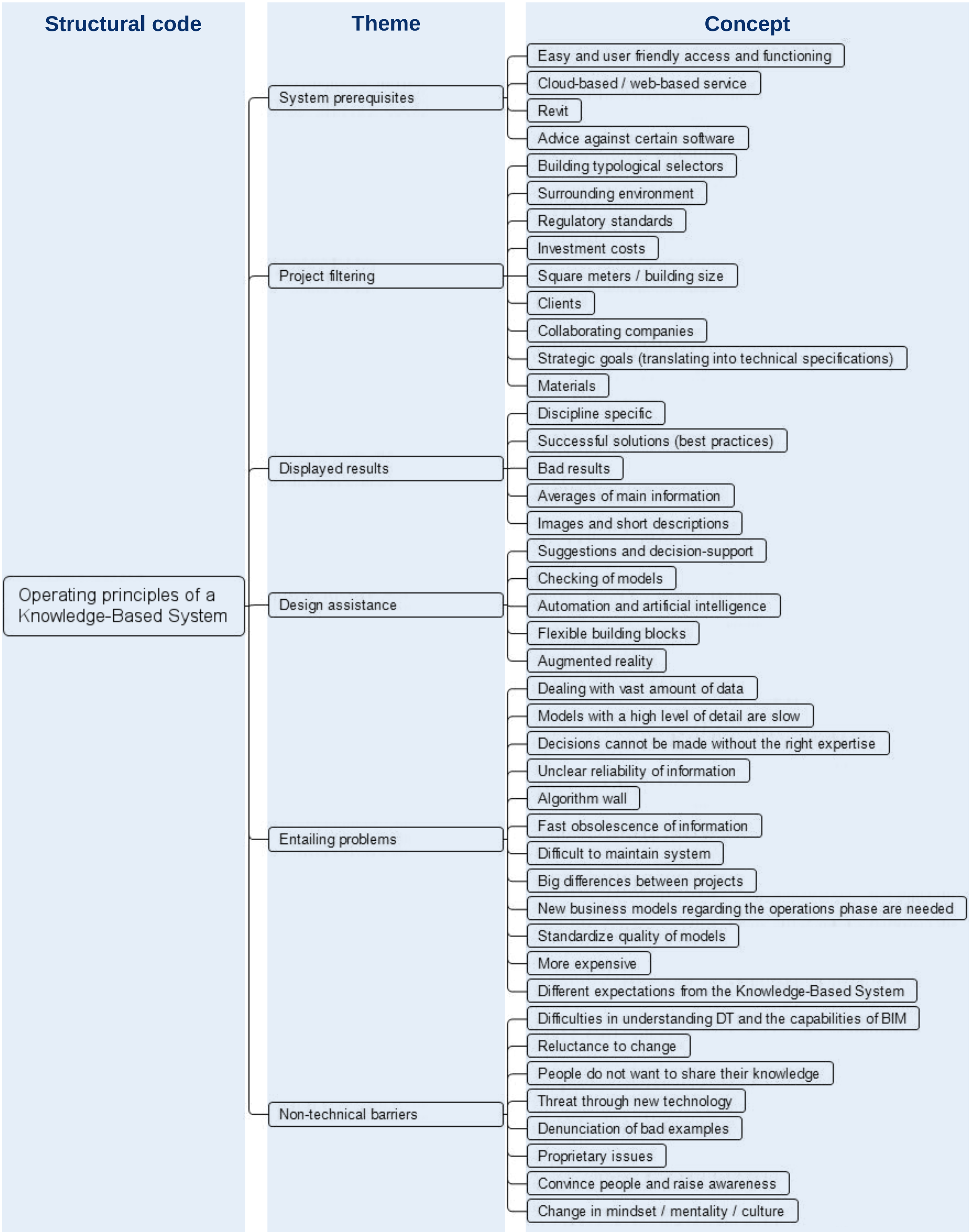


Figure D.2: *Coding tree for structural code 'operating principles of a Knowledge-Based System'.*

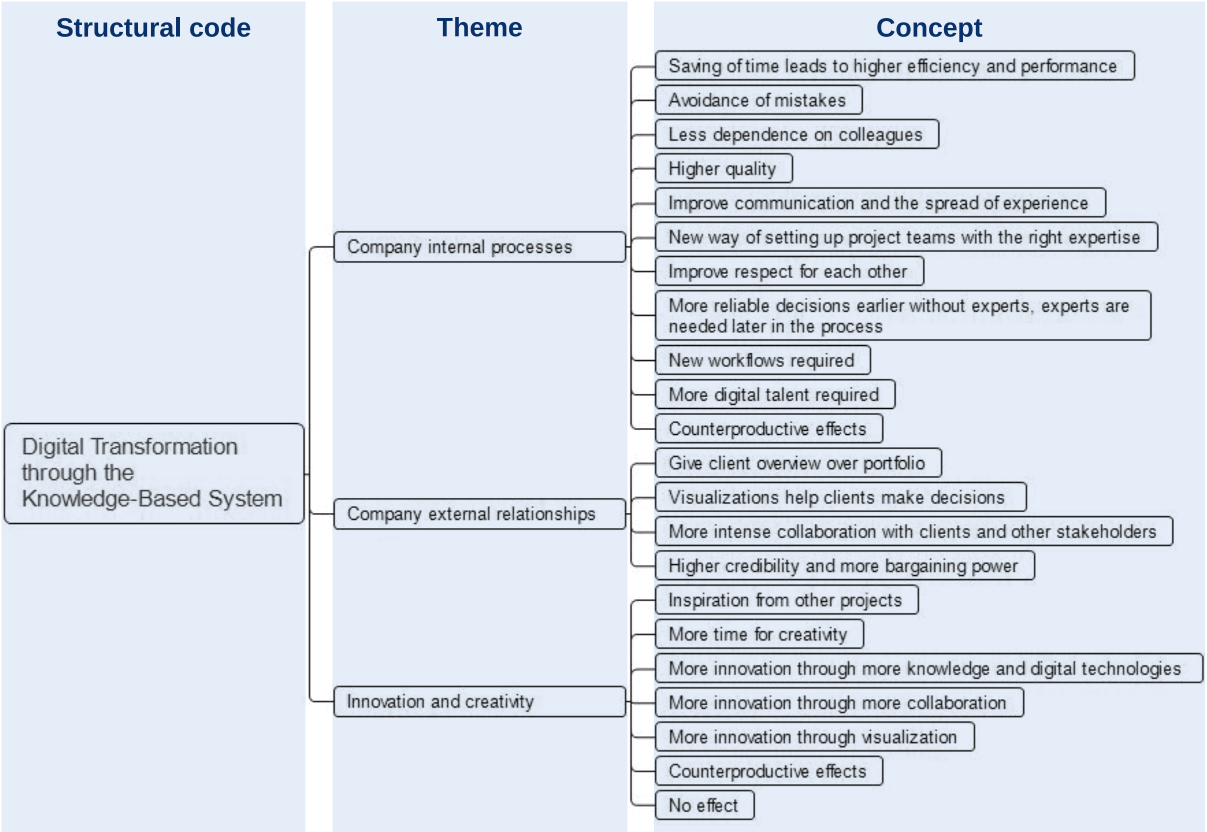


***Figure D.3**: Coding tree for structural code 'Digital Transformation through the Knowledge-Based System'.*

Appendix E – Focus Group Guide

Introduction

I study a Master in Sustainable Business and Innovation at Utrecht University. Right now I am writing my master thesis here at Arcadis. Through my research I want to facilitate the digital transformation of the company. Therefore, I focus on the transfer of information and knowledge across projects.

In this respect, I conducted and analyzed sixteen interviews with Arcaids employees. I identified different types of knowledge which should be made accessible to and (re)usable for all employees. The knowledge which is deemed useful can be classified into project specific and element specific knowledge. Project specific knowledge is general information about a project as a whole. In contrast, element specific knowledge is information on the different elements of a building's BIM model.

Part One

I defined the operating principles of a system to make both project and element specific knowledge accessible.

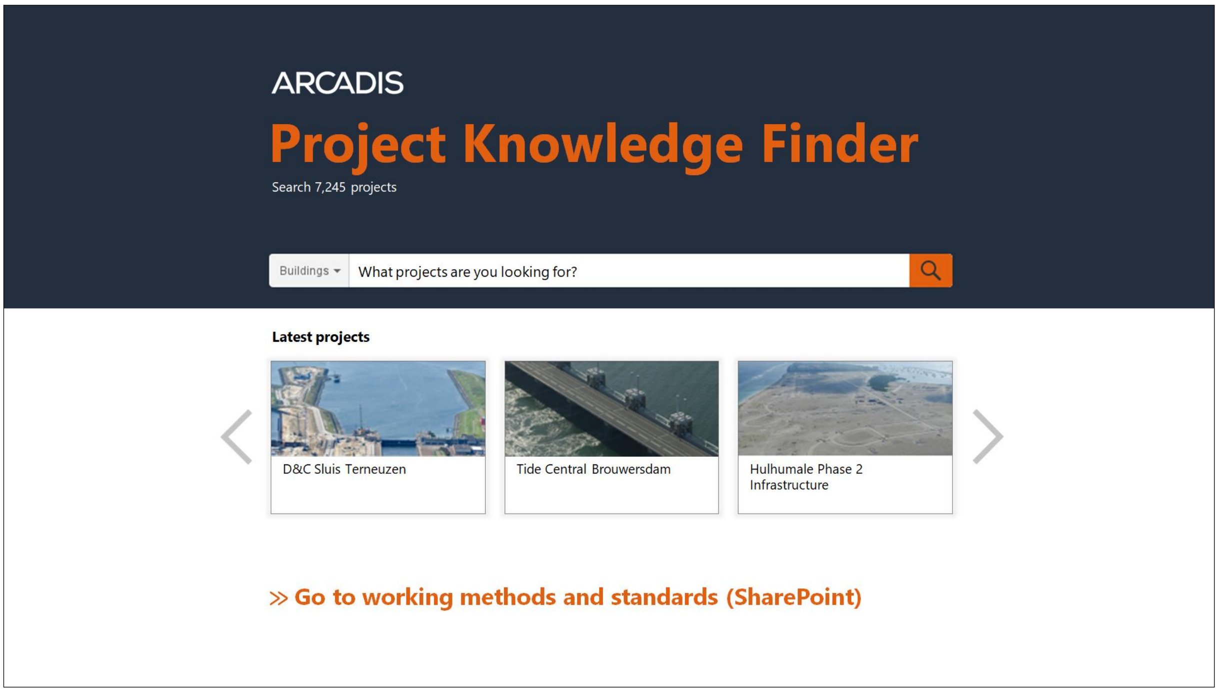


***Figure E.1**: Preliminary KBS concept – start page.*

The start page of the KBS as the first point of contact for the users was designed to look familiar and welcoming. Characteristic are the predominant central search field. Below the search field, suggested projects are shown. For the fast access to working methods and standards, a link to standard templates and guidelines is attached at the bottom of the start page. On the start page, users search for the project they want to find information on.

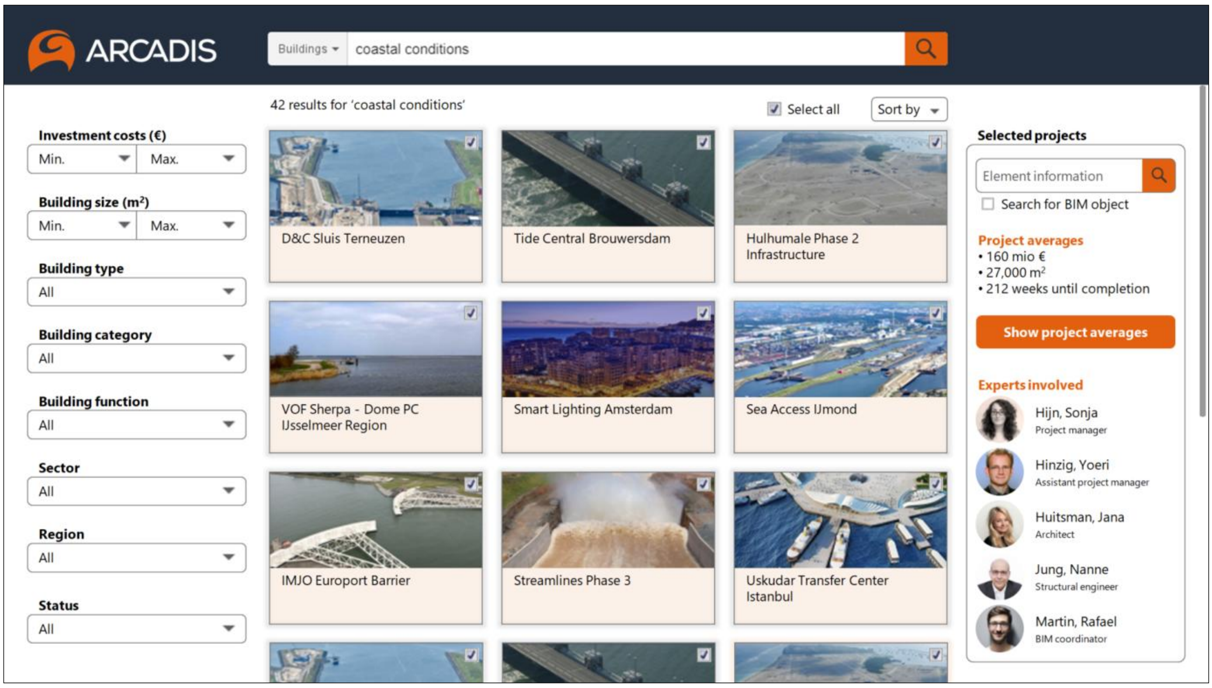


***Figure E.2**: Preliminary KBS concept – search results of project search, all projects selected.*

On the search results page, the different projects are presented with a picture and title. Filter options are on a left side bar. On a right sidebar, average information and relevant expert contacts are shown. A search field enables users to search for element specific knowledge in the selected projects. In case a 3D object model is wanted for an element, this can be specified by ticking 'Search for BIM object' below the search field.

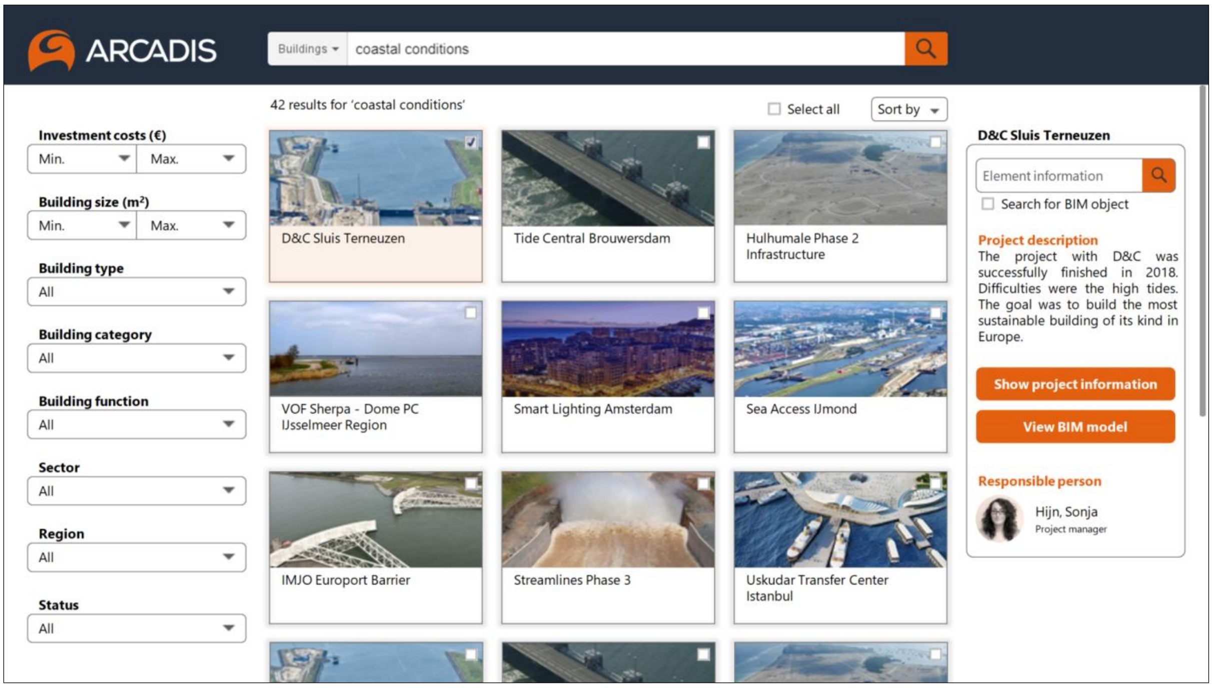


***Figure E.3**: Preliminary KBS concept – search results of project search, one project selected.*

When the users select one project only, they have the option to view general project information, to view the project's BIM model, and again, to search for element specific knowledge of the project.

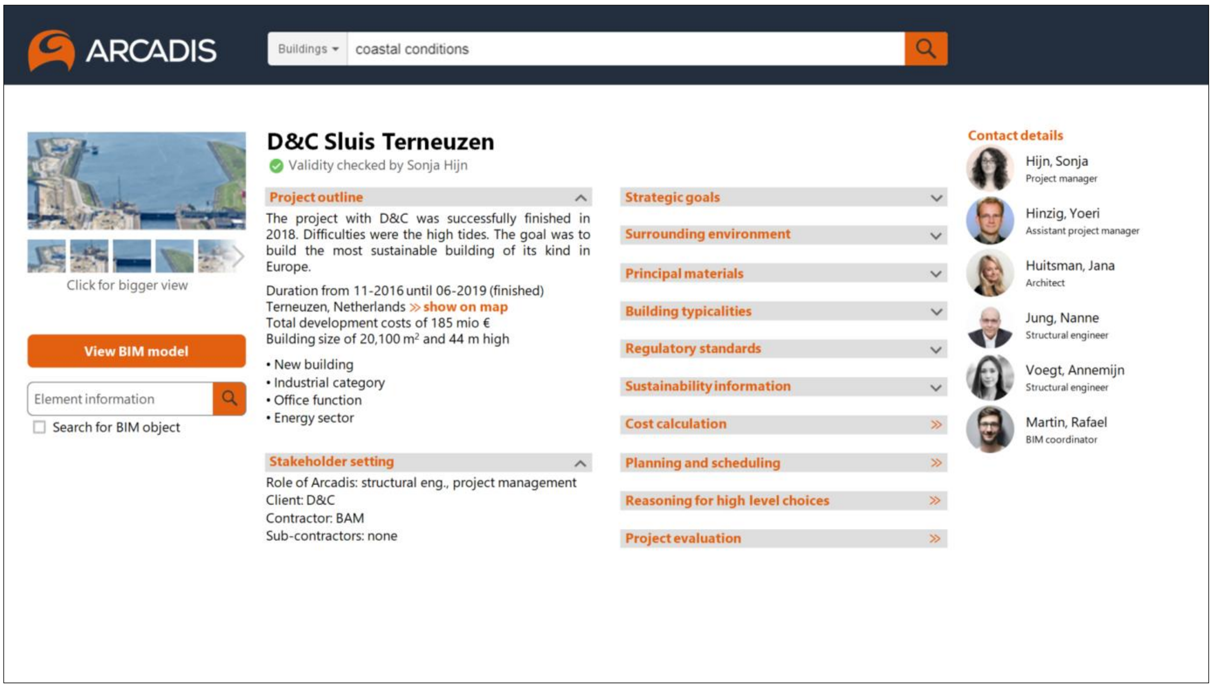


Figure E.4: *Preliminary KBS concept – project page with project specific information.*

When users want to show the project information, they get them presented in an overview.

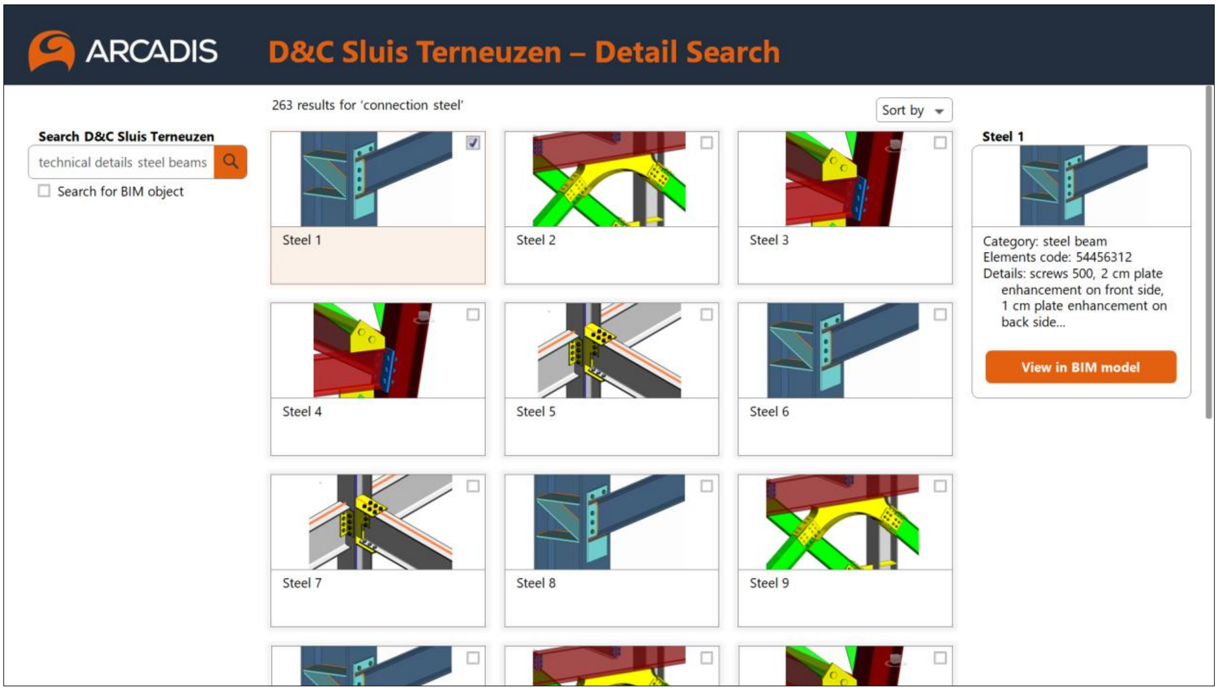


Figure E.5: *Preliminary KBS concept – search results for the search for specific project knowledge.*

The results of the search for element specific knowledge are presented in a similar manner. Therefore, pictures are generated from the BIM model(s) and details and the option to view the section in the model are given. In practice, the pictures generated from the BIM model would look far more simplistic because usually the level of detail of the models is not as high as in the pictures. For the sake of comprehensible graphic representation, pictures with a higher level of detail were deemed adequate.

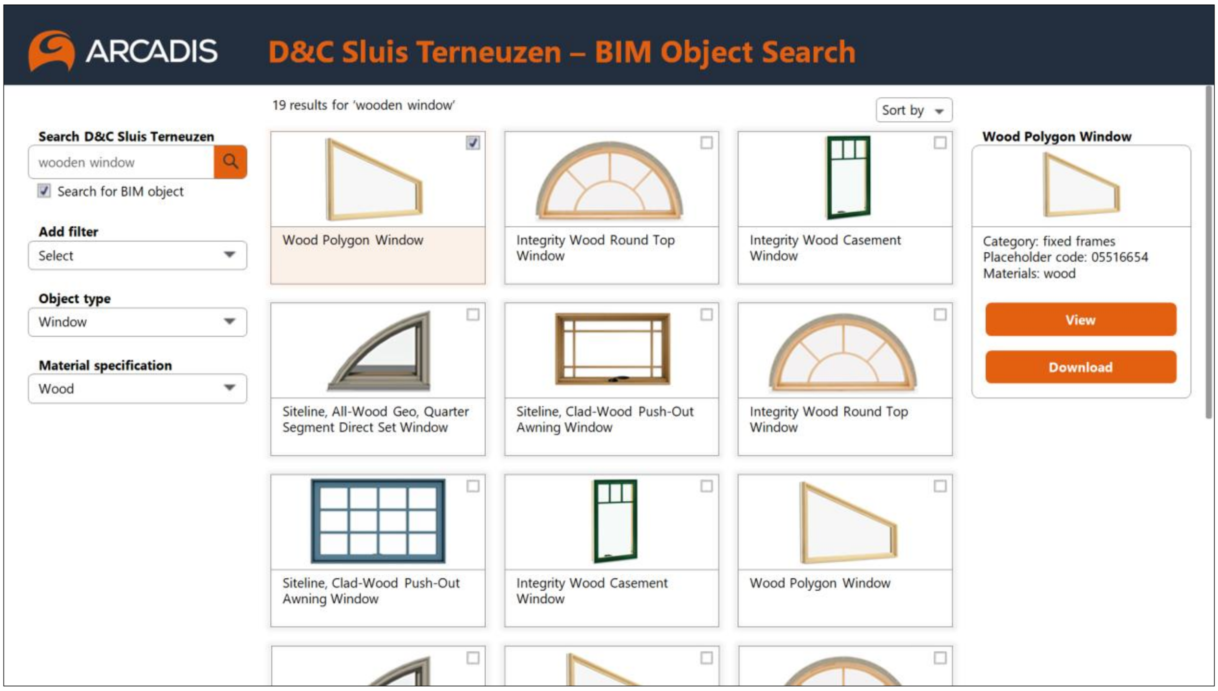


Figure E.6*: Preliminary KBS concept – search results for the search for BIM objects.*

When users search for BIM objects, thus 'Search for BIM object' was ticked, they are presented with graphic representations of BIM objects (Revit families) extracted from the BIM model(s). They have the options to view the 3D models of particular objects and can download them to reuse them in their current project.

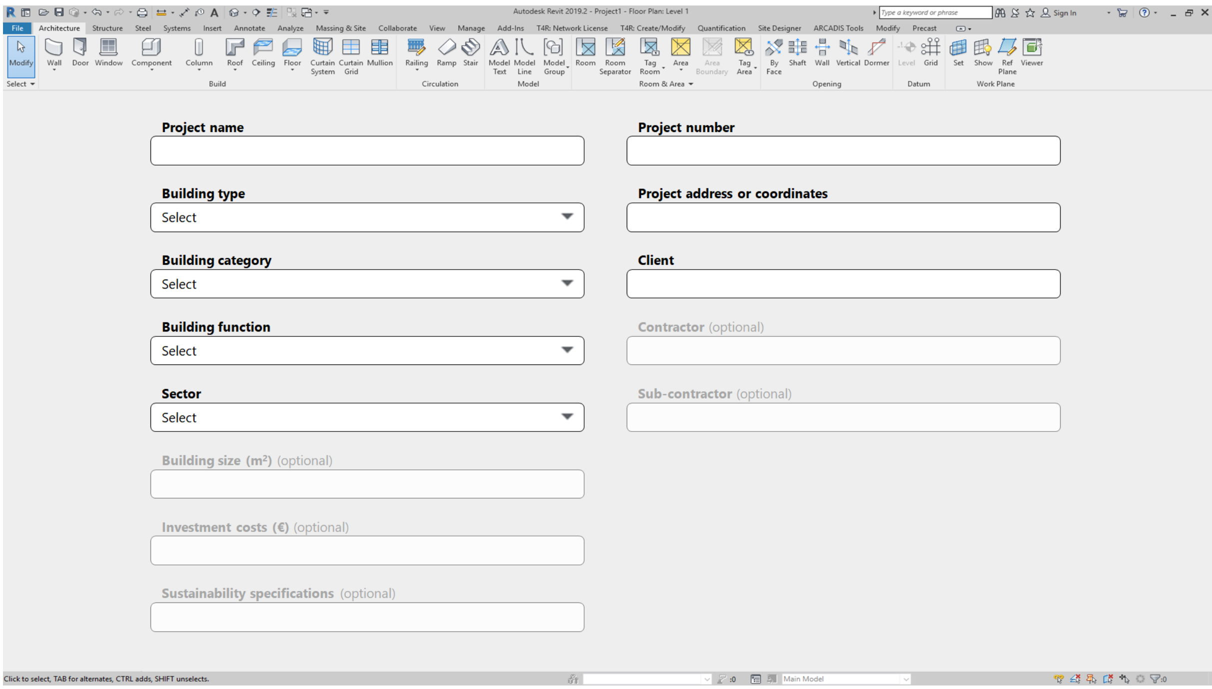


Figure E.7*: Preliminary KBS concept for Autodesk Revit integration – parameter specification at the beginning of the design process.*

Some key parameters would have to be predefined at the start of new projects for the system to be able to find most similar projects. This could be done at the project setup in Revit.

What is your opinion on the functioning and the concept of the system?

Part Two

During the interviews, different statements were made on the effects such a system would have.

The proposed system…

	Unlikely				Likely
… saves time which leads to higher efficiency and performance.	○	○	○	○	○
… helps to avoid mistakes.	○	○	○	○	○
… makes employees less dependent on colleagues to get needed information.	○	○	○	○	○
… enables a higher quality of results.	○	○	○	○	○
… improves communication and the spread of experience.	○	○	○	○	○
… provides a new way of setting up project teams with the right expertise.	○	○	○	○	○
… improves the respect for each other('s work).	○	○	○	○	○
… enables to make more reliable decisions earlier without experts. Therefore, experts are needed later in the process.	○	○	○	○	○
… requires new workflows inside the company.	○	○	○	○	○
… requires more digital talent to be recruited.	○	○	○	○	○
… leads to less conversations, diminishing the exchange of important side information.	○	○	○	○	○
… helps convince clients by being able to give them an overview over the company's project portfolio.	○	○	○	○	○
… helps clients to make decisions through visualizations taken from the system.	○	○	○	○	○
… leads to a more intense collaboration with clients and other stakeholders.	○	○	○	○	○
… improves the credibility and bargaining power of the company, as facts can be used as arguments instead of opinions.	○	○	○	○	○
… spurs creativity through inspiration from other projects.	○	○	○	○	○
… allows for more time for innovation and creativity.	○	○	○	○	○
… enables more innovation through the accessibility of more knowledge.	○	○	○	○	○
… stimulates more innovation through more collaboration.	○	○	○	○	○
… drives innovation through comprehensible visualizations made accessible through the system.	○	○	○	○	○
… leads to less conversations which trigger creativity and adversly affects innovation and creativity by (re)using previous solutions.	○	○	○	○	○
… has no effect on innovation and creativity in the company.	○	○	○	○	○

Figure E.8*: Scheme to rank potential DT effects on the likelihood of their occurrence.*

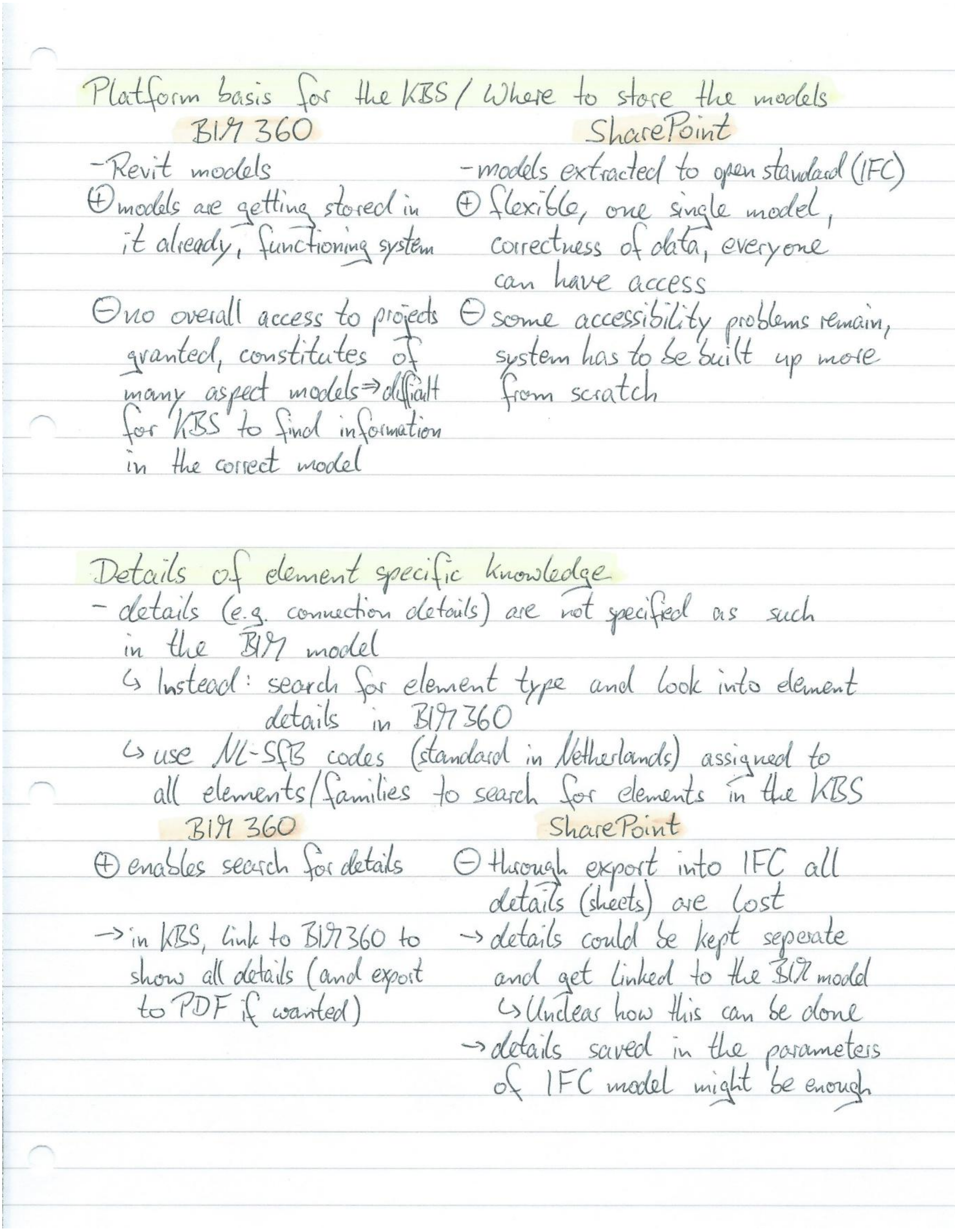
Could you together decide on how likely those statements are to occur?

Closing

Thank you for your time and in helping me with my research. If you are interested in my results, I can provide them to you. Also, I will give a lunch presentation on the topic in Amersfoort at the end of the month.

Appendix F – Focus Group Results

F.1 Part One: Handwritten Notes



Platform basis for the KBS / Where to store the models

BIM 360

- Revit models

⊕ models are getting stored in it already, functioning system

⊖ no overall access to projects granted, constitutes of many aspect models ⇒ difficult for KBS to find information in the correct model

SharePoint

- models extracted to open standard (IFC)

⊕ flexible, one single model, correctness of data, everyone can have access

⊖ some accessibility problems remain, system has to be built up more from scratch

Details of element specific knowledge

- details (e.g. connection details) are not specified as such in the BIM model
  ↳ Instead: search for element type and look into element details in BIM 360
  ↳ use NL-SfB codes (standard in Netherlands) assigned to all elements/families to search for elements in the KBS

BIM 360

⊕ enables search for details

→ in KBS, link to BIM 360 to show all details (and export to PDF if wanted)

SharePoint

⊖ through export into IFC all details (sheets) are lost

→ details could be kept seperate and get linked to the BIM model
↳ Unclear how this can be done

→ details saved in the parameters of IFC model might be enough

***Figure F.1**: Handwritten notes for focus group part one – page 1.*

Provision of BIM object models (Revit families)
- already started to implement shared library
  ↳ entailing problems: making sure that data is correct, therefore families have to be checked by an appointed person (other one for every family), many projects finish at final design and do not make it to detail design
    ↳ possible solution: while designing in Revit, designers check 'validated' if/when correct data was added ⇒ family gets automatically extracted and made available via the KBS
      ↳ problem: not in favor to change workflows
- How to bring families from the KBS into own project?
  ↳ no need to download whole model but extracted family only
- How to extract families from a BIM model?
  ↳ it is possible with Forge (see website) and UNIFI

Collection of project specific information
- some information is already collected and available on: SharePoint, collaboration hub, reference sheet for future tenders
  ↳ automatically fetch and link this data to the BIM models on the KBS to reduce the need to add information manually

Additional system features
- option to share project information with clients digitally, generate online access point to view information
- maybe option in the search function to in what aspect (discipline) model to search for information

***Figure F.2**: Handwritten notes for focus group part one – page 2.*

F.2 Part Two: Filled in Scheme

How likely are the following statements to occur?

The proposed system…	Unlikely				Likely
… saves time which leads to higher efficiency and performance.	O	O	O	X	O
… helps to avoid mistakes.	O	X	O	O	O
… makes employees less dependent on colleagues to get needed information.	O	O	O	X	O
… enables a higher quality of results.	O	O	X	O	O
… improves communication and the spread of experience.	O	O	O	X	O
… provides a new way of setting up project teams with the right expertise.	O	O	X	O	O
… improves the respect for each other('s work).	X	O	O	O	O
… enables to make more reliable decisions earlier without experts. Therefore, experts are needed later in the process.	O	X	O	O	O
… requires new workflows inside the company.	O	O	O	O	X
… requires more digital talent to be recruited.	O	O	O	X	O
… leads to less conversations, diminishing the exchange of important side information.	O	O	O	X	O
… helps convince clients by being able to give them an overview over the company's project portfolio.	O	O	O	X	O
… helps clients to make decisions through visualizations taken from the system.	X	O	O	O	O
… leads to a more intense collaboration with clients and other stakeholders.	X	O	O	O	O
… improves the credibility and bargaining power of the company, as facts can be used as arguments instead of opinions.	O	O	O	X	O
… spurs creativity through inspiration from other projects.	O	O	O	X	O
… allows for more time for innovation and creativity.	O	O	X	O	O
… enables more innovation through the accessibility of more knowledge.	O	O	X	O	O
… stimulates more innovation through more collaboration.	O	O	X	O	O
… drives innovation through comprehensible visualizations made accessible through the system.	X	O	O	O	O
… leads to less conversations which trigger creativity and adversly affects innovation and creativity by (re)using previous solutions.	O	X	O	O	O
… has no effect on innovation and creativity in the company.	X	O	O	O	O

***Figure F.3**: Filled in scheme for focus group part two.*

Appendix G – KBS Constraints

G.1 Choice of Platform Basis

The eligible platforms BIM 360 and SharePoint both allow for the demanded web-based access to the KBS. However, the two platforms each have up- and downsides. Table 4 summarizes the main advantages and disadvantages of each platform.

Table G.1*: Comparison of BIM 360 and SharePoint (based on the open standard IFC).*

	Main advantages	Main disadvantages
BIM 360	• Functioning system, • Enables access to detail sheets.	• No overall access granted, • Dependency on Autodesk.
SharePoint (open standard IFC)	• Accessibility, • Flexibility.	• Detail sheets are lost through export in IFC.

Both stated platforms have abilities which are crucial for the proposed KBS – BIM 360 enables the access to detail sheets and SharePoint ensures overall accessibility. This is a dilemma for the choice of one platform over the other. As a consequence, both platforms should be combined to utilize the advantages of both of them.

Combination Principles

Forge, cloud-based developer tools from Autodesk, can be used to extract the BIM models from Revit or BIM 360 to the IFC standard. These extracted IFC models are saved in a database on SharePoint. Through this, detail sheets are lost; however, elements are still distinguishable in the models and their related parameters can be searched. One model in Revit usually constitutes of the different aspect models of the disciplines involved. By Deshpande *et al.* (2014) as well as during the interviewees it was stated that the results should be discipline specific; therefore, this study suggests extracting those aspect models separately to the KBS database on SharePoint to enable the search for elements in the desired aspect model.

G.2 Accessing Specific Project Knowledge

In SharePoint, most project specific knowledge of a project can be examined directly, the element specific knowledge also to a certain extent. However, as stated during the focus group, specifications such as connection details are not specified as such in BIM models, why they would not be searchable/findable via the KBS. Instead, it is searched for types of 3D elements (families in Revit) and this way, those details could be found.

Elements of interest can be identified and their parameters can be seen; however, further detail sheets of elements or a floor of a building are not accessible via SharePoint. Hence, two approaches can enable the access to those detail sheets. The first option is to provide a link to direct to the BIM 360 model or specific elements in that model. To be able to access the models in BIM 360, the KBS has to be granted overall access to all models by the higher management of the company. It is probable that this is granted for most projects (except for secret projects) because just read only access is needed for the KBS. The second option requires saving the original Revit files of all projects alongside the extracted IFC files on SharePoint. To access detail sheets, users have to download the whole Revit model of a building, open it in Revit on their computer and manually search for what they are looking for. By outsourcing the viewing of detail sheets, those two approaches allow to combine the advantages of Autodesk software and SharePoint.

G.3 User Prerequisites

The aim of the KBS is that employees can (re)use *project knowledge* and understand the setup and/or process from their own professional perspective. During the interviews, however, the concern was expressed that "you'll have to be more a specialist" [7] to be able to use the KBS adequately. Otherwise, "people are applying solutions to a situation which they cannot fully oversee and judge" [4]. Newell *et al.* (2006) mention that a project team must be knowledgeable enough to use knowledge beyond the confines of their own project as a useful tool to help to improve progress on their project. Based on the statements of interviewees, this study argues it can be assumed that all employees of the firm are experts in their domain. Therefore, they are looking for knowledge specific to their field of expertise. As the reuse of larger parts of a model is unlikely [9], everyone understands the principles of their looked up more specific *project knowledge* and is able to adequately use the KBS. In case questions arise, contacts to the originators are provided (see Chapter 5.1).

G.4 Privacy and Security

Despite the expected benefits from sharing knowledge across projects (Tserng & Lin, 2004; Lin *et al.*, 2005; Deshpande *et al.*, 2014; Prusak, 1997; Ho *et al.*, 2013; Kamara *et al.*, 2002), as knowledge moves freely within and beyond the company, privacy concerns arise. Some knowledge is "protected by privacy settings or laws, so you can't reuse it" [9]. Hence, some secret *project knowledge*, parts of projects or entire projects have to be excluded from making it/them available over the KBS. Furthermore, read only access to whole BIM models ensures that no entire model with all its knowledge can be copied. Eventually, large parts of a model are usually not suited for reuse [9]. For the similar reasons, "we can't show our model to another supplier of the same product" [14]. Although, given the right framework conditions and mutual consent, the sharing of knowledge with other parties can lead to mutual benefits (Chesbrough & Bogers, 2014), having no control over what knowledge is shared externally can be disadvantageous in the competition with other companies (Ahmad *et al.*, 2014). After all, knowledge is the most important resource and asset for companies (Stewart, 1998) and “the most strategic resource of the firm” (Daud, 2012, p. 4224). Hence, the sharing of *project knowledge* with external parties has to be restricted based on the relationship of the focal firm with the external party. Therefore, by default, some information is not selected (or available) to be shared over the built-in sharing functionality. Depending on what information is shared, for the external party granted access to the shared information, the web-based access might be protected by a password or other security measures.

G.5 Adding of Project Knowledge at the Project Beginning

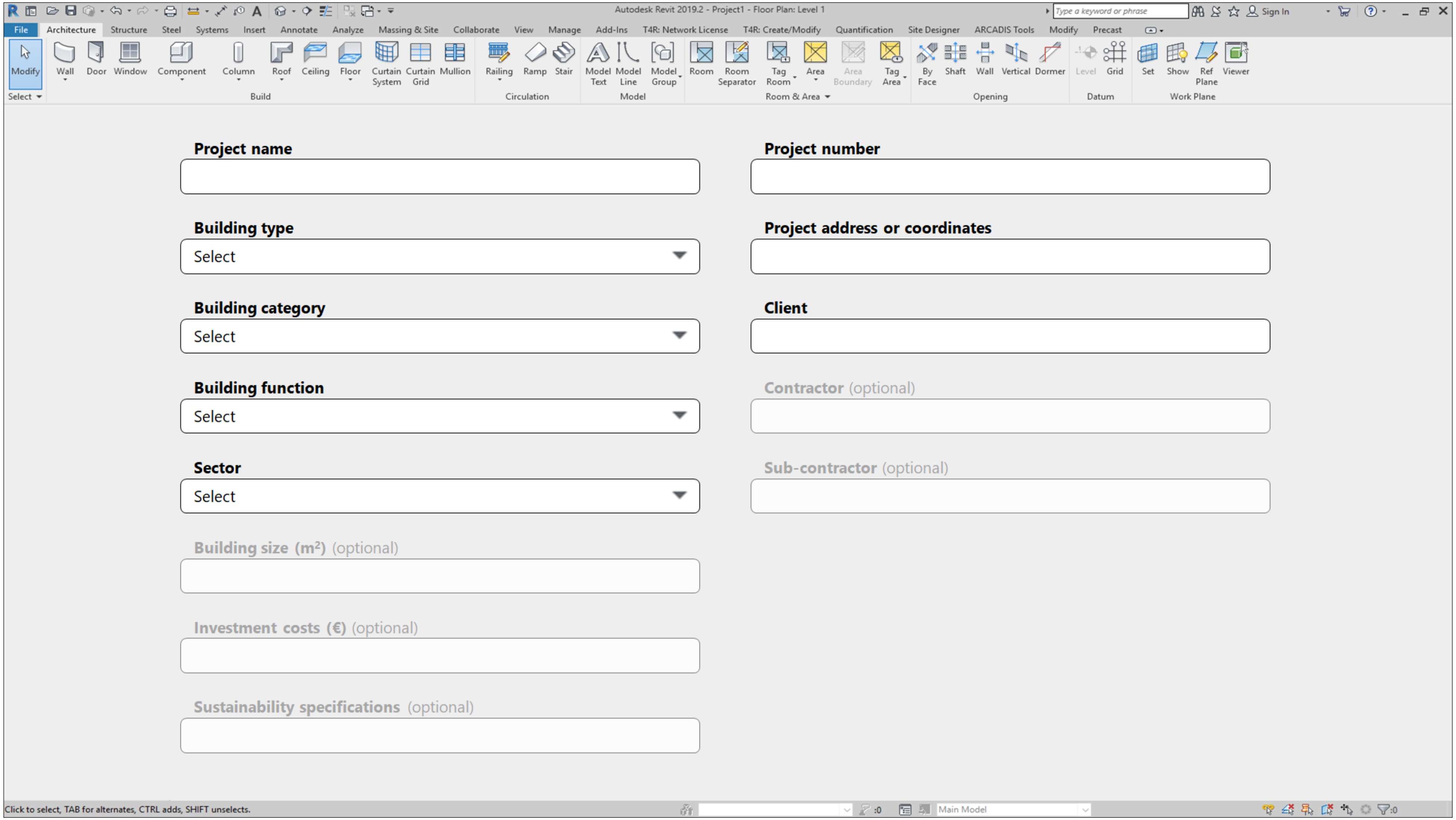


***Figure G.1**: KBS concept for Autodesk Revit integration – parameter specification at the beginning of the design process. Parameters are added directly in Revit.*

Appendix H – KBS Interface Concept

Based on the findings and discussed aspects, a concept design of the KBS interface was developed. This will be discussed in detail below. Chapter H.1 gives an overview over the main KBS 'Project Knowledge Finder' developed in this study. Chapter H.2 exemplifies advanced design assistance developments on the basis of the primary KBS.

H.1 Project Knowledge Finder

The start page of the KBS (Figure H.1) as the first point of contact for the users was designed to look familiar and welcoming. Characteristic are the predominant central search field, inspired by the Google search start page. Likewise, below the search field, suggested projects (websites on Google) are shown. As discussed in Chapter 5.1, working methods and standards are not tied to the circumstances of a specific project. Therefore, for the fast access to those, a link to standard templates and guidelines is attached at the bottom of the start page. In the case of the focal firm, those are available on a seperate SharePoint site.

The results for the project filtering (Figure H.2 and H.3) was inspired by Amazon and Bol.com. Their search results pages present an overview over the different products – in this case projects – with a picture and title. Previously discussed filter options are on a left side bar. In addition, on a right sidebar, average information about the selected projects is shown (Figure H.2). Above the average information, a search field enables users to search for element specific *project knowledge* of the selected projects. In case an extracted 3D object model is wanted, this can be specified by ticking 'Search for BIM object' below the search field. When the users select one project only (Figure H.3), again, they can search for element specific *project knowledge* in the project. Moreover, they have the option to view project specific knowledge and the project's BIM model (or go to the BIM 360 model or download its Revit file). When the BIM model is displayed, ideally, operations information is visualized in colors in the model. Depending on the data collected – for which a standard has to be defined, – the usage of facilities, energy consumption, the flow of people, and the usage of spaces amongst other data can be viewed.

Figure H.4 shows the project page with all relevant project specific knowledge. Once the project specific knowledge has been verified by a responsible employee, this is indicated below the project title. Again, the option to view the BIM model and search for element specific knowledge are given. Furthermore, as addressed during the focus group, an option to share and provide this information externally was added. In doing so, it can be selected which information wants to be shared and a link is generated for giving an external party web-based access.

The results of the search for element specific *project knowledge* (Figure H.5 and H.6) are presented in a similar manner than the results for the project filtering. They display a selection of all different types of the searched element integrated in the project(s). Following Ho *et al.'s* (2013) emphasis on the BIM-based illustration of knowledge, for the results for element specific knowledge, pictures are generated from the BIM model(s). Some details are given with the option to view the section in the model to better understand the setup or obtain further details. Based on the search keywords, the KBS automatically shows the results for the corresponding aspect model which can be changed top right (next to 'Sort by'). When users search for BIM objects (Figure H.6), thus 'Search for BIM object' was ticked, they are presented with graphic representations of BIM objects (Revit families) extracted from the BIM model(s). They have the options to view the 3D models of particular objects and can download them to reuse them in their current project. Hence, to implement a family into a user's own project, not the whole BIM model of the other project has to be downloaded but the extracted family only.

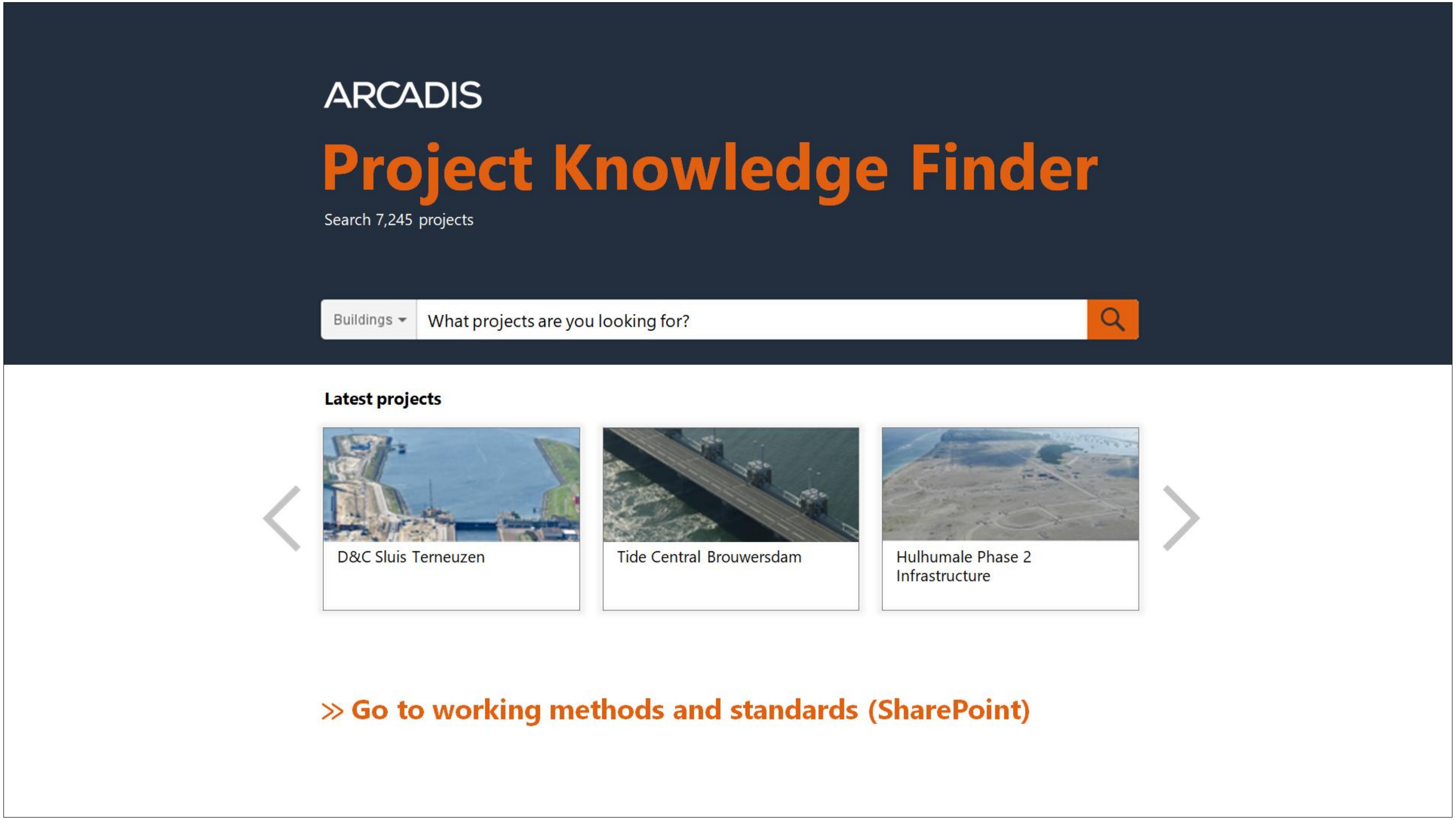


Figure H.1*: KBS concept 'Project Knowledge Finder' – start page.*

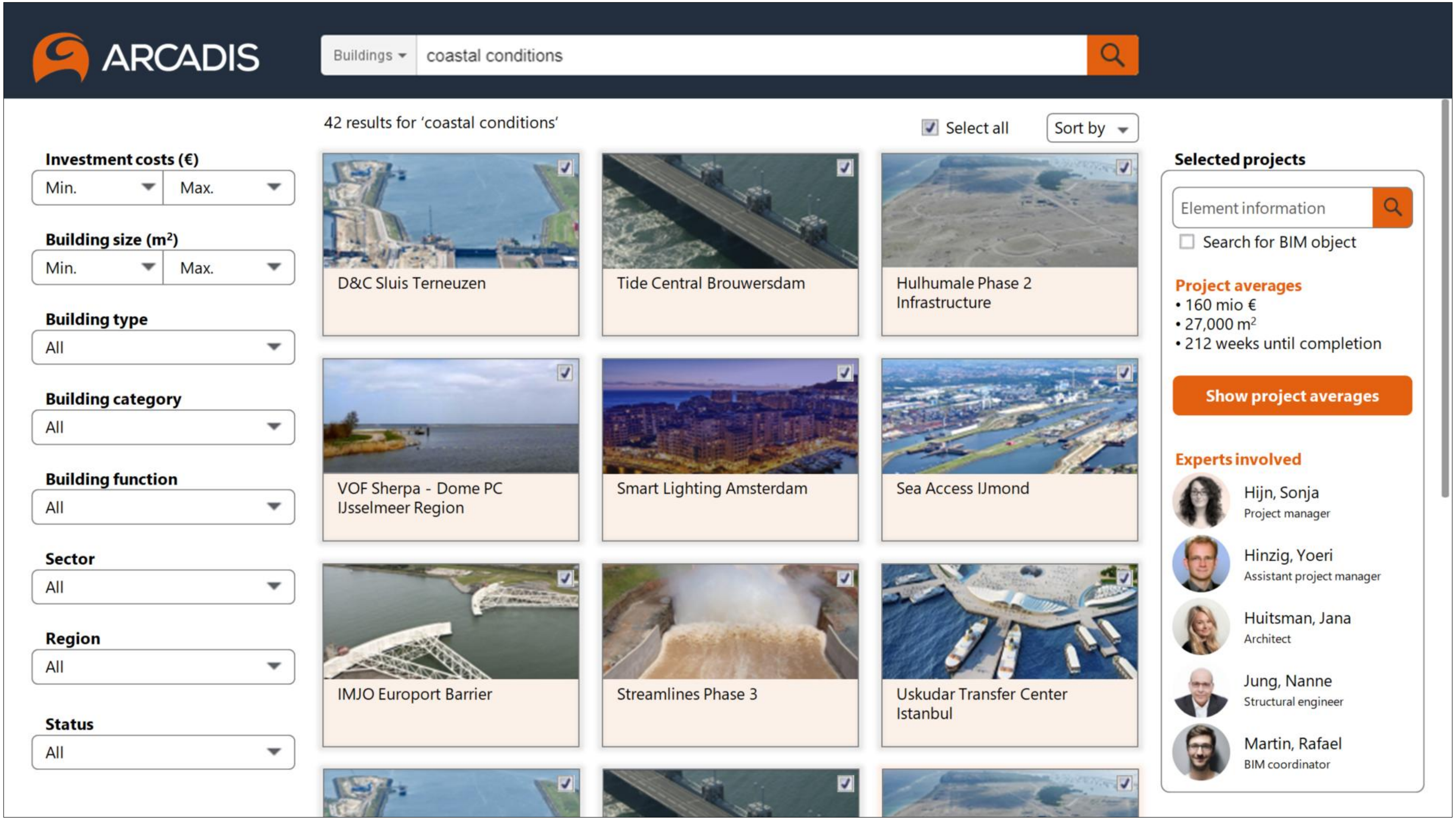


***Figure H.2**: KBS concept 'Project Knowledge Finder' – results of project search, all projects selected. Main criteria for project filtering (left), results (middle) and average information of selected projects and a search field for the search for specific project knowledge in the selected project are displayed (right).*

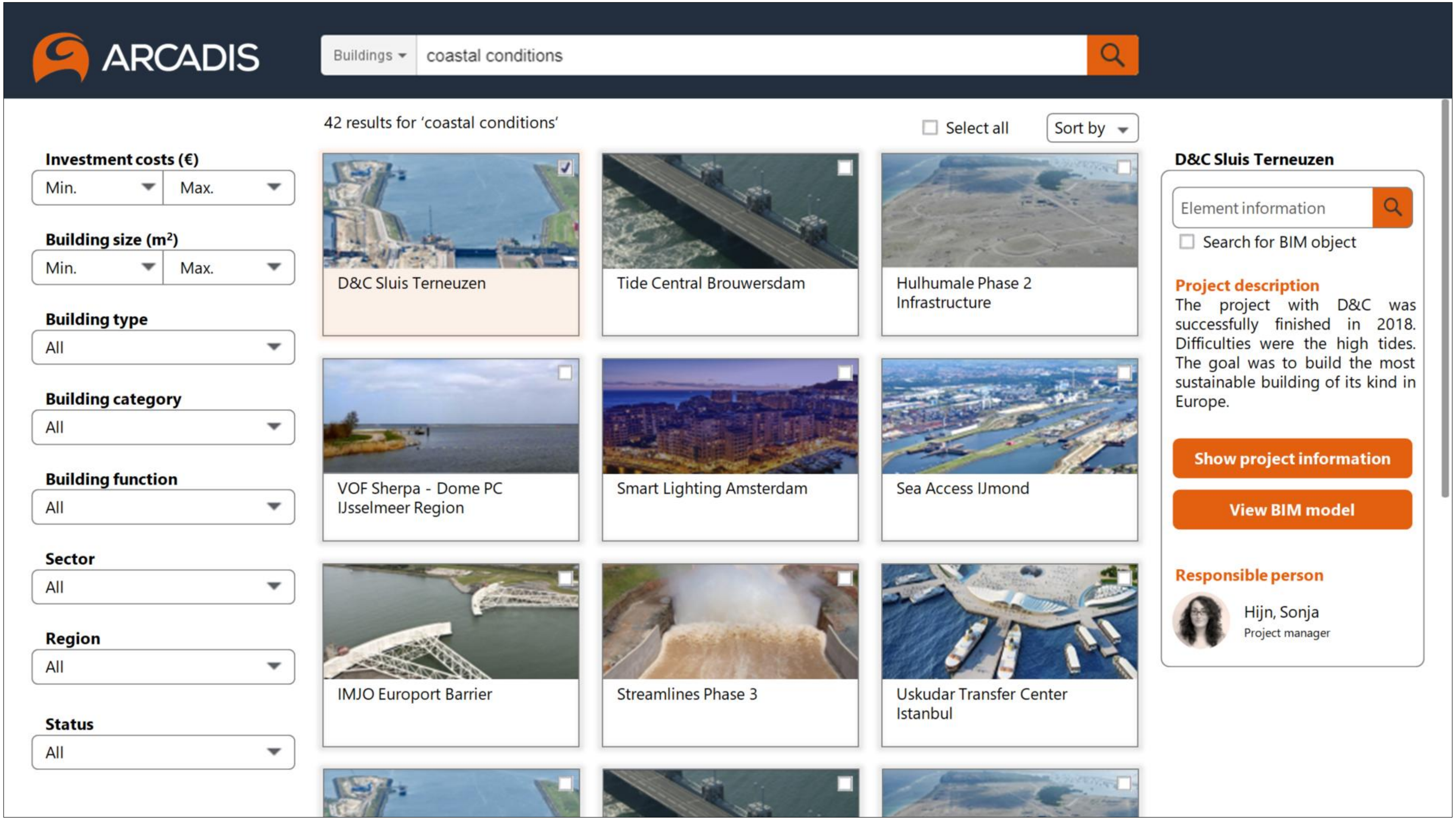


Figure H.3: *KBS concept 'Project Knowledge Finder' – results of project search, one project selected. The details and a search field for the search for specific project knowledge in the selected project are displayed (right).*

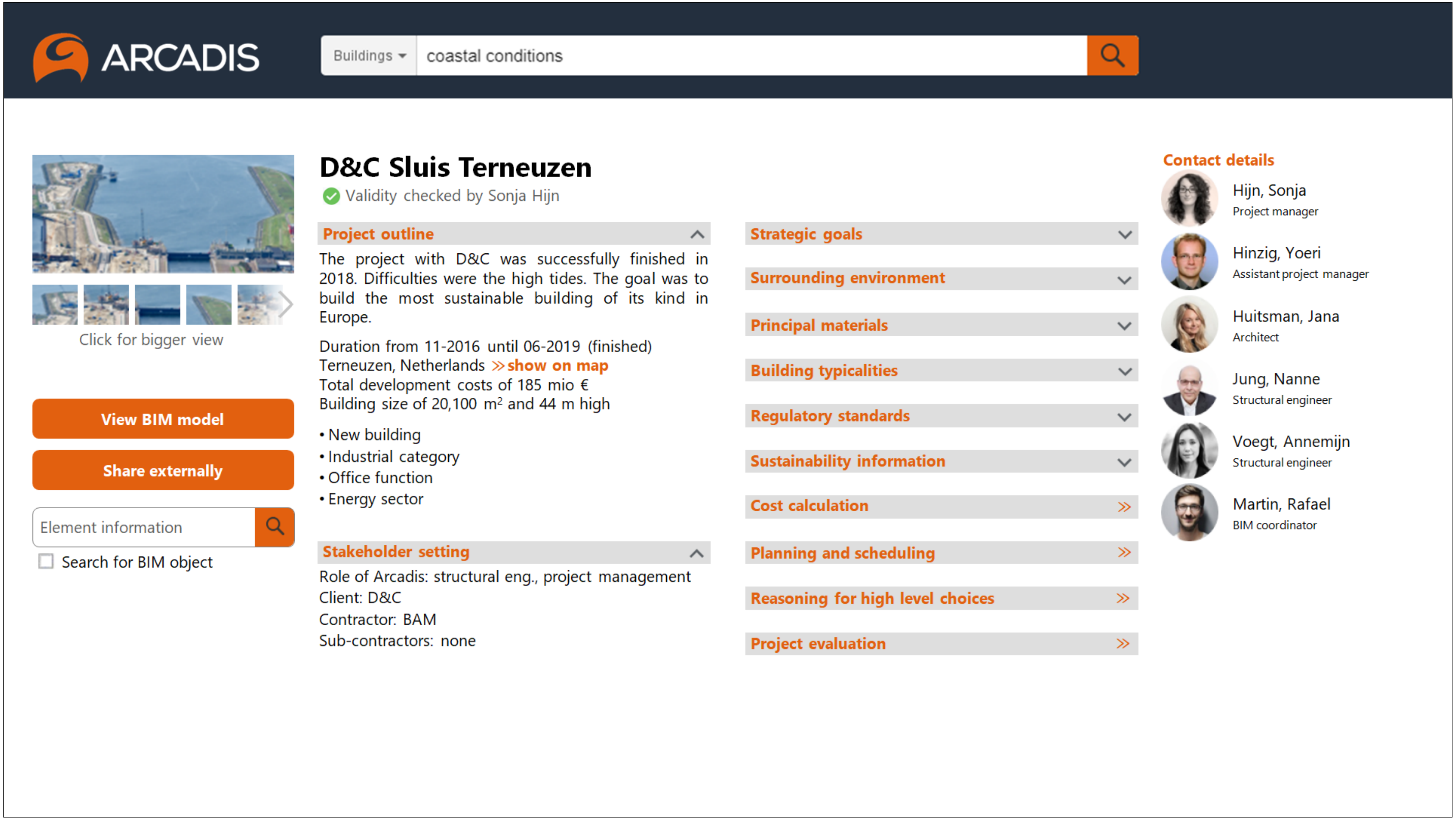


***Figure H.4**: KBS concept 'Project Knowledge Finder' – project page with project specific project knowledge.*

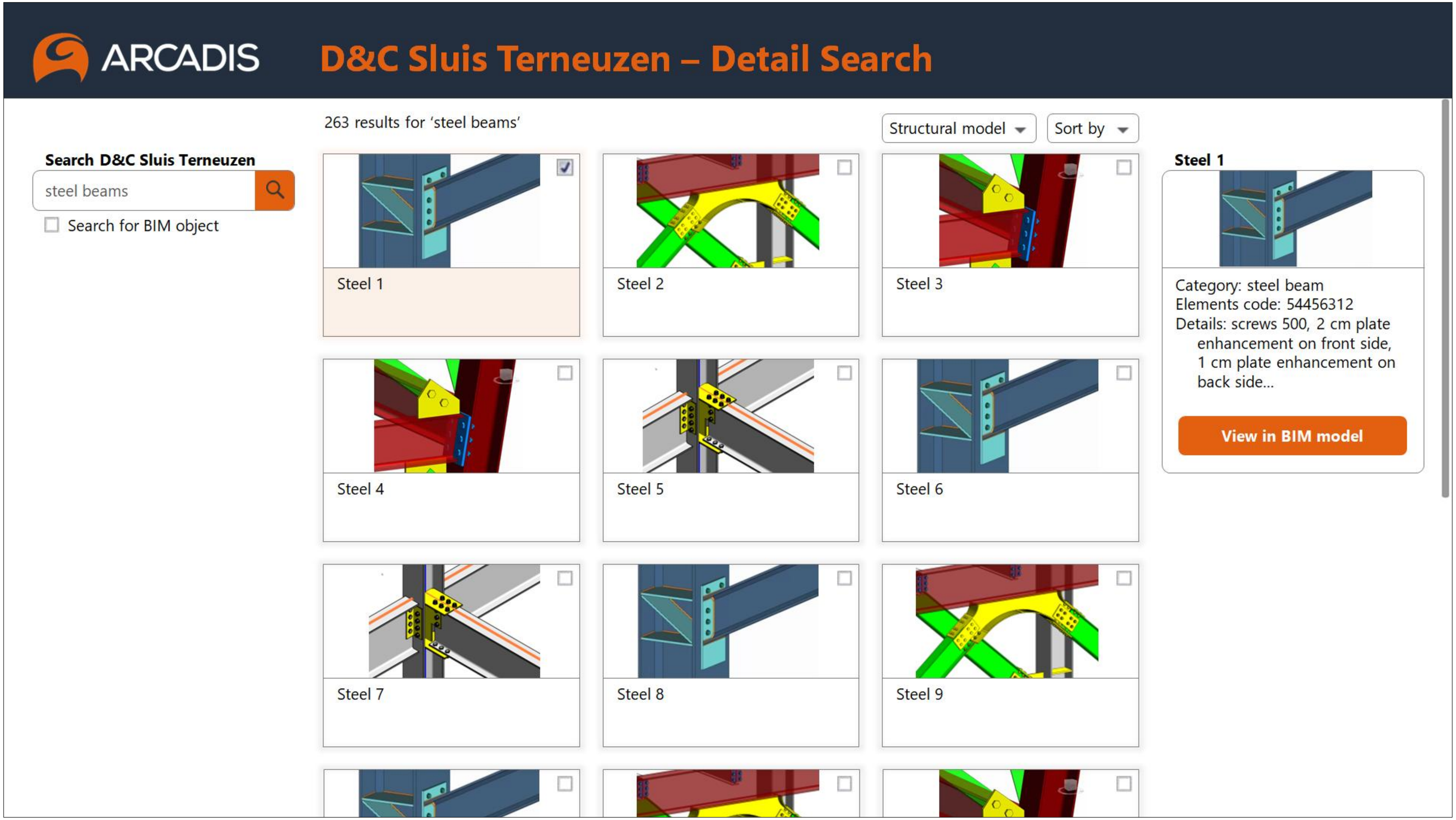


***Figure H.5**: KBS concept 'Project Knowledge Finder' – results for the search for element specific project knowledge (same if multiple are selected). The search results for 'steel beams' display a selection of all types of steel beams integrated in the project(s). In practice, the level of detail of the images would be lower.*

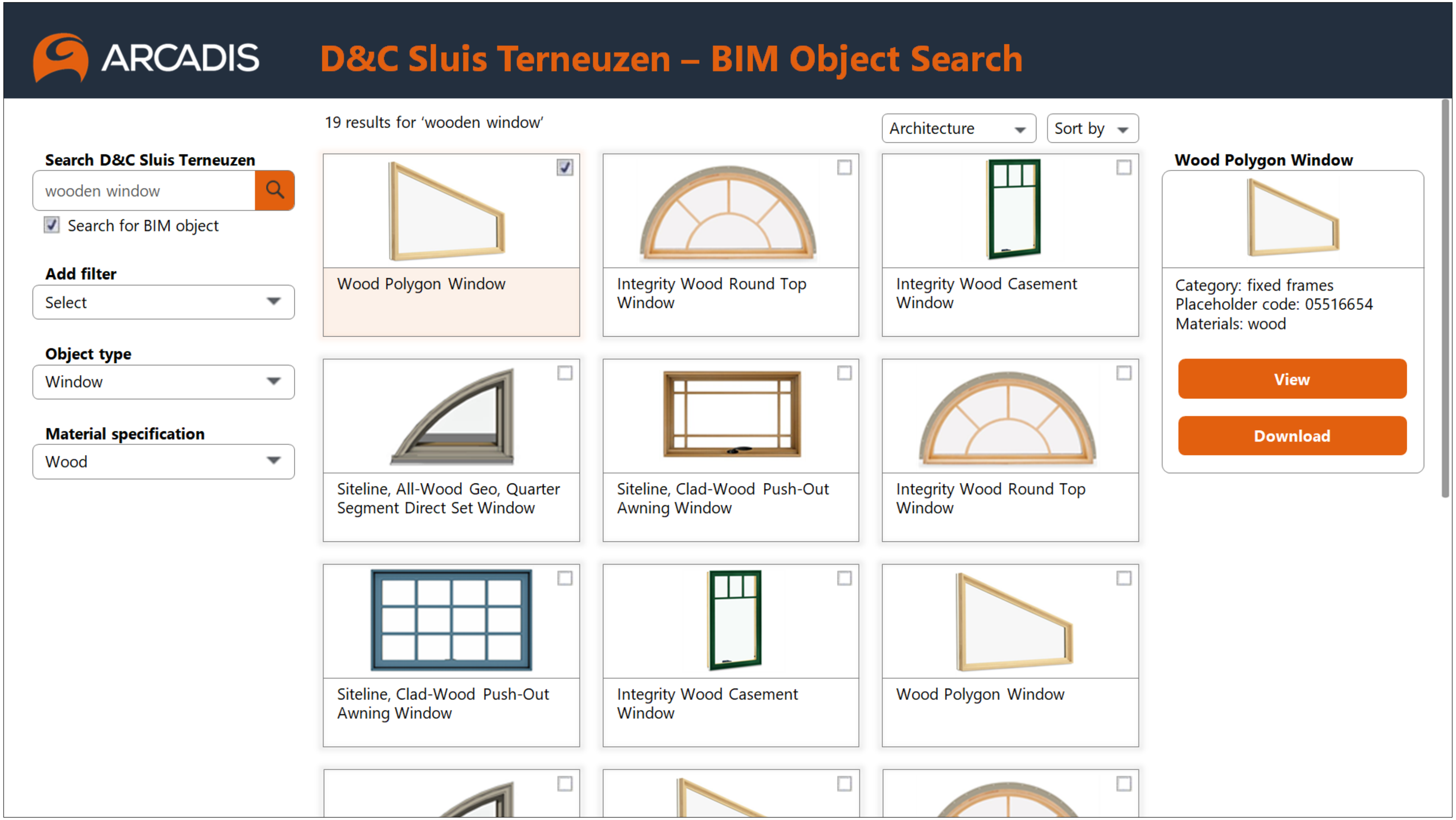


Figure H.6*: KBS concept 'Project Knowledge Finder' – search results for the search for BIM objects (same if multiple are selected). The field 'Search for BIM object' was ticked.*

H.2 Design Assistance

Besides the described KBS, during the interviews, design assistance functions were considered. These functionality proposals can be divided into three categories:

1) The checking of the model after the design,
2) Suggestions and recommendations during the design, and
3) Design automation.

The design is done with specialized software – in the case of the focal firm with Autodesk Revit. For this purpose, unlike the primary KBS interface which should be web-based, a plug-in for a secondary KBS interface for assisting building designers and engineers would be the preferred option. With the help of machine learning, previous projects could be analyzed automatically. Based on the analysis of similar projects, the system could provide (1), (2) or (3). Hereby, the technical requirements are increasing, hence, the ‘intelligence’ of the system has to be higher for (2) than for (1), and for (3) higher than for (2). At an advanced stage (3), the system would be able to interpret previous BIM models in such a way that it could design automatically, “you say created and it’s being created” [9]. Figure H.7 shows an example for design assistance at category (1).

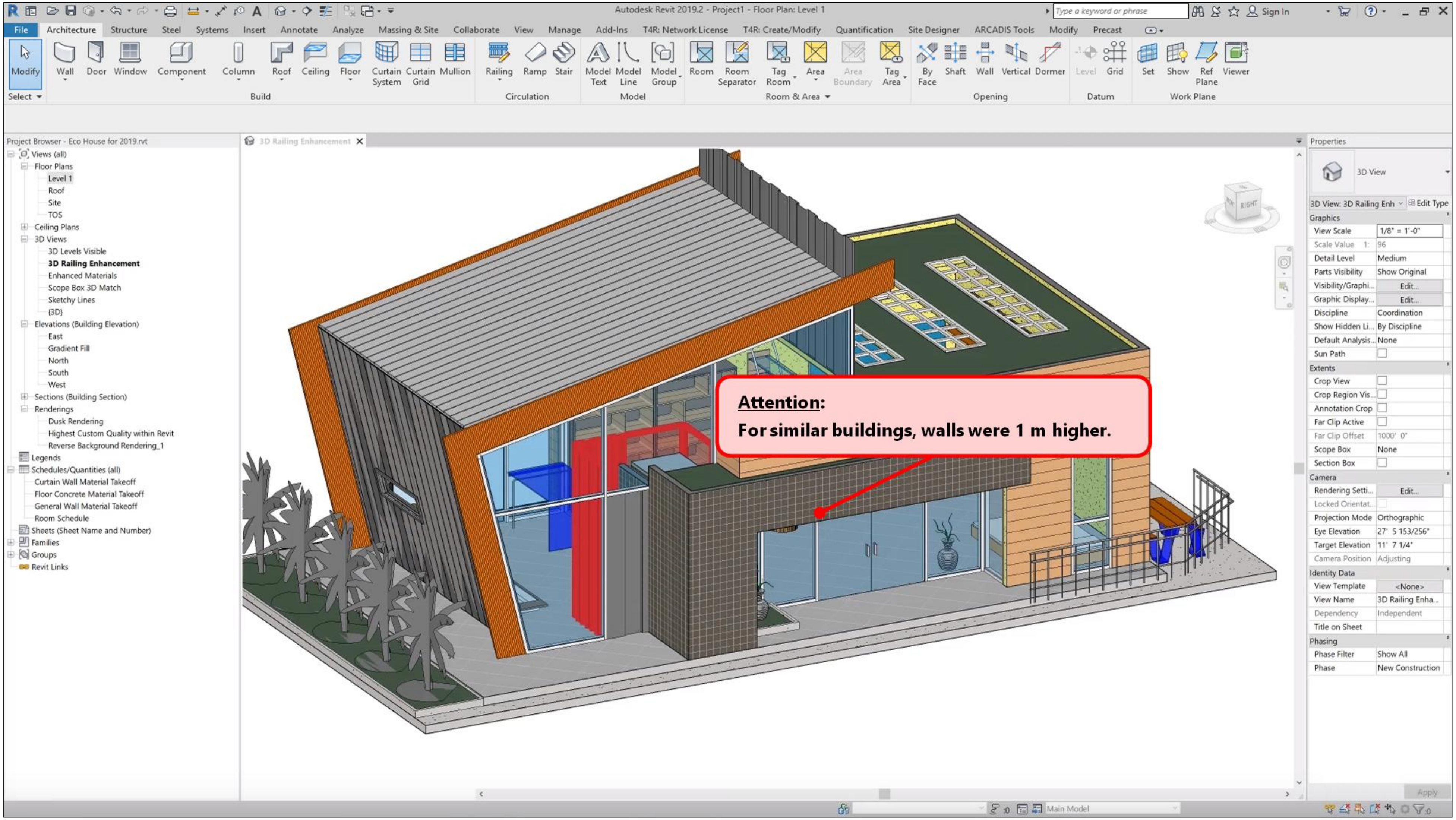


***Figure H.7**: KBS concept for Autodesk Revit integration – design assistance example for category (1).*