Towards digital twins for space use in hospital real estate

The Erasmus Medical Center as a case study
for the identification of the specifications of a digital twin for space use,
aiming to support decision makers and users of hospital real estate.

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Preface

The present report is the final outcome of the graduation project for my master studies in *Management in the Built Environment*. It lies within the convergence of the fields of real estate management and digitalisation in design and construction management. Both of those fields were part of the master's educational curriculum that fostered my fascination and ignited my curiosity to investigate further in my thesis. Additionally, the recent pandemic that pressured healthcare organisations made me choose hospital real estate as a type of building to focus into and research potential tools that could assist in managing them. Eventually, digital twins were chosen as a technological focus, due to their promising, yet nascent application in the building sector.

The research would not have been possible without the participation of the *Erasmus Medical Center* and in particular the *Programma Integrale Bouw*, the team that is responsible for the administration of the building assets at a strategic and operational level in one of the largest medical centres in Europe. Their diligent work is facilitating the realisation and maintenance of a complex, yet exceptional hospital building portfolio that is paradigmatic for its innovativeness and functionality for many other healthcare organisations. Even more specifically, I am thankful to Jan Jaap Zijl, who has been always available to guide me with his expertise in information management and made me feel welcome in this organisation.

My two mentors, Monique Arkesteijn and Alexander Koutamanis, have been an integral part of the development of this research. Monique's sharp eye for detail and Alexander's broad perspective are a combination that has been very pivotal by guiding me on the small details or in advising me on the overall picture. They have been always actively involved by providing me with tips and pointing out my weak spots, leading to a continuous improvement of the final research product.

Finally, I cannot help but acknowledge the contribution of all my friends, across the canal or across the ocean, who have been helping me with conversations, advice and jokes and have made this project a more feasible and enjoying endeavour. I am obliged to express my gratitude to my family who has never refused to support me and has been unconditionally assisting me to continuously develop and meet my professional and personal ambitions.

Zisis Vomvas
Delft, August 2022

Abstract

Information systems are increasingly deployed by healthcare organisations to support decision makers and users of hospitals. As a result, digital twins have recently emerged as an information system with promising application prospects. However, the limited deployment of them leads to the research gap that is addressed by the present research, which aims to answer "how can a digital twin for space use support decision makers and users of hospital real estate" and identify specifications for its development by healthcare organisations.

The research approach is conducted by deploying a design science research framework. In this framework, a literature review is carried out first by analysing academic publications in the topics of hospital real estate management, space use in hospital real estate, digital twins for space use and digital twins for hospital real estate. Then a case study is conducted in a healthcare organisation, by analysing the organisational characteristics, the real estate portfolio, the deployed information systems for space use and the building documentation databases. This is being done through a set of interviews with employees of the organisation, together with a documentation analysis. Two lists of design and utilisation principles are then extracted from the literature review and the case study analysis.

The two sets of principles are utilised for the development of a conceptual design of a display of a digital twin for space use in hospitals. This display is based on a time frame window, a building orientation window, a user profile window, a building visualisation window and a performance palettes window. The display is then assessed through evaluation interviews and the comprehensiveness of its design is validated. The interviewees further suggest utilisation scenarios that they can perform with a similar tool.

It is eventually concluded that a digital twin can be used by different stakeholder perspectives, by providing historical, real time or simulation information at a room, floor, building or campus scale resolution to support operational, tactical and strategic utilisation processes. The outcomes of this research can eventually be used by healthcare decision makers in order to develop similar tools.

keywords: digital twin, hospitals, hospital real estate management, space use, information systems
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Executive summary

Introduction

Corporate real estate management practices are deployed in the management of space in hospitals, due to the high cost of healthcare provision and a change in the Dutch healthcare regulations. Therefore, information systems such as smart tools, BIM and building management systems are deployed by hospital real estate decision makers. Digital twins, a promising novel technology van display historical and current information or conduct simulations for future sue of buildings. However, due to a lack of consolidated technological definition and because of a requirement of a plethora of building and sensor data, there is a limited deployment of digital twins.

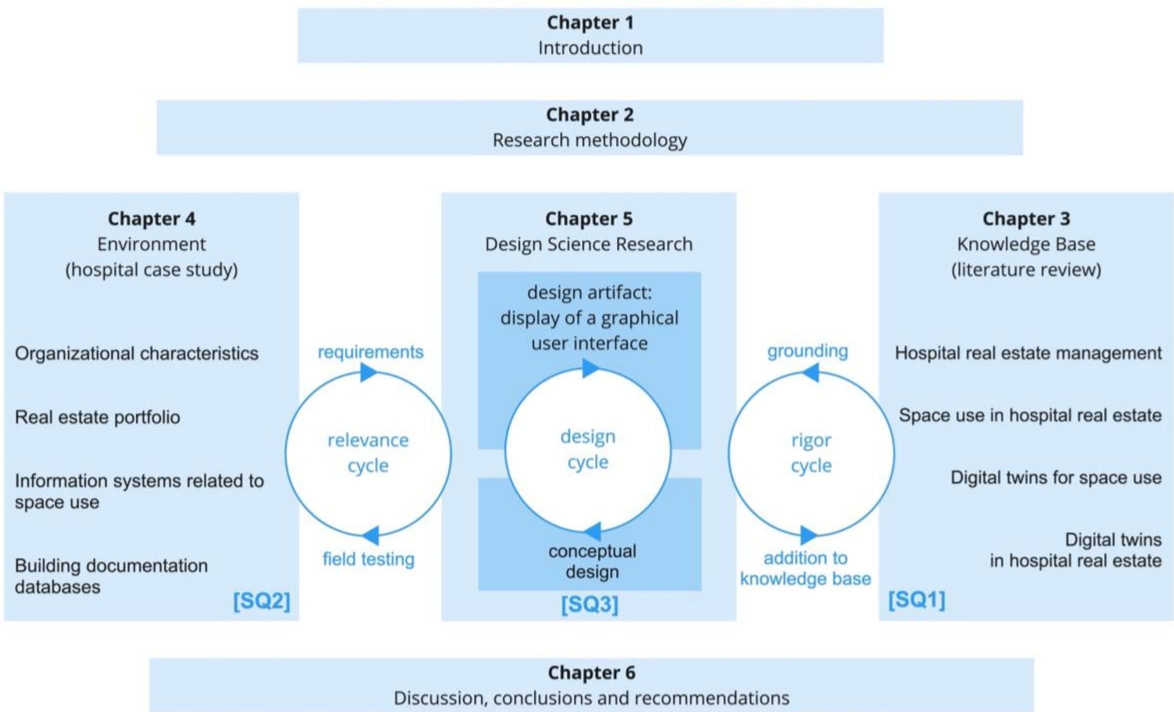
The present research is framed through the scope of digital twins, space use and hospital real estate. Furthermore, it is conducted through the following main research question:

"How can a digital twin for space use support decision makers and users of hospital real estate?"

The aim is to investigate how a novel technology can contribute to the real estate management process of a hospital. Additionally, it is aimed to assist potential developers and users for the development of a similar tool.

Research methodology

The research is approached by deploying a conceptual framework by Hevner (2007) for design science research, as seen on the figure below. It is made out of three main parts, that were also translated to phases of the research. The knowledge base, which entails a literature review. The environment, which is an analysis of a hospital case study. The design science research, which is based on the evaluation of a design artefact.



The research framework (source: author, based on Hevner (2007)).

Knowledge base (literature review)

The literature review is approached by investigating the topics of hospital real estate management, space use in hospital real estate, digital twins for space use and digital twins in hospital real estate. The topics start from a managerial focus and end to a more technical one and analysed with the aim of identifying design and utilisation principles for a digital twin. The three first sections are conducted through a snowball literature review. The last section of the literature review (digital twins for hospital real estate) is conducted through a systematic approach and by deploying the PRISMA guidelines.

The first section of the literature review analyses the real estate management theories that are applicable for hospital buildings. Alignment theories are presented first followed by stakeholder alignment, information management, real estate performance management and concludes to management focus and adding value. The second section of the literature review provides an overview of space use in hospitals. By defining the term space use as an integrative notion that incorporates quantitative aspects such as space allocation and occupancy but also qualitative measures such as space management. Topics such as occupant, temporal and spatial resolution, patient journey and space management goals are touched upon. The third section of the literature review focuses on the theory behind digital twins for space use. Initially the concept of a digital twin and its design approaches in system based and data based are presented. The following section offers an overview of the system architecture (Lu et al., 2019). It is made out of five layers: data acquisition layer, transmission layer, digital modelling and data complementary layer, data-model integration layer and application layer (Lu et al., 2019). the final section of the literature review is the systematic part where 8 publications about digital twins in hospital real estate are briefly presented. The section concludes with a with an overview of some of those displays. They are examples of patient journey, space utilisation and environmental monitoring.

Environment (case study)

The next chapter of the research is the analysis of the environment. In this chapter, a hospital case study is approached and analysed with the aim of identifying design and utilisation principles for a digital twin. The research approach was based on document analysis, personal communications and semi-structured interviews with ten real estate management professionals. The chosen case study is that of the Erasmus Medical Center.

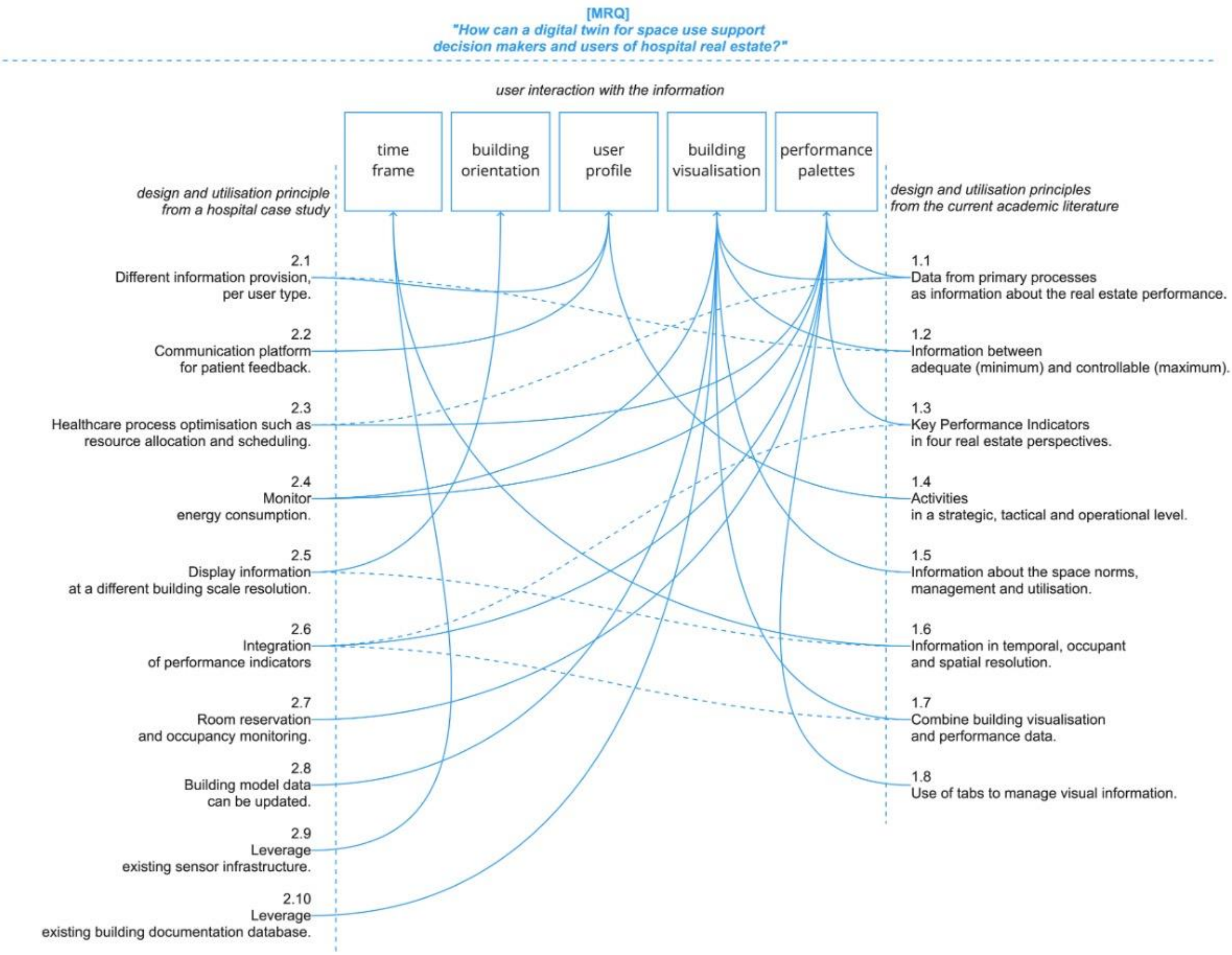
In the first section of the case study analysis, the organisation is presented. Starting from the impact and the organisational structure, it is aimed to understand the complexity of the organisation and its operations. The analysis of the organisational strategy and its objectives aims to understand the goals that the organisation strives for. The next section focuses on the real estate portfolio of the EMC. The analysis starts by presenting the current state of the real estate portfolio, the several buildings and the functional departments but also some metrics, such as square meters and numbers of operating rooms, in order to understand the scale of the portfolio. The strategic objectives to transform the hospital complex into a healthcare campus is then presented in order to present the intention of the organisation to create an even bigger building complex and accommodate even more functionalities. The next section is about the information systems for space use that are currently in use at the EMC. Through a series of personal communications, a data catalogue is created with information that can be leveraged and integrated in a digital twin for space use. the final section of the case study is about the building documentation databases and visualisation means that are used in the EMC. It is evident that the organisation uses a plethora of building documentation means, that could be leveraged and introduced in the system of a digital twin.

Design science research

Throughout the two previous chapters, a set of design and utilisation principles were identified for the design of a display of a digital twin. As seen on the conceptual framework below, the sets of these principles is set across each other, in reference to the framework of Hevner (2007). When commencing the design process of the conceptual design of a digital twin for space use (see next age), those principles were associated with five window types that together form the design of the display of the digital twin, as seen on the framework below. By doing so, the design process is substantiated and emerges from the findings of the literature review and the case study analysis.

The time frame window associates the time dimension with the design. By toggling between options in the past, present and simulations (future), the information is directed in a temporal resolution. The building orientation window aims to assist in the navigation within the hospital complex and can control the spatial resolution, starting from room, up to campus. The user profile window is intended to filter the provided information based on the user who is accessing the tool. The building visualisation window is the main screen of the display whereby real estate performance is presented on top of a building model. Finally, the performance palettes window offers the control to the user to toggle between different performance clusters and choose the type of information they want to access.

The final conceptual framework (source: author)



The conceptual design of a display of a digital twin for space use (source: author)

Next, the evaluation process was conducted by presenting the conceptual design to eight interviewees who represented decision makers and users of the hospital. In the first set of questions the interviewees validated the conceptual design, as they all found its display comprehensive. They were additionally prompted to think of modifications of the tool in order to improve its functionality. All interviewees suggested minor changes, in the form of additions (such as extra annotations about the weather, or another performance type).

In the following set of questions, the interviewees were prompted to consider utilisation scenarios of the digital twin. Most of the results were directed towards patient journey related operations and space utilisation and capacity management. This is because the hospital has a very limited amount of space and the decision makers try to allocate the space as efficiently as possible. The suggestions related to the patient journey may have been related with the fact that healthcare provision is the primary process of the organisation.

In the final set of questions, the interviewees were prompted to assess the feasibility and identify any potential bottlenecks. The most prevalent topic of discussion was the challenge of privacy issues. Since extensive monitoring can be carried out with systems like the digital twin, the decision makers and users were concerned up to which extend private data could become available from the tool. Other topics of discussion are related with the technical dimension and how easy or financially feasible to integrate data from several data sources.

Conclusions

The limitations of the research include the fact that it was conducted in a single case study, whereby the primary processes of the hospital had to be strictly respected. Additionally, the relatively nascent type of technology of digital twins requires more development and application to yield more accurate results. Finally, the limited timeframe and a certain degree of researcher's bias are related with the fact that this is a student project which had to be carried out with a master program from an inexperienced researcher.

Further design suggestions could be proposed for further research. An example was made with a different utilisation scenario, that of patient journey. The medical professional was interviewed once again to provide feedback on the different utilisation scenario of the tool. even though the graphical design and the principles were the same, the interviewee offered a series of valuable information on how it could be improved.

As a conclusion the answer to the main question was presented. In particular, it is stated that a digital twin can be used by different stakeholder perspectives, by providing historical, real time or simulation information at a room, floor, building or campus scale resolution to support operational, tactical and strategic utilisation processes. This answer tries to incorporate findings from all the previous sub questions and synthesize them in a concise manner.

When thinking about recommendation for practice, the facilitation of cross-organisational collaboration to minimise the silo effect and the development of future information systems with integration in mind. by streamlining the building documentation design process and by involving users in the design of a tool, it is expected for the tool to perform more optimally. Finally, it is recommended for healthcare organisations who deploy such tools to acknowledge potential security threats and act upon any privacy concerns.

Finally, the report concludes with recommendations for future research. it is suggested to conduct future research on the same topic in a comparative manner that would involve more hospital case studies or to perform similar research in other types of real estate. Another recommendation is to analyse the perspective of the supply side of such tools, for example that of software developers. Finally, it is recommended to conduct future research on the impact of such tools. This will require some time for digital twins to become prevalent.

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Glossary

Building Information Modelling (BIM)
"A collaborative way for multidisciplinary information storing, sharing, exchanging, and managing throughout the entire building project lifecycle including planning, design, construction, operation, maintenance and demolition phase" (Eastman et al., 2011).

Building Management System (BMS)
"A system that monitors the activities and affairs of buildings and, when necessary, automatically applies the necessary changes due to differences in environmental conditions" (Zurmatai, 2020).

Corporate Real Estate Management (CREM)
"The management of a corporation's real estate portfolio by aligning the portfolio and services to the needs of the core business (processes), in order to obtain maximum added value for the business and to contribute optimally to the overall performance of the corporation" (Krumm et al., 2000).

Digital Twin
"Physical product in real space, virtual product in virtual space and the connection of data and information that ties the two spaces together" (Grieves & Vickers, 2017).

Hospital
"An institution that is built, staffed, and equipped for the diagnosis of disease; for the treatment, both medical and surgical, of the sick and the injured; and for their housing during this process" (Scarborough et al., n.d.).

Hospital Real Estate Management (HREM)
The process of managing the real estate portfolio of a hospital aiming to provide optimal accommodation and align it with its strategic objectives (van der Zwart, 2014).

Information system
"The totality of technological and human components that work together to produce the information services that are needed, for organisational purposes" (Bytheway, 2014).

Smart tool
"A service or product with which information on space use is collected real-time to improve utilization of the current campus on the one hand, and to improve decision-making about the future campus on the other hand" (Valks et al., 2018).

Space Management:
The process that aims to improve the spacial layout with the objective of increasing the efficiency and improving the safety of a hospital (Moatari-Kazerouni et al., 2015)

Space Utilisation:
The product between frequency and occupancy rate (Space Management Group, 2006).

System architecture
A theoretical model aiming to describe the structure, the behaviour and other views of a system (Jaakkola & Thalheim, 2011).

Chapter 1
Introduction

In the first chapter of the report, the research context and its subsequent problematisation are delineated. These lead to the research aims which are the intentions for carrying out the research. In the next section, the description of the scope intends to describe the research boundaries, through the definitions of the main research concepts that are being investigated. Eventually, the several research sub-questions structure an incremental approach in answering the main research question for the research.

1.1 Research context

The needs of an aging population, a constantly increasing quality of life and a high demand of expensive medical and technical innovations lead to a high cost of healthcare provision (van der Zwart et al., 2009). In many countries, Hospital Real Estate Management (HREM) is being conducted by healthcare organisations in a similar manner that corporations manage their real estate resources. Besides facilitating healing environments that support their primary organisational objectives, HREM professionals adopt Corporate Real Estate Management (CREM) practices that facilitate added values for the healthcare organisations such as cost reduction, increased environmental sustainability, productivity and employee wellbeing (van der Zwart & van der Voordt, 2016). This applies to the Netherlands, which according to the Healthcare Facilities Law (WTZi) of 2008, a reformation of the healthcare system led to healthcare providers in having more control over their real estate resources, but also undertaking the potential financial risks for managing them (van der Zwart, 2014).

Recently, the spread of the Covid-19 virus has revealed the importance of effective HREM in the face of a pandemic. For example, ineffective bed management in hospitals has been linked to an increase in medical errors (Pecoraro et al., 2021). Hospital bed capacity management is part of the hospital HREM administration process, which deals with space use (Grigg et al., 2009). Thus, during times of high demand for healthcare provision, such as during a pandemic, management of scarce resources, such as hospital space use is deemed critical (Pecoraro et al., 2021).

To deal with this matter, healthcare organisations increasingly deploy information systems (Atkin & Bildsten, 2017) such as *Smart Tools* and *Building Management Systems* (BMS), aiming to optimise the space use of hospitals (Li & Bentwood, 2003). However, traditional building management systems do not utilise the capabilities of integrated data and oftentimes fail to provide effective visualisation (Yang & Ergan, 2014). In a similar manner, the application of *Building Information Managem*ent (BIM) technologies can be used by hospital real estate decision makers to document the physical assets and administer construction and building management activities (Alvanchi & Seyrfar, 2020). Those systems have been recently advancing within the context of the fourth industrial revolution by incorporating cloud computing, data analytics and Internet of things (IoT) applications (Starr et al., 2020).

A digital twin is one of the leading technologies closely linked to the Internet of Things and industry 4.0 (Adamenko et al., 2020). They are digital representations of physical assets that utilize several data inputs that monitor the past or present and simulate the future conditions of a building (Lu et al., 2020a). By integrating occupancy data from smart tools and building information data, they can function as digital platforms for optimised decision making regarding the use of space in real estate (Küsel, 2020). This can provide to real estate decision makers information about the building lifecycle, thus facilitate operations, development and service processes (Adamenko et al., 2020). Steins (2017) conducted extensive research demonstrating the potential benefits of information systems to generate simulations of the future demand of hospital resource requirements. Accordingly, Collison et al. (2019, p. 13) state that "the health sector will take advantage of staff and patient simulations to minimize friction and bottlenecks, allocate medical supplies more efficiently, and optimize staff rostering to meet current needs and to predict future ones".

1.2 Research problematisation and gap

Even though information systems are widespread in the administration of hospitals, there is still a very limited application of digital twins (Koch et al., 2019). Regardless of the potential advantages of this technology, many organisations are hesitant in investing for their development (Jones et al., 2020). This is mainly because this is a relatively nascent technology and a consolidated definition within the real estate and construction sector is still missing (Jones et al., 2020). Another reason is the fact that a digital twin requires a plethora of information that is often absent from existing buildings because of insufficient building documentation databases or scarce availability of real-time sensor data (Lu et al. 2020d).

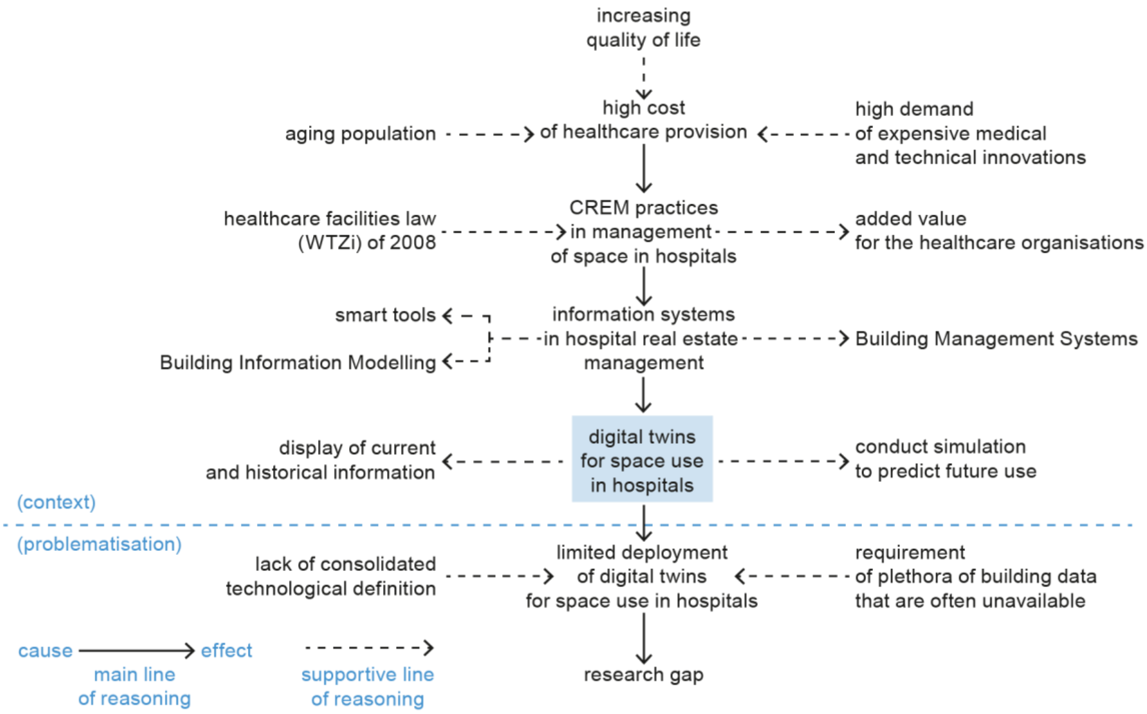


Figure 1: Overview of the context and the problematisation of the present research (source: author).

As noted by Jones et al. (2020), there are few and often divergent opinions and definitions regarding the digital twins in the building sector, thus calling for more research. Eventually, this necessitates for further investigation on the characteristics and potential applications of such tools aiming to optimise the space use of hospitals and generate value for the healthcare organisations. This is further evident in the absence of scientific publications in the overlap among the concepts of hospital real estate, digital twins and space use (Figure 2), which is elaborated in section 2.1.1 of the following chapter.

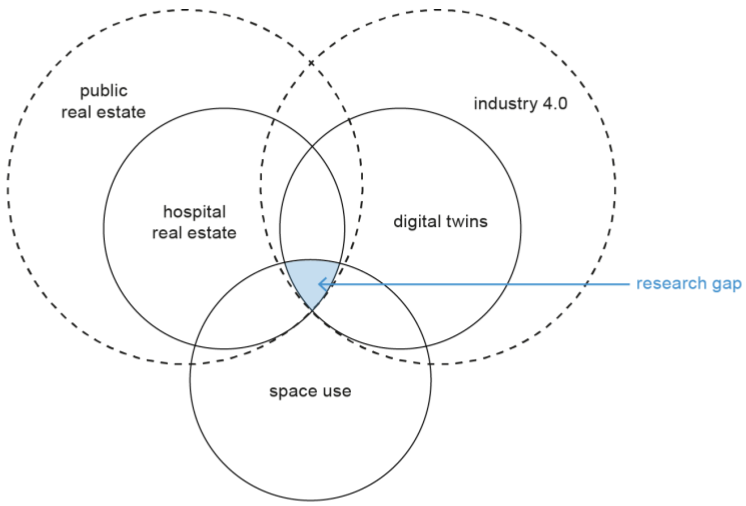


Figure 2: Schematic representation of the main research concepts and their gap (source: author).

1.3 Research aims

From the point of view of scientific relevance, the present report aims to investigate how a novel technology, such as the digital twins, can contribute to the managerial processes related to the use of space in hospitals. The research lies in the convergence of a technological field with a managerial one, leading to a multidisciplinary approach that combines the attributes of both sciences, by deploying the capabilities of the former (technological), to pursue objectives in the later (managerial). This is in line with the findings of Jylhä et al. (2019), whereby a changed paradigm in CREM research demands for more focus in the application of new technologies.

From a societal perspective, it is aimed to optimise the way hospitals are managed, which belong to the category of public real estate. This has the potential of a more efficient and effective resource allocation of healthcare organisations that can lead to lower costs and a higher quality of healthcare provision (van der Zwart & van der Voordt, 2016). Additionally, the deployment of a digital twin can facilitate a more efficient response towards a pandemic, such as the COVID-19 which has been negatively affecting today's societies.

The third aim of the research is the utilisation potential of its findings. As it is explained in Section 2.1, it is conducted within the framework of design research (Hevner, 2007), that aims to develop and evaluate the design specifications of a digital twin in the form of an information structure and the display of a graphical user interface. This design artefact can be consulted by healthcare organisations and software developers who could possibly want to develop a digital twin for space use.

1.4 Research scope

As seen on Figure 2 whereby the research gap is presented, the following thesis is developed under the three concepts of hospital real estate, digital twins and space use. The next paragraphs aim to create a firm conceptual basis and frame the research scope by elaborating on those three concepts.

The concept of **hospital real estate** refers to the building assets that accommodate the processes of healthcare organisations (Scarborough et al., n.d.). Hospital real estate management is the set of administration activities aiming to optimise the organisational alignment with its real estate resources (van der Zwart, 2014). A very similar but marginally different discipline to real estate management is that of facility management (van der Voordt et al., 2012). This research acknowledges the difference of those disciplines, which are also evident in the studied organisation (Chapter 4). However, they are considered as two highly overlapping disciplines and thus will be referred to within the same context.

The concept of **space use** is given a more multifaceted interpretation (Figure 1.3). It can be related to what type of space and where it is located, thus referring to space allocation, which is the decision-making process that leads to the location and placement of the building functions. Similarly, it is related to the term space utilisation, which is the product between occupancy and frequency rate, thus *who* is using a space and *when* (Space Management Group, 2006). Further research underlines the importance of assessing the quality of the use of space through performance indicators, thus *how well* a space is used (Flemming et al., 2019). These topics are further elaborated in section 3.2.

Figure 3:
The research scope
of the concept space use
(source: author).

Digital twin technologies emerged from the aerospace engineering field and later became prevalent in the manufacturing industry (Grieves & Vickers, 2017). Thus, most of the current research on these tools is focused on the manufacturing disciplines (Errandonea et al., 2020). This is because of the capacity of digital twins to simulate industrial processes which offers significant control to the relevant decision makers. Digital twins are still less commonly used in the real estate context, even though they can be considered as an evolution of the pre-existing information systems which are largely used in the built environment (Lu et al., 2020a). Such an example are the conventional building management systems. The concept of digital twins in the present research will refer to the information system that can support decision makers and users of the built environment by providing them with real-time and historical data, together with possible simulations (Errandonea et al., 2020).

1.5 Research questions and objectives

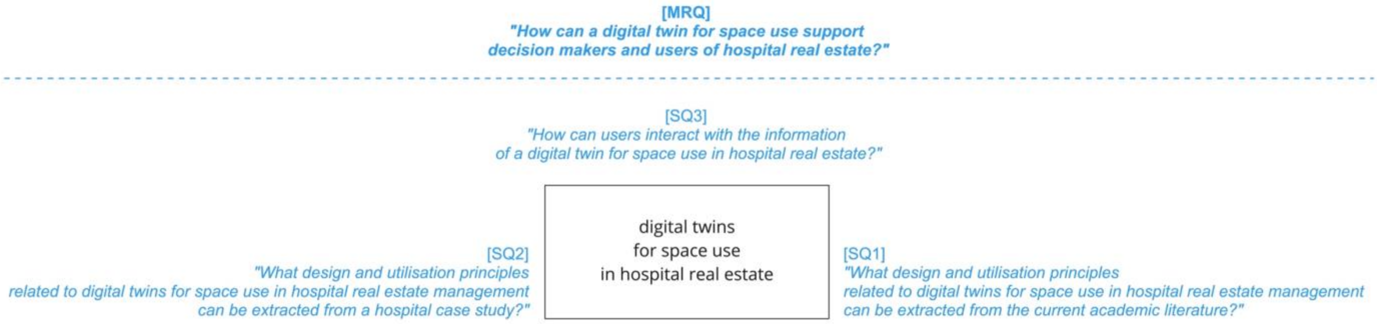
By combining the problematisation, gap and aims of this research and by framing it within the scope of the three concepts of hospital real estate, space use and digital twins, the following main research question emerges:

[MRQ]
"How can a digital twin for space use support
decision makers and users of hospital real estate?"

According to Blaikie and Priest (2019), the objective of a "How" question is to propose a change. They suggest that regularly this type of question aims to investigate how something can be carried out in a different way. In the present research, the difference is proposed by the deployment of novel technology, that of digital twins. This technology can be used by decision-makers and users of hospitals, who have been relying predominantly in the use of other types of digital tools. Accordingly, the above question will eventually function as the backbone of the present research. In order to identify how a digital twin can support decision makers and users of hospital real estate, it is aimed to identify design and utilisation principles that are related with it. The design principles can determine the ways that this technology can be developed and the utilisation principles can identify the ways that it can be used.

Three subquestions are formulated that together make up the research components that aim to compose an answer for the main research question. As seen on the conceptual framework of the figure below, the three research subquestions are interrelated as components and all three request for the research of design and utilisation principles of a digital twin. Even though all three investigate the same topics, the research approach is different, thus leading to different findings. The methodology of research is elaborated on section 2.1 of the next chapter.

Figure 4: Conceptual framework of the relationship between the research questions (source: author).



An elaboration of the objectives of each of the respective subquestion is the following:

[SQ1]
"What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from the current academic literature?"

The first research subquestion aims to identify and describe on one hand the ways with which a digital twin can be designed and has a technological focus which can shed light upon the architecture of a digital twin, their required relationships and their eventual functionality as a system. The second part of this subquestion aims to identify the principles with which a digital twin can be used and lies predominantly within the context of real estate management theory. Being a "what" type of question and according to Blaikie and Priest (2019), the objective of this question is to identify and describe the utilisation and design principles of a digital twin. This research question directs towards a literature review and constitutes the starting point for the formulation of the answer to the main research question.

[SQ2]
"What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from a hospital case study?"

The second research subquestion positions the research focus in a hospital environment. It aims to connect the design principles of a digital tool and the principles for its use with the characteristics of a hospital environment through a case study. Its research findings overlap with those of the first subquestion and, being a "what" type of question, its objective is to explore (Blaikie & Priest, 2019) the several principles that can be defined through a hospital environment and can be introduced to the design and utilisation process of a digital twin for space use. Organisational characteristics, the real estate that provides accommodation for them, some existing information systems and building documentation practices are investigated within the context of the hospital case study. By exploring those principles, the development of a digital twin is expected to become bespoke for a specific organisation and, therefore, a more feasible design artefact.

[SQ3]
"How can users interact with the information of a digital twin for space use in hospital real estate?"

The third research subquestion aims to investigate the interaction of a digital twin with its potential users. In order to answer this research subquestion, the design development of a display of a graphical user interface and its subsequent information structure is commenced. Being a "how" type of question and according to Blaikie and Priest (2019), this question is related with the act of an intervention and change. In this case it is through the interaction of users with a digital twin. Users who are familiar with information types that can be displayed through a graphical user interface of a digital twin are requested to expose their opinions on the characteristics of the display and its functionality and suggest ways in which this artefact can be used. The outcomes of this question are utilisation and design principles, similarly with the previous two subquestions. However, the design principles are limited to those that are related with the display of a digital twin and not the entirety of its system architecture.

Chapter 2
Research methodology

In the second chapter of the report, the research methodology is presented. Starting from the general research approach, the research framework is analysed. This will dictate the research choices which are elaborated in the following subsections. Those include a literature review that formulates a knowledge base, a hospital case study that introduces environmental aspects for the research and the design science research approach that is structured through the evaluation of a design artefact. The chapter concludes with a section on research validation, a section on the data plan and a section on the ethical considerations of the research.

2.1 Research approach

The main research question entails the need for an improvement of an environment (space use in hospital real estate) by introducing a novel artefact (digital twins). According to Simon (1996), this reasoning is the motivation for the application of a research approach that conforms to the discipline of "design research". Hevner (2007) proposes a framework to conduct design research for information systems by utilising three cycles of activities. The rigor cycle iterates from the applied theories that are required for the design artefact while the design output will, in turn, provide a new addition to the knowledge base of the topics that are addressed. The relevance cycle deals with the introduction of the environment of the designed artefact and provides the requirements to the design research while it can be used for field testing in return. The design cycle concerns the research activities that are based on the generation of a design artefact, by iterating through evaluation moments.

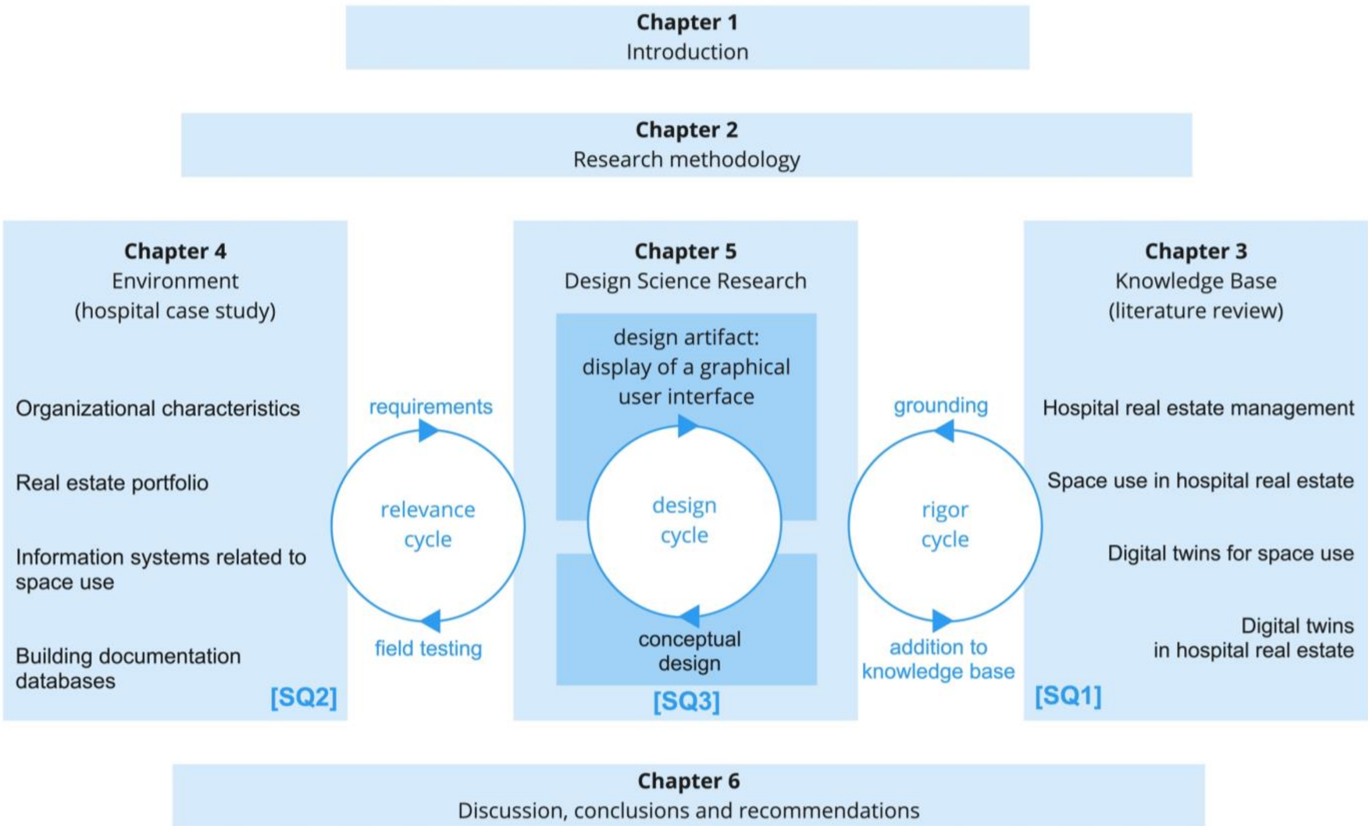


Figure 5: The research framework and structure (source: author, adapted from Hevner (2007)).

The present research is structured by applying the framework of Hevner (2007), as seen on the figure above. Apart from the first chapter (introduction) and the second one (methodology), the third chapter formulates the knowledge base through a literature review, the fourth chapter aims to describe the environment through a case study of a hospital organisation and the fifth chapter elaborates on the design development and its evaluation interviews. The report concludes with a chapter on discussions, conclusions and recommendations.

Each of the research chapters corresponds in answering one of the research subquestions (see section 1.5), which in turn lie in one of the three sections of the research framework by Hevner (2007). This is being done by applying a different research method with an appropriate research focus (theoretical, empirical and operational). The responses of all three research subquestions lead to an answer for the main research question, which is elaborated on the conclusion of the present report. Therefore, the table below, provides an overview of each one of the research steps.

	Chapter 3	Chapter 4	Chapter 5
Research framework area:	Knowledge Base	Environment	Design Science Research
Main research question	[MRQ] "How can a digital twin for space use support decision makers and users of hospital real estate?"		
Research subquestion	*[SQ1] "What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from the current academic literature?"*	*[SQ2] "What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from a hospital case study?"*	*[SQ3] "How can users interact with the information of a digital twin for space use in hospital real estate?"*
Study focus:	Theoretical	Empirical	Operational
Method of study	Systematic literature review	Environment analysis	Design science research
Data collection method	Systematic analysis of scientific publications	Document analysis Personal communications Semi-structured interviews	Design development Semi-structured interviews
Research output	Theoretical principles for the design and utilisation of a digital twin for space use in hospital real estate.	Principles for the design and utilisation of a digital twin for space use through the environment of hospital real estate.	Evaluation of the design artefact, proposals of additions and changes and suggestion of utilisation scenarios.

Table 1: Research overview (source: author).

The research is developed as an iterative process among the chapters three to five, therefore not linear. Starting from a literature review, several concepts related to hospital real estate management and digital twins are initially researched. Those preliminary results already provide the first input for several concepts of the design process. In the next step, the hospital case study is analysed, which provides further input for the design research. Next, the literature review is reassessed for more detailed findings that can provide information for analysis of the existing results of the other two chapters. According to Bryman (2016), a literature review should be dealt as an ongoing research process that does not stop at an early phase of the research. In this way, the cohesion among the three chapters is reinforced. Eventually, the process concludes with the design research and the evaluation processes. In the next three subsections follows an elaboration of these three research approaches.

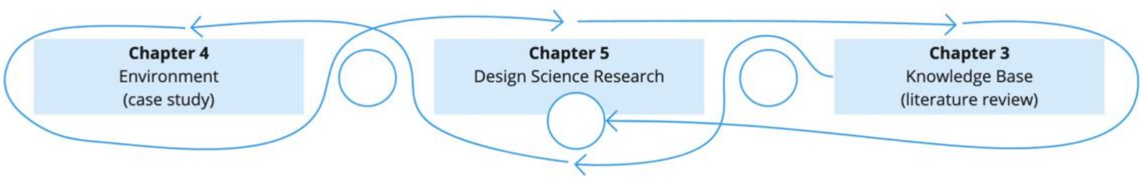


Figure 6: The development of the research process (source: author).

2.1.1 Knowledge base: literature review research approach

The knowledge base is formulated through a literature review which is initially conducted by analysing the overlaps of the three research concepts that were identified as the scope of the research (see section 1.4). Therefore, each section of the literature review deals with one of the following topics: hospital real estate (section 3.1), space use in hospital real estate (section 3.2), digital twins for space use (section 3.3) and digital twins for hospital real estate (section 3.4). The search query that includes all concepts, yields only one result in the Scopus database and only four in Google scholar (last screening day: 9 of June, 2022). Therefore, the research gap that is mentioned in section 1.2 is validated through the absence of relative academic publications. Ultimately the literature review aims to answer the first research sub question [SQ1] and, thus, lead to the identification of utilisation and design principles for a digital twin.

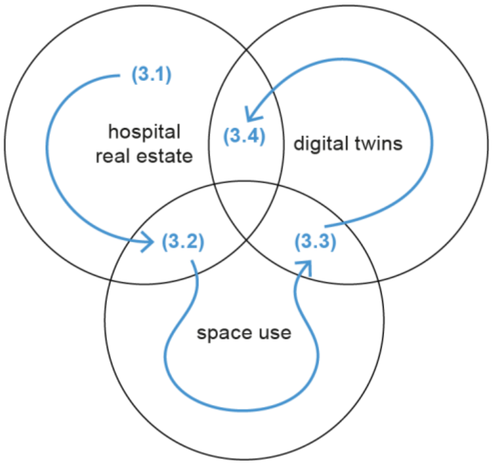


Figure 7:
Structure and order of the sections of the literature review (source author).

The three first sections (3.1, 3.2 and 3.3) are explored through the method of a snowball literature review. Academic publications are analysed based on several of the keywords and their combinations, as seen in Table 2. Those keywords were identified as derivative terms through the scope of the present research which was presented in section 1.4. By doing so, the research context can be set and several concepts and notions are dealt with that are utilised for the development of the present research.

Table 2:
Overview of the concepts and the terms for the literature review (source: author).

Concept 1	Concept 2	Concept 3
Hospital real estate	Space use	Digital twin
hospital	space use	digital twin*
healthcare real estate	space planning	
healthcare building*	space management	
healthcare facilit*	space utilisation	
healthcare propert*	space allocation	

As a following step, in section 3.4 a systematic literature review is conducted in the intersection of the two concepts of hospital real estate and digital twin, together with their derivatives, as seen on the above table. Two databases are used for the retrieval of literature findings, that of *Scopus* and that of *Google scholar*. A search query is created using the Boolean operations "AND" and "OR" of the concepts and their related and derivative terms as seen on the following Table. It should be noted that the query was slightly modified for the search in *Google scholar* from the one that was used for the search in *Scopus*, in order to conform with their respective searching requirements.

Search query (for search on Scopus)	Scopus (09/06/2022)	Google scholar (09/06/2022)
(TITLE-ABS-KEY (hospital OR "healthcare real estate" OR "healthcare building*" OR "healthcare facilit*" OR "healthcare propert*") AND TITLE-ABS-KEY ("space use" OR "space planning" OR "space management" OR "space utilisation" OR "space allocation") AND TITLE-ABS-KEY ("digital twin*"))	1	4
(TITLE-ABS-KEY (hospital OR "healthcare real estate" OR "healthcare building*" OR "healthcare facilit*" OR "healthcare propert*") AND TITLE-ABS-KEY ("digital twin*"))	35	6

Table 3:
The two search queries and the number of results in each database
(source: author).

For the search in *Scopus* database, the search was conducted in the title, abstract and key words and for all the years. For the search in the *Google scholar* database, the search was conducted in the title of the article and for all the years. The second query yielded 35 results in *Scopus* and 6 results in *Google scholar*. The publications that were identified above are further analysed by applying the PRISMA guidelines (Moher et al., 2009). A selection process is carried out as seen on the figure below. Next, the selected publications of the two databases are analysed for duplicates, their titles and keywords, their abstract and eventually the entire text before they are selected for the review of section 3.4. This incremental approach of analysis of the publications eventually leads to a gradual reduction of the selected publications from forty-one to eight.

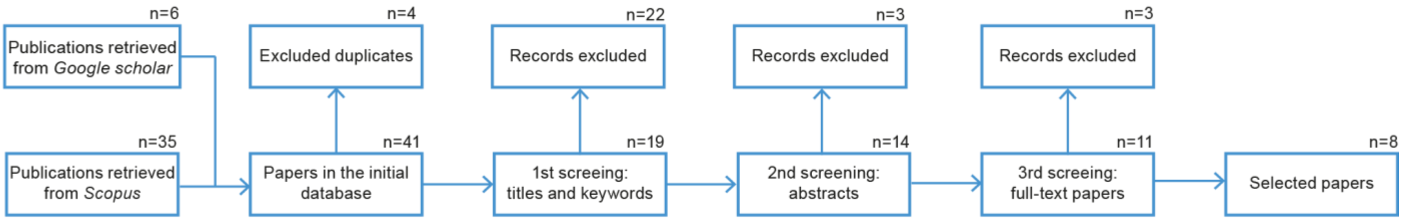


Figure 8:
Overview of the selection process for the literature review in section 3.4
(source author).

The analysis of the publications is based on inclusion and exclusion criteria that were considered, as seen on the table below. After excluding the duplicates, three screening phases are conducted, as seen on the figure above. At the beginning, the language and type of publication are considered as apparent determining factors of inclusion and exclusion. However, as the screening process commenced, factors such as the contents of the research were used to exclude unrelated publications. For example, digital twins are developed in several fields such as medical or mechanical processes and, while they appeared in the conducted search queries, they were considered unrelated with the topic of the present research.

Inclusion criteria	Exclusion criteria
Publications are written in English language.	Publications are not written in English language.
Publications are articles, book chapters or conference papers.	Publications are case study video presentations or undergraduate theses.
Research focus on management of healthcare real estate, building or facility resources.	Research focus on medical, aeronautical, mobility or other types of processes.
Setting is related to hospital buildings.	Setting is related to other types of healthcare provision facilities.
Study is related to a digital twin for hospital real estate management during non-critical events.	Study is related to a digital twin for hospital real estate management during critical events, such as during an earthquake.
Study is directly related to the development or application of a digital twin system.	Study is not directly related to the development or application of a digital twin system but implies that could be used to indirectly support one.

Table 4:
The inclusion and exclusion criteria of the literature review
(source: author).

2.1.2 Environment: the hospital case study research approach

The next chapter of the research is conducted through the analysis of a case study. For this reason, a hospital is selected in order to be investigated as the environment, according to the research framework that was presented in section 2.1. This also constitutes the input for the relevance cycle, according to Hevner (2007). Thus, the environmental characteristics of the case study will be introduced as principles for the development of the design artefact. The chosen hospital case study is that of the Erasmus Medical Center, due to its complex real estate portfolio that provides a challenging organisation for analysis at multiple scales and the inclination of the organisation in the deployment of novel technologies for a more efficient administration of its real estate resources (Erasmus MC & Programma Integrale Bouw, 2019). Eventually the outcome of the analysis is the answer to the second research subquestion [SQ2] which requests for design and utilisation principles of a digital twin through a hospital environment.

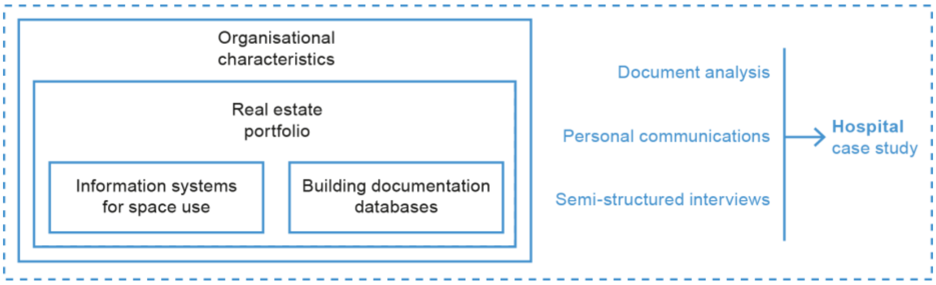


Figure 9:
The single case study, the units of analysis and their data collection methods (source author).

According to the Yin (2009), this is an embedded case study design, because a single case is analysed at different units. Those units are the organisational characteristics, its real estate portfolio, the deployed information systems for space use and their building documentation databases. Those research units are also the respective sections of chapter 4. The data collection of the case study is carried out through document analysis, such as organisational and strategic reports, personal communications and semi-structured interviews with building experts that work at the studied organisation. The interviewed building experts are chosen aiming to diversify the representation of stakeholder perspectives (see section 3.1.2) and the different departments that make up the organisation.

Id	Interviewee role	EMC Department	Perspective	In-text citation
E.1	Healthcare real estate development consultant	PIB	strategic & physical	(E.1, 2021)
E.2	Technical manager	PIB	physical	(E.2, 2021)
E.3	Healthcare real estate consultant	PIB	strategic & physical	(E.3, 2021)
E.4	Healthcare real estate manager	PIB	physical	(E.4, 2021)
E.5	Technical consultants	PIB	physical	(E.5, 2021)
E.6	Facility management and procurement director	Procurement & Facility management (Service company)	financial & physical	(E.6, 2021)
E.7	Security professional	Procurement & Facility management (Service company)	functional & physical	(E.7, 2021)
E.8	BIM manager	PIB	physical	(E.8, 2021)
E.9	Energy consultant	PIB	physical	(E.9, 2021)
E.10	Healthcare business intelligence consultant	Data & Analytics (Service company)	strategic & functional	(E.10, 2021)

Table 5:
List of interviewees for the analysis of the hospital environment part (source: author).

2.1.3 Design science research approach

The third part of the research framework of Hevner (2007) is that of the design science research (see section 2.1). In this part a design artefact is created and evaluated by key experts on some of its aspects (chapter 5). The present research deals with the design of the display of graphical user interface of a digital twin, while the evaluation interviews provide an assessment of the artefact through the expertise of eight decision makers and users of hospital real estate, as seen on the table below. Ultimately, it is aimed to delineate an answer for the research subquestion 3 [SQ3], which requests for the investigation of the interaction of users of hospital real estate with a digital twin. The Interviewees are selected in a similar manner with the interviewees of the environment part of the research (section 2.1.2). Thus, they represent different stakeholder perspectives, and eventually a diverse range of opinions can be leveraged through the interviewing process (see table below).

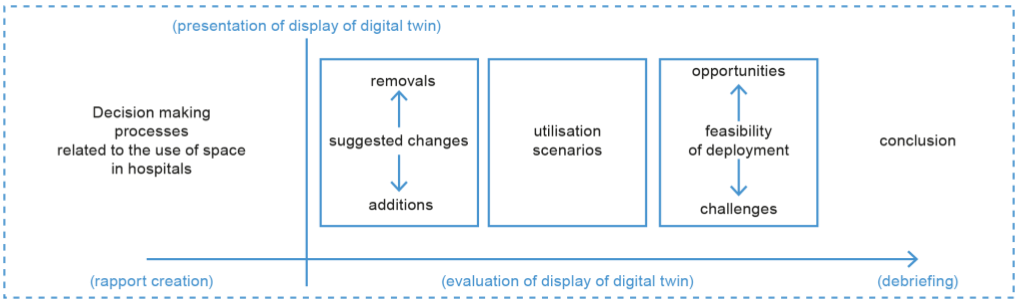


Figure 10:
The structure
of the evaluation interviews
(source author).

Being in line with Bryman (2012), semi structured interviews are selected as a data collection method, in order to allow for the participants to freely express their opinions and the interviewee to steer the process towards the topics that they are keen on elaborating. In order to do so, a set of core topics are created (see figure above), starting from general decision-making processes that are related with the interviewee's role in the hospital, in order to facilitate rapport and introduce the interviewees to the topic. Then, the display is presented, and the interviewees are asked to suggest any changes on the design, think of utilisation scenarios that they could carry out with it and discuss about the feasibility of its deployment, such as opportunities and challenges. Eventually, the interviews conclude with a conclusion and a debriefing. The interview protocol that was used as a guide for the process can be found in appendix 1.

Id	Interviewee role	EMC Department	Perspective	In-text citation
A.1	Healthcare real estate information manager	PIB	physical	(A.1, 2021)
A.2	Medical professional	Thema Daniel	functional	(A.2, 2021)
A.3	Healthcare real estate development consultant	PIB	strategic & physical	(A.3, 2021)
A.4	Technical consultant	PIB	physical	(A.4, 2021)
A.5	Healthcare business intelligence consultant	Data & Analytics (Service company)	strategic & functional	(A.5, 2021)
A.6	Healthcare real estate policy consultant	PIB	strategic & physical	(A.6, 2021)
A.7	Healthcare real estate policy advisor - sector manager	PIB	financial & physical	(A.7, 2021)
A.8	Healthcare facility project manager	Procurement & Facility management (Service company)	physical	(A.8, 2021)
B.1	Medical professional	Thema Daniel	functional	(B.1, 2022)

Table 6:
List of interviewees for the analysis of the design science research part
(source: author).

2.2 Research validation

The validity of the collected data for the present research is fostered through certain research choices that are introduced by Yin (2018). Initially, a plethora of peer-reviewed publications is used in order to foster the validity of the literature review. For the collection of interview data, by conducting a test interview, the accuracy of the questions is ensured and any clarifications are mentioned, thus updating the interview protocols. Finally, a final review of the research by an industry expert aims to confirm the accuracy of the present research. By deploying multiple methods and sources of data, such as literature findings, personal communications, organisational reports, semi structured interviews and an expert review, it is aimed to create triangulations of data sources.

2.3 Data plan

The data management approach of the present research conforms to the standards of the *FAIR* principles that are described by Wilkinson et al. (2016). The four principles request for data to be findable, accessible, interoperable and reusable. By conforming to those principles, the data reusability can be enhanced, fostering a better knowledge integration for the scientific community.

Each of the principles is dealt with in the following manner:

In order for the data to be **findable**, they are being stored locally at the author's personal computer. Upon completion of the graduation project, the report will become publicly available at the educational repository of the Technical University of Delft, as part of the graduation process.

In order for the data to be **accessible**, all raw data (such as interview transcripts) are kept at the personal storage of the author. In the event that a researcher requests access to them, they can contact the author in the email that is mentioned in the colophon. All data will be anonymised with respect to any ethical considerations that are mentioned in the next section.

The **interoperability** of the data is being facilitated by conducting the research in English. Since the research is carried out in a Dutch context, any documents or images that are being referenced in the present report are translated accordingly from Dutch to English, without altering any of the original meaning.

In order for the data to be **reusable**, the report conforms to the standards of the academic referencing format of the *APA 7 style*. Therefore, any source of academic or non-academic publication is cited accordingly and included in the references section of the report.

2.4 Ethical considerations

From an ethical point of view, the present research conforms to the ethical considerations that are delineated in Blaikie and Priest (2019). They are related with an ethical social conduct and refer to the duties, consequences, virtues and situation ethics of social research.

When it comes to the **duties** of the research, its purpose is to improve healthcare provision through the deployment of a specific digital tool, thus establishing the project's worthiness. The researcher's competence and integrity are facilitated through his academic training and the consultation of his mentors, who are experienced researchers. Appropriate methodological criteria are applied, as stated in the data plan, in order to generate research that meets the needs of the scientific community. Finally, organizations that contributed to the initiative, such as the TU Delft and the Erasmus Medical Center, are duly acknowledged.

When it comes to the **consequences** of the research, aiming to diminish any potential risk or harm of the research participants. Anonymisation procedures will ensure that they have every right to privacy. Their potential identification is examined, and if this poses any risk, the participants will be notified, and they will have the ability to withdraw from the study at any time. If it is deemed necessary to remove any sections of the research after its publication, the researcher is obliged to agree and act accordingly in order to avoid any potential harm.

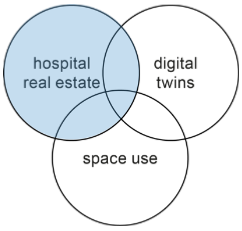
When it comes to the **virtues** of the research, no adjustments or modifications are made in the processing of the information that are collected in the research, thus ensuring the *credibility of the collected data*. The research participants are appropriately informed about the process and the objectives of the research, thus *avoiding any potential deception*. The researcher does not express any personal opinion that could alter the research findings or influence the interviewing processes; thus, diminishing any potential *abuse of power and trust*.

When it comes to **situation ethics**, the researcher will ensure that the process will unfold in an objective manner. No data related to medical processes will be included in the research and the participants will be informed accordingly. The data analysis will be carried out without any intervention that would manipulate or change the quality of them. As mentioned in the data plan, the data will be presented according to the academic rules, while for any potential publication, this will occur through a peer-reviewed procedure.

Chapter 3
Knowledge base

The knowledge base of the research approach is elaborated in this chapter. As mentioned in section 2.1.1, this also constitutes a literature review on the three main concepts of the research. It is structured by analysing the thematic intersections of those topics, namely: hospital real estate management, space use in hospital real estate, digital twins for space use and digital twins in hospital real estate. Those are the four sections of the chapter. The conclusion deals with utilisation and design principles for a digital twin, which, in turn, provides an answer to the first research subquestion [SQ1] and is used as an input for the rigor cycle of the research framework (section 2.1).

3.1 Hospital real estate management



The first section of the knowledge base addresses the academic theories that are relevant to the process of hospital real estate management. The alignment frameworks and the stakeholder perspectives form a cornerstone in real estate management theories. Information management and performance assessment of hospital buildings is deemed relevant for the development of a decision-making tool and its utilisation. Finally, the management focus leading to added values is considered the desirable outcome of this process.

3.1.1 Alignment frameworks in real estate management

Corporate real estate managers (CREM) aim through their administrative actions to align the real estate resources of an organisation with its organisational demands, thus aiming to provoke value creation (Osgood, 2009). Eventually, this principle has led to an extensive development of alignment frameworks by researchers in the real estate industry (Heywood & Arkesteijn, 2018). As mentioned in section 1.1, decision makers of hospital real estate adopt practices similar to corporate real estate professionals (van der Zwart & van der Voordt, 2016), even though hospitals are a type of real estate with a highly public function. Therefore, in the field of HREM, decision makers strive for the alignment of building resources to the objectives of a healthcare organisation.

An analysis of 14 corporate real estate (CRE) models' theoretical frameworks was conducted that led to 12 components that were used to model CRE alignment (Heywood & Arkesteijn, 2018). Those components can be grouped in four building blocks: understanding corporate strategy, understanding real estate performance, making a real estate strategy and implementing a real estate strategy (figure below). While all models had components of the four Building Blocks, only a few had all 12 components, while all had at least seven. Additionally, various feedback mechanisms between the components were also visible. The researchers mention that completeness of representation should not be equated with alignment process effectiveness (Heywood & Arkesteijn, 2018). It is noteworthy that understanding the real estate performance is one of the necessary building blocks in the alignment process.

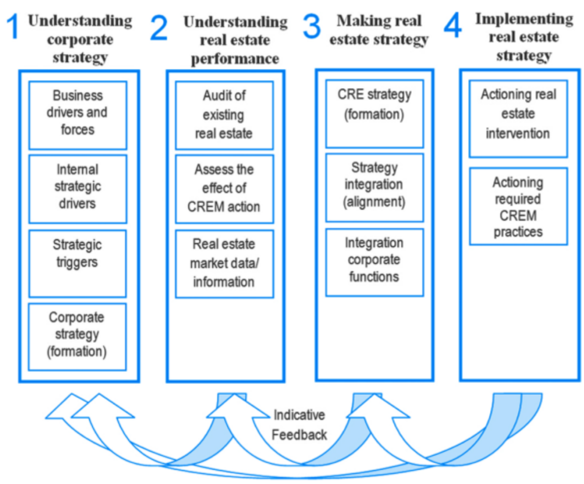


Figure 11:
The CRE alignment,
(Heywood & Arkesteijn, 2018, p. 17).

3.1.2 Hospital real estate management stakeholders

Den Heijer (2011) frames the CREM profession in the alignment of four stakeholder perspectives, those of the strategic, functional, financial and physical. For the **strategic perspective**, the real estate assets are considered as a resource that contributes to the production and influences the institutional goals, which can be either positive or negative. This perspective leads to decisions that can contribute to the improvement of the quality and effectiveness of the organisation's primary processes (Den Heijer, 2011). For a healthcare organisation, that would be the healthcare provision. The **financial perspective** focuses on the actions related with the financing and cost structures. It is responsible for the assessment of real estate investment decisions and represented values from the real estate resources (Den Heijer, 20211). In the scenario of the healthcare organisation, that would be related with the financing of the hospital buildings. The **functional perspective** deals with the real estate from the point of view of the primary processes and the users. It can support decision making that addresses the capacity and the quality for the use of spaces (Den Heijer, 2011). This perspective can be represented through the medical professionals and the patients of a hospital. The **physical perspective** focuses on the physical aspects of the real estate resources, such as the technical characteristics and the operational activities that are needed for an orderly use (Den Heijer, 2011). In the case of a hospital, that would be represented through all the technical experts that enable a functional building portfolio.

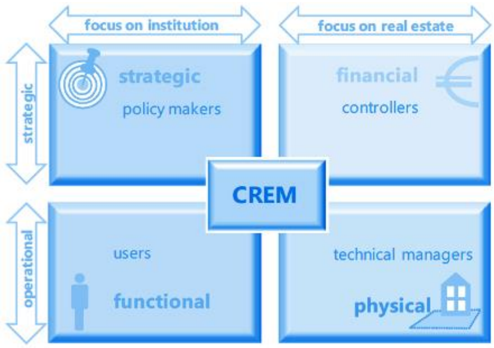


Figure 12:
The four real estate stakeholder perspectives (den Heijer 2011, p. 106).

The stakeholders of a hospital organisation were mapped by van der Zwart (2014) and grouped in internal and external. The former referring to those who lie within the organisation and have a direct interest in it and the latter those who are external to the organisation and have an indirect interest in it (Winch, 2010). In the table below, the internal stakeholders are presented with some of their attributes, as they were identified by van der Zwart (2014). The present research focuses on the direct decision makers and the users of hospital real estate; thus, the analysis of only the internal stakeholders can be deemed as relevant.

Internal stakeholders	Position	Interest	Stakeholder perspective
Patients	Healthcare consumer	Good quality healthcare, clean and safe hospitals	Functional
Doctors, medical staff and healthcare professionals	Healthcare delivery	Good practice of medical treatment of patients, working environment	Functional
Pharmacy	Delivery support	Service oriented delivery of medicine	Functional
Facility management and ICT	Delivery support	Support primary process	Functional / Physical
Hospital board	Policy and management	Daily management considering quality and efficiency	Strategic / Financial
Supervisory board	Policy and management	Overall performance organisation, end results	Strategic / Financial

Table 7:
Internal stakeholders of a hospital organisation (van der Zwart (2014, p.91)).

3.1.3 Information management in real estate decision-making

Decision making related to real estate management requires the existence of operational information of the organisational processes. As stated in the various CRE alignment frameworks, primary processes of an organisation and strategic objectives are oftentimes adjusted to the available real estate resources, but also the real estate resources should follow the primary processes of an organisation and its strategic organisational objectives, thus creating a bidirectional relationship (Heywood & Arkesteijn, 2018). Data related with the organisational performance can direct real estate decisions and real estate performance data can direct organisational decisions. Information management thus becomes critical in contributing to the decision making of real estate resources (Atkin & Brooks, 2021). In turn the decision-making processes lead to the generation of further data that could be used as input for future decisions. This leads to a cyclical relationship between decision making and available information (Lohman, 1999).

Lohman (1999) analysed the aforementioned cyclical process in his diagram (Figure below). Reading from 1 to 5 one can trace the flow that leads to the generation of management information. One can, however, follow the opposite process (from 5 to 1) in order to determine the data needs for a specific decision. Thus, data from the primary processes of an organisation can be transformed to information about the performance of the real estate resources which in turn can be used for further decision making.

[knowledge base finding] →

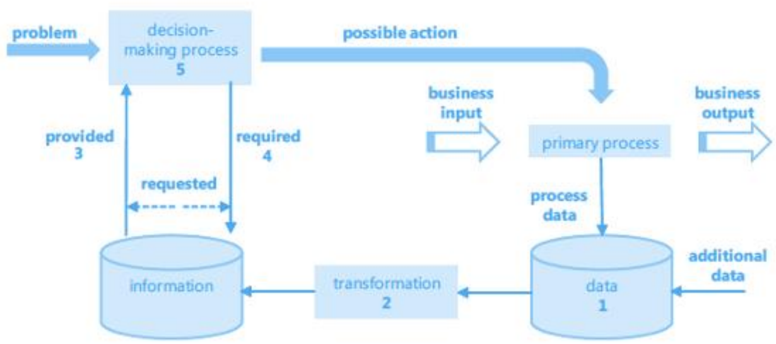


Figure 13: Generating management information (den Heijer, 2011, p. 111, from Lohman (1999)).

In CRE the amount of available building data is related with the level of influence of a decision. (Glatte, 2021). As seen on the figure below, a funnel model can describe the relationship between the amount of information that is required in relationship to the amount of real estate resources that a decision-making process will impact. Therefore, when the number of properties that are considered increases, the level of detail of the information system has to decrease in order to provide an operational amount of big quantity of information. This is related with the information overload that provokes hindrances in the decision-making process of organisations (Edmunds & Morris, 2000).

[knowledge base finding] →

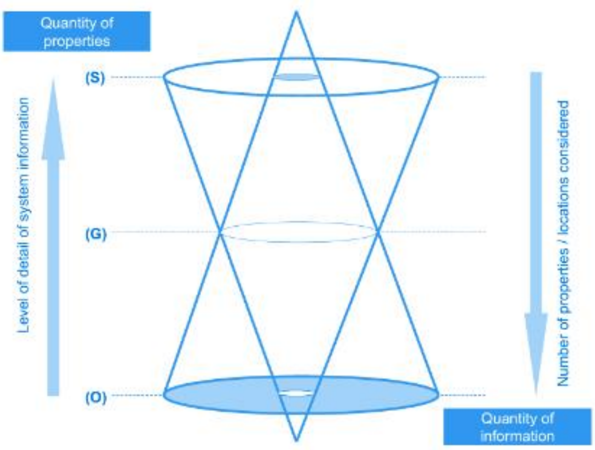


Figure 14: The Funnel model for real estate information systems (Glatte, 2021, p.21).

3.1.4 Assessing the performance of hospital real estate

In order to generate information regarding the performance of a real estate, data are required about the organisational performance and data about the several real estate variables (Den Heijer, 2011). Historical references from past performance can be introduced in this process. This can lead to the creation of key performance indicators (KPIs). The basis for collecting data for the generation of management information lies in the process of real estate adding value to the performance of an organization. The concept of added value is analysed in the following section (Den Heijer, 2011).

It is suggested that the different stakeholder perspectives can lead to different sets of KPIs Thus she proposes a set of performance indicators called productivity (related to the functional perspective), such as students per square meter and publications per year, etc (Den Heijer, 2011). A set of KPIs related with the profitability of a university, thus representing the financial perspective, such as revenues minus costs. A set related to competitive advantage of a university, thus representing the strategic perspective such as international rankings. Finally, a set of KPIs is presented, which is called sustainable development and represents the physical perspective.

Nine international healthcare providers have been reviewed with regards to the deployed performance indicators of their real estate resources (Rodriguez-Labajos et al., 2016). That research was carried out with the aim of developing a framework that can be used by hospital decision makers to support their objectives. According to the results, each organisation uses KPIs for their real estate that correspond to the organisational policies and objectives. Even though they were different organisations, they all used a similar set of KPIs (Rodriguez-Labajos et al., 2016). Most of the dominions of the KPIs that were identified can be associated directly with a stakeholder perspective.

[knowledge base finding] →

Dominion	Attribute	Stakeholder perspective
Financial	Operational costs Maintenance costs Backlog maintenance cost Resource allocation Productivity	Financial
Physical	Physical condition Age Remaining economic life	Physical
Safety	Statutory compliance Level of risk associated with outstanding backlog maintenance Fire incidents	Physical
Functional	Utilisation Surplus Available capacity Functional suitability	Strategic/Functional
Patient experience	Quality of the building Single bedrooms Patient feedback	Functional
Environment	Energy performance Water and waste Sustainability	Physical

Table 8: Attributes and KPIs (source: author, adapted from Rodriguez-Labajos et al., (2016)).

3.1.5 Management focus and adding value

[knowledge base finding] → According to Glatte (2021), corporate real estate management aims for value creation through the administration of real estate resources with activities at a strategic, tactical and operational level. Additionally, those three levels of management focus are correlated with the level of building perspective that they correspond to, ranging from an individual service or building up to the whole real estate portfolio of an organisation. Eventually this can lead to a different level of a value driver (figure below). This is in accordance with Haynes et al. (2017) who suggest that the real estate no longer functions as a solely operational tool but can have a strategic function. Thus, it can be considered as a strategic organisational asset. In hospital real estate, this is even more evident, since the hospital buildings constitute one of the principal organisational assets for the provision of healthcare services (van der Zwart, 2014).

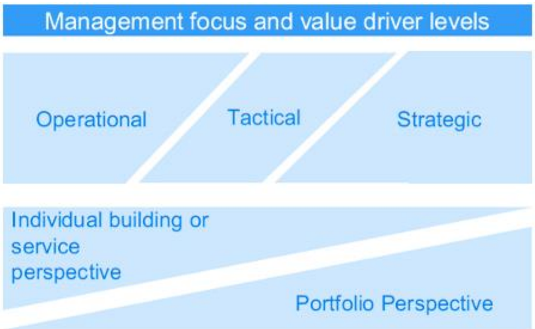
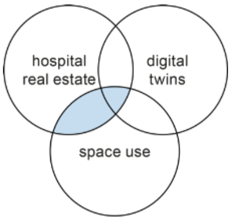


Figure 15: Management focus levels (adapted from Glatte (2021, p.3)).

The concept of adding value to an organization through its real estate resources has long held a prominent position among CREM (Jensen & van der Voordt, 2016). Real estate managers aim to generate value for an organisation by conducting specific interventions on the buildings occupied by it. Added value parameters such as satisfaction, image, culture, risk and sustainability can be directly affected by certain choices that impact the real estate resources. The researchers stress the importance of strategic alignment and effective stakeholder management in order to succeed in the value adding process (Jensen & van der Vordt, 2016).
When it comes to HREM, research was conducted with the aim of identifying the relevant added values that real estate professionals aim to address in the healthcare field (van der Zwart & van der Voordt, 2016), concluding in nine types. Those are reducing costs, imprving productivity, increasing user satisfaction, improving culture, increasing innovation, supporting image, improving flexibility, improving financial position and controlling risks.

3.2 Space use in hospital real estate



The second section of the knowledge base addresses the intersection of the concepts hospital real estate and space use. It primarily focuses on the aspects of space use and its derivative notions, such as the space norms, space management and space utilisation. By placing it in the hospital context, it is aimed to understand how space norms are defined in healthcare facilities. The relationship of space management and added values is presented next and, finally it concludes with some theory related to space utilisation.

3.2.1 Space use in hospitals and its related concepts

While a definition of space use has already been provided in order to define the scope of the present research (see section 1.4), it is deemed necessary to analyse the relationship of space use with other notions that define its characteristics in the context of hospital real estate management. Valks (2021) in his dissertation about smart tools in campus real estate suggests that space norms define space utilisation which in turn informs them. Space planning as being the process of realising the space norms is interrelated with space management being the decision-making processes that define the space use. In turn the management of space creates the conditions on which the space will be used, leading to the notion of space utilisation, the relationship between occupancy and frequency of the use of spaces. Having these topics in mind, figure 3, which framed the research's scope can be expanded, as seen on the figure below, to connect its aspects with the terms space norms, management and utilisation respectively. Eventually, as suggested in section 1.4, space use is used as an umbrella term that encompasses all three notions.

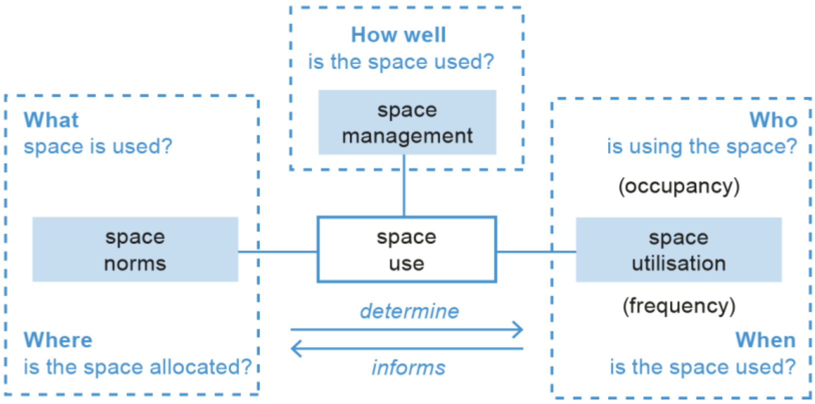


Figure 16:
The extended scope of space use
(source: author, adapted from Valks, 2021, p.124).

Valks (2021) further suggests that the requirements for spaces may change over time, leading to different space norms. These can indicate a different way of using the spaces, but also how an organisation (in his study a university) will occupy a space. By assessing the utilisation rates of their spaces, organisations can reconfigure their norms. This can create a feedback loop, based on which the accuracy of the exchanged information can lead to more effective ways of expressing the accommodation demands of an organisation.

[knowledge base finding] →

In a similar manner to universities, hospital real estate accommodation demands require specific space planning that can support the complexity of healthcare provision (Grigg et al., 2009). Therefore, the interrelationship of space norms, management and utilisation and the feedback loop of determination and information can be transcribed to space use in hospital real estate management.

3.2.2 Space norms in hospitals

The definition of space norms is interrelated with space planning in healthcare facilities, which is the process of (re)designing the layout of real estate and (re)configuring the types of spaces and their functions (Li et al., 2017a). Otherwise named as space allocation, it is a critical process that determines what types of spaces and where they are located in the premises of a hospital. The physical requirements for healthcare provision and the financial constraints of a healthcare organisation frame the conditions under which space planning is conducted. Minior et al. (2004, n.p.) point out that "by strictly adhering to institutional goals, space can be allocated fairly and utilized optimally on the basis of program quality, mission-relatedness, demonstrated need and availability of sponsored research support".

The planning process of a hospital is organised by identifying the demands of diagnosis related groups (DRGs) (Hessel, 2004). Those groups define the patient journey that describes the process that a patient will go through in order to receive the healthcare services. When translated in spatial configurations, this creates a hierarchy of facility infrastructures that primarily support the patients' processes (such as a ward and an operation room), but also infrastructures that support sub-processes (such as waste disposal, catering, laundry services, etc) (Hessel, 2004). This chain of facility requirements leads to the configuration of space allocation in hospitals. It is suggested that the patient journey of the respective DRGs can be used by hospital planners in order to assess the average time intervals and space units which in turn correspond to a cost structure (Diez & Lennerts, 2009).

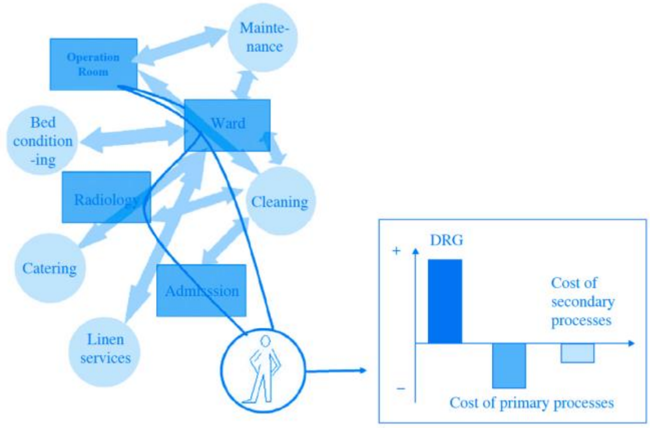


Figure 17:
The patient journey of a diagnosis related group, (Diez & Lennerts, 2009).

Kunders (2004) suggests that the most important principle in planning a hospital is its circulation. Similarly, Emmerson Goble (1960) in his seminal work about hospital design had mentioned that (a designer should) "Separate all departments yet keep them all close together; separate types of traffic yet save steps for everybody; that is all there is to hospital planning". This principle suggests that optimising the patient journey and the journey of the medical professionals is as crucial in space planning as deciding the amount of spaces that will be allocated for each medical department.

A well conducted space allocation in hospitals is expected to lead to increased utilisation of medical resources and facilitate the working processes of medical personnel (Cayirli & Veral, 2003). Space allocation is usually conducted by facility managers of hospitals that in turn set the norms for space planning (Wiggins, 2010). The perspective of healthcare facility managers is deemed crucial in assessing space planning (Zijlstra et al., 2014). Decision making processes regarding space allocation are informed based on demand and supply of resources (either real estate or medical) and can be assessed through waiting time minimisation for specialists and patients (Cayrli & Veral, 2003). A digital tool that provides information about the use of spaces can be utilised to inform about the capacity of the current real estate resources of a hospital and assist in a more efficient space allocation, while abiding by the space norms.

3.2.3 Space management in hospitals

There are several definitions with regards to space management in hospitals. For some researchers it deals with the optimisation of space layout with the aim making the hospital more efficient and the improvement of the safety and the occupational health (Moatari-Kazerouni et al., 2015). On the other hand, for Sliteen et al. (2011), space management deals with the space utilization rates in relation to operation and maintenance costs in healthcare facilities. As it can be seen from both definitions, space management as a concept can be interpreted both as a process related to space norms but also related to space utilisation.

In order to investigate the objectives of space management, a systematic literature review was conducted to identify the space management goals in healthcare facilities (Li et al., 2017b). This research concluded in nine space management goals (SMGs), as seen on the table below. The connection between SMGs and the real estate added values that were mentioned in section 3.1.5, is immediately evident. As seen on the table below, some associated added values were identified, in an effort to describe the relationship between the two concepts. Through a brief analysis, it can be concluded that the improvement of productivity and user satisfaction are the two real estate added values that are mostly associated with the SMGs. Similarly, to facilitating added value for an organisation, a digital twin can be used to optimise hospital space management, thus attaining space management goals.

Theoretical SMGs	Descriptions	Added value to core business or space-related performance	Associated real estate added value
SMG 1: providing a comfortable, safe, and healthy environment for users	Includes warm-style design, good ventilation, comfortable lighting, safety layout, clean environment, and effective noise control.	Good indoor physical environment has positive impacts on the quality of elderly care, residents' satisfaction, and staff productivity.	Improve productivity, Increase user satisfaction
SMG 2: optimizing the space occupancy cost	Includes space rent or building depreciation and reconstruction costs, utility costs, housekeeping costs, repair and maintenance costs, HSE costs, and moving costs.	This goal is vital to organizational profitability growth since space occupancy costs are usually the second largest component of total cost in organizations.	Reduce cost
SMG 3: optimizing the space functionality	Strives to ensure that each space fulfils the functions of its intended use, such as sufficient space and critical function for various intended operations and users' requirements.	This goal's objective is to support users' space requirements and the organizational business processes.	Improve productivity
SMG 4: improving the space flexibility	Requires the building to accommodate frequent alteration, renovation, and multiple use quickly and economically. Strategies include space sharing and open-space design.	This goal can enhance organizational profitability through quickly responding to business changes, reducing renovation costs, increasing the space utilization rate, and improving staff productivity.	Improve flexibility
SMG 5: improving the space accessibility	Involves person-environment interaction that includes barrier-free environment, alternative orientation systems, minimizing circulation distances, and efficient workflows and logistics.	This goal directly increases elderly residents' satisfaction and staff productivity.	Improve productivity, Increase user satisfaction
SMG 6: efficient responsiveness to users' space requirements	Strives to ensure the FM department can respond to space-related problems or users' space-related requirements efficiently.	This goal can increase the elderly residents' satisfaction and can be an indicator to evaluate staff productivity.	Improve flexibility, Improve productivity, Increase user satisfaction

SMG 7: facilitating informatization of space management	Utilizes building information to perform space planning, space inventory, and cost charges through IT tools.	This goal can add value to organizational profitability through optimizing space use resources and reducing personal costs.	Reduce costs, Improve financial position
SMG 8: optimizing the space utilization rate	Optimizes the efficiency of space use on the premise of end-user satisfaction. This rate is determined by the occupancy area and the occupancy time.	This goal ensures elderly residents' satisfaction and the efficient use of space resources.	Reduce costs, Improve productivity, Increase user satisfaction
SMG 9: strengthening the organizational culture	Uses space management to the business brand and to strengthen the organizational culture since is a medium for expressing organizational culture and values.	This goal adds value to staff productivity and elderly residents' satisfaction.	Improve culture, Improve productivity, Increase user satisfaction

Table 9:
Space management goals and added value (source: author, adapted from Li et al., 2017b).

3.2.4 Space utilisation in hospitals

In the following section, space use is analysed from the perspective of space utilisation, as introduced in in the scope of the research (section 1.4).

Several researchers have been investigating the impact of space utilisation in healthcare facilities in the recent decades (Rodrigueaz-Labajos et al., 2016). It has been associated as one of the most important measures for the evaluation of the performance of a facility, since it is considered as the main driver for the costs of the real estate resources (Wauters, 2005). It has been proven that optimised space use can lead to reduced costs and increased energy savings (Rodrigueaz-Labajos et al., 2016). By optimising space use a better fit can be created between demand and supply of real estate.

Space utilisation measures are conducted based on frequency and occupancy (Space Management Group, 2006). The former refers to how often a space is used, thus related with the time dimension of the utilisation of a space. Occupancy deals with the capacity of a space to accommodate one or more people. Three types of resolutions for occupancy are suggested (Christensen et al., 2014). The first type is related with the occupant resolution and deals with the level of detail of analysis, starting from merely knowing that a space is occupied, up to identifying the person or even the activity they are conducting. The spatial resolution deals with the physical characteristics of the occupied space. Finally, a temporal resolution is suggested that analyses the amount of time that a space is occupied. To conclude, an information system for space use can be designed to display information in temporal, occupant and spatial resolution.

[knowledge base finding] →

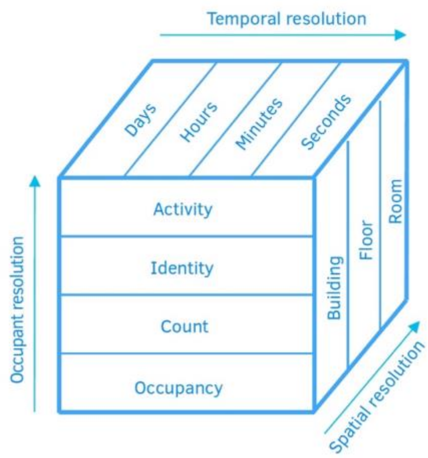
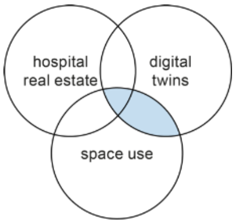


Figure 18:
The three types of building occupancy resolution (Christensen et al. 2014, p.8).

3.3 Digital twins for space use



The third section of the knowledge base deals with the intersection of the concepts space use and digital twins. In essence, a literature review is conducted on academic publications related to applications of digital twins in the built environment. The section starts with a brief analysis of the concept of digital twins and it further delves into its system architecture. By analysing one by one each of the layers that comprise the system architecture of a digital twin, it is aimed to facilitate a better understanding of this technology and the ways it can be used.

3.3.1 The concept of Digital twin for space use

A digital twin for space use is interpreted as an information system that can be utilised for data processes that regard the physical spaces of buildings. This is in contrast to other types of digital twins that can be used in other fields, such as in healthcare, manufacturing or industrial processes (Errandonea et al., 2020). The technology of digital twin lies under the umbrella of the digital transformation that is enabled through industry 4.0 and internet of things (Aheleroff et al., 2020). Therefore, it is based on the scalability and interconnectedness of several data sources.

The main concept behind a digital twin is the reception and delivery of data that provide information about the lifecycle of a product (Errandonea et al., 2020). The digital twin paradigm lies in the integration of physical and digital data, as seen on the figure below (Boje et al., 2020). The physical part refers to the spaces of a building and the virtual part to its digital representation. Each one of these parts is connected to the other through information flows, thus enabling the existence of the digital twin (Boje et al., 2020).

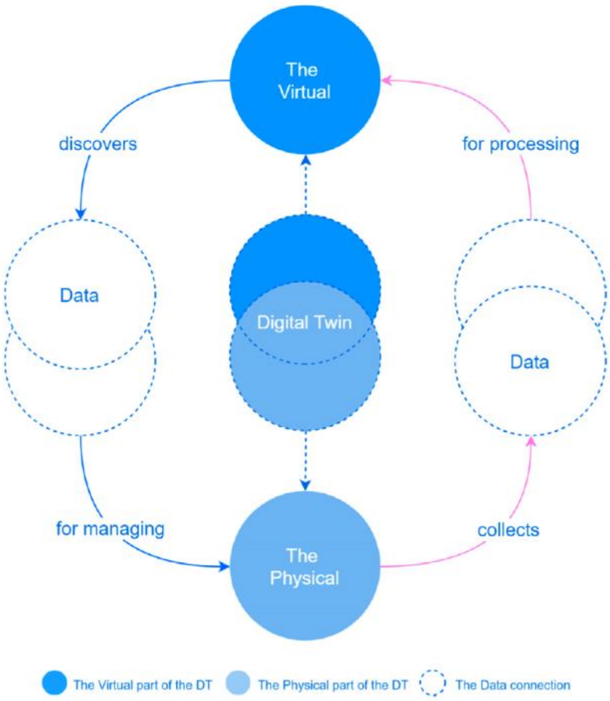


Figure 19:
The digital twin paradigm
(Boje et al., 2020).

The level of integration between a digital model and a physical counterpart plays an important role in the definition of a digital twin (Kritzinger et al., 2018). When thinking of a physical-digital data integration of a building, the terms digital model, digital shadow and digital twin can be used, however they have essentially dissimilar meanings. The difference lies in the types of data flows between the physical and the digital objects (figure below). In a digital model, both data flows are manual, therefore an operator has to insert them in order to provoke any changes. In a digital shadow, the physical object provides the digital object data automatically, however this does not happen conversely. As a result, the digital object is continuously informed by the physical, however it does not send automated data back. The digital twin is characterised by potentially both automated data flows, thus intervening in the physical after processing the data (Kritzinger et al., 2018).

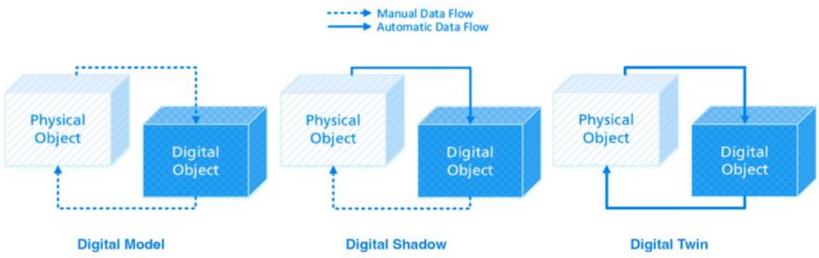


Figure 20: Flows of information in a digital model, shadow and twin (Kritzinger et al., 2018).

3.3.2 Design approaches for a digital twin

The process of designing a digital twin is not standardised in any methodological approach, which leads to several approaches that vary per use and application case. However, two different approaches can be distinguished in handling the design process: a data-based digital twin and a system-based digital twin (Adamenko et al., 2020). Even though different, the combination of a data-based and a system-based approach to designing a digital twin is possible, which under the right circumstances can prove to be a very effective way of designing a digital twin.

A **data-based digital twin** is based on the structure of data that are identified and introduced in a platform through certain criteria. This is an approach that starts from the availability and scarcity of suitable data. In the next step, the criteria and the algorithms that will process the data will be determined based on the required functionality of the system (Adamenko et al., 2020). The advantage of this approach is that a digital twin requires less technical information and the information structure can be decided at a later stage by the user (Adamenko et al., 2020).

A **system-based digital twin** is based on twinning process of the physical object as a system (Adamenko et al., 2020). Thus, it has the physical object as a starting point whereby the required processes are identified, which set the requirements for data needs. Existing partial models, such as CAD building documentation or other systems are merged into different layers of systems of the physical object. Other types of data can be further introduced through the use of interfaces and the required parameterization so that the digital twin remains functional (Adamenko et al., 2020).

3.3.3 System architecture of a digital twin

For Jones et al. (2020), the main complexity of a digital twin lies in the system structure and the various components that form its entirety. A system architecture was proposed in research about the development of a digital twin at a building level that could provide space use functionalities (Lu et al., 2019). The basis for this design is a literature review from the perspective of available data, thus it was conceived as a data-based digital twin (Adamenko et al., 2020). The proposed system architecture aims to integrate heterogeneous data sources and assets with their applications and provide effective O&M management, smart asset management and facilitate the connection between human interaction with buildings/cities through more sustainable, smart and visual means (Lu et al., 2019). The system architecture of a digital twin for space use is made out of five layers: data acquisition layer, transmission layer, digital modelling and data complementary layer, data-model integration layer and application layer (Lu et al., 2019). The following sections analysed the respective layers.

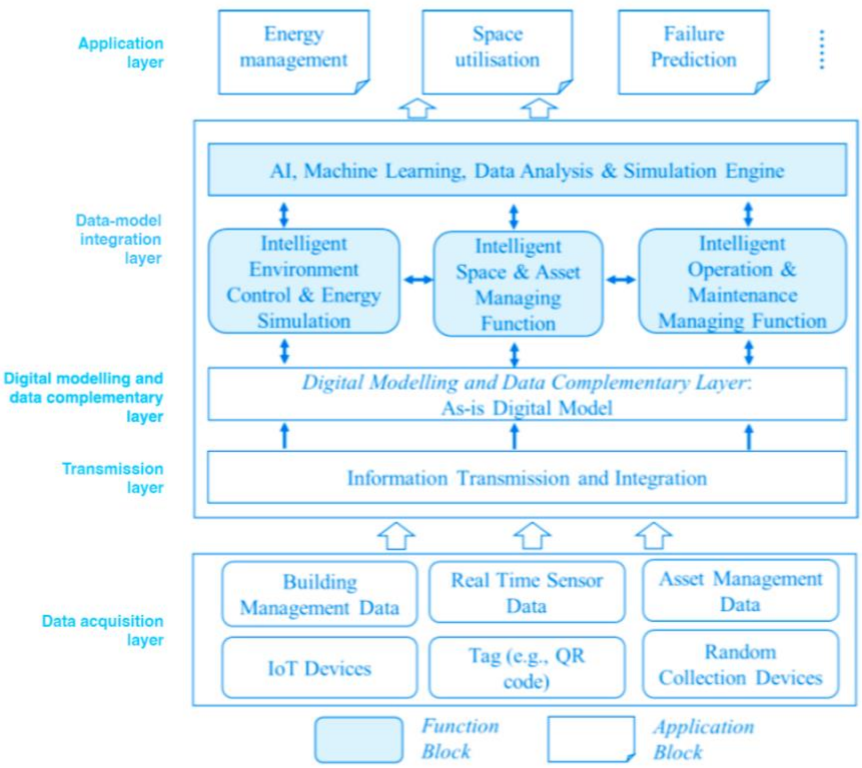


Figure 21:
The system architecture of dynamic DT development in a building level
(Lu et al., 2019).

3.3.4 Data acquisition layer

The first two layers of the digital twin system architecture deal with the collection and integration of data with the main system (Lu et al., 2019). The data acquisition layer functions as the starting point of the digital twinning process. Data relevant to space use and other building functions are collected through sensors or other information sources. Specifically, Küsel (2020) identifies seven information sets that are linked to processes related with real estate management: construction data, geospatial data, building systems IoT data, organisational data and external data (see figure below). When it comes to a digital twin for space use, the "IoT data" information set matches its data requirements. This information set includes sensor data, occupancy data and indoor environment data (Küsel, 2020).

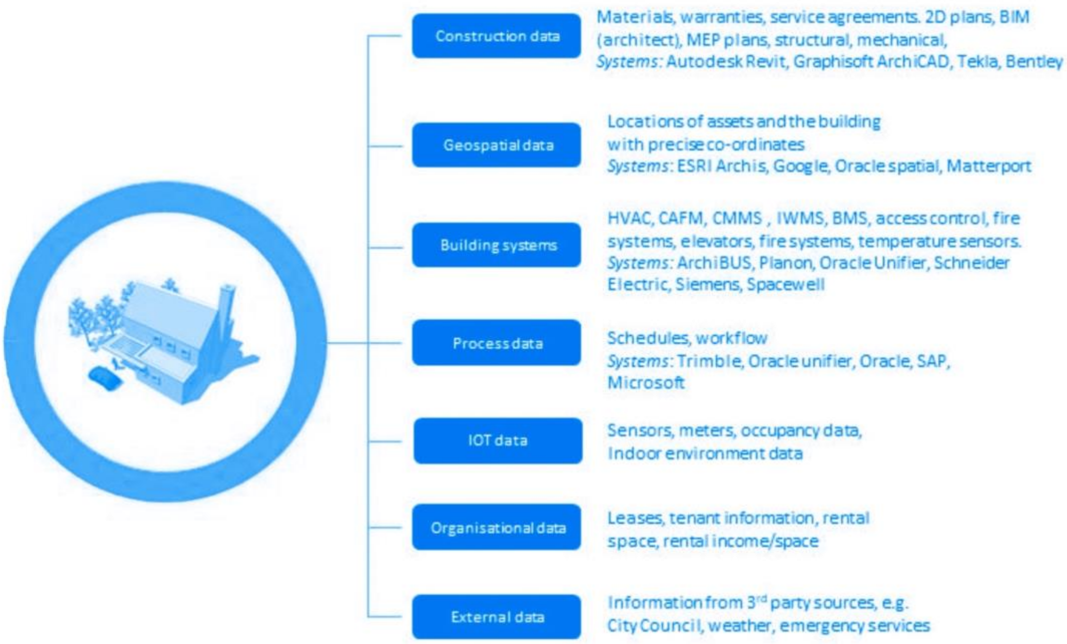


Figure 22: Information sets linked to property management (Küsel, 2020).

More specifically, when it comes to data related to space use, sensor systems that measure them can be categorised in explicit systems and implicit systems (Christensen et al., 2014). The former are developed and installed explicitly for the measurement of space use with new infrastructure. While the latter, the implicit systems, have not been originally developed for occupancy detection, however they can be used for this process, since they collect relevant data, which can be leveraged in order to assess the occupancy metrics of a space. The accuracy of those systems is oftentimes contested in academic literature, such as in Serraview (2015), who state that there is no system that can carry out a fully accurate utilisation measurement in a building. There are several factors that can influence this level of accuracy, such as different environments (indoors or outdoors) (Mautz, 2012). In order to increase this accuracy, it is suggested that space use sensing can be conducted by complementary systems (Serraview, 2015). For example, by combining sensors that assess the occupancy of the same space, a more accurate estimation can be established (Trivedi & Badarla, 2019). When designing a digital twin for space use, IoT data can be introduced to the model from implicit and explicit systems. The data from different data sources can overlap, thus offering more accuracy.

Space use is measured through the use of several occupancy sensing technologies, as seen on the figure below (Valks, 2021). The Wi-Fi network is used as an implicit occupancy sensor, by measuring the present of mobile devices within its range (Mautz, 20212). The extensive utilisation of mobile devices and the increasing accuracy of Wi-Fi networks, constitutes this sensing technology a promising one. A similar sensing technology is that of Bluetooth, which again uses the signals of the mobile devices of occupants to measure their space use. Even though Bluetooth is more accurate than Wi-Fi in sensing, it requires the installation of specific infrastructure and an application in the mobile devices of users in order to function (Serraview, 2015). RFID sensors comprise of a chip with connectivity capability and a stable reading device. They are usually installed in doors and have a limited detection range (Mautz, 2012). Cameras can also be used for occupancy detection through the existence of specific software that processes their captured images in real time (Triverdi & Badarla, 2019). They can be categorised as video cameras (when the light is adequate) and infrared cameras (that measure the infrared radiation). Infrared sensors are another type of sensing technology (Mautz, 2012). They are categorised as AIR or PIR, with the former measuring the interruption of a beam between a transmitter and a receiver and the latter measuring energy variances in a room. Valks (2021) suggests that other types of sensing can be deployed, usually implicitly, such as when a device is used (for e.g., PC login) and indoor climate devices for the optimisation of comfort, such as lighting, temperature and CO2 sensors. All of the aforementioned sensor types, apart from their occupancy sensing capabilities have to be assessed about any potential privacy concerns by the occupants of the buildings that they may be installed at (Mautz, 2012).

Figure 23: Technologies for space use measurement (source: Valks (2021), based on Mautz (2012))

3.3.5 Data transmission layer

The following layer of the system architecture is that of the transmission layer (Lu et al., 2019). This layer comprises of the connection of the data receptors with the rest of the digital twin system, thus transferring the data to the upper layers. After the collection of data from sensors, the data are transported through communication technologies, such as 5G, LP-WAN and the widely applicable WLAN, which is based on Wi-Fi technologies (Lu et al., 2019). The last transmission option is the most prevalent one, however concerns regarding security issues have been raised (Lehr & McKnight, 2003). It is suggested that based on network energy efficiency and transmission speed, light fidelity (Li-Fi) and LP-WAN can be favourable alternatives for an extensive development and converge of digital twins (Khandal & Jain 2014; Lu et al. 2020a; Silva et al. 2018). Data transmission layer in a digital twin is responsible for transferring the sensor data to the digital model and can be supported by several technologies, depending on factors such as sustainability, security and transmission speed.

3.3.6 Digital modelling and data complementary layer

The next layer of the digital twin system architecture is that of the digital modelling and data complementary layer (Lu t al., 2019). In this layer, the digital model of a building, is introduced to the system. That can be, for example, an energy simulation model or an agent-based model. A BIM model can hold the capacity of providing several types of utilisable information at a modelling level and thus, is the most common one (Boje et al., 2020). In the development process of a digital twin, a pre-defined digital model type is essential, and an addition of complementary data can follow (Lu et al., 2019). Eventually the building model can function as the background of the digital twin, whereby the data can be mapped onto (Lu et al., 2019).

It is common for digital building documentation to be outdated with regards to the existing conditions of the building (Klein et al., 2012). Therefore, the digital model of a building has to be continuously updated in order to be representing the exact spaces of the building (Jones et al., 2020). For example, when a renovation process occurs, the updated drawings have to be introduced to the digital model. this can be done manually, by adjusting the existing building models or by deploying technologies such as 3D laser scanning and photogrammetry (Klein et al., 2012). Eventually, when designing a system of a digital twin for space use, digital building documentation has to be introduced to the system, always making sure that the digital models contain accurate information of the existing conditions of the building spaces.

3.3.7 Data-model integration layer

The data-model integration layer lies in the core of the digital twin system architecture (Lu et al., 2019). In this layer, data and building model are stored, integrated, processed, and analysed, supporting decision-making functions (Glaessgen and Stargel, 2012). Data related with the performance of the building spaces are visualised above a building model, in the form of a dashboard or integrated as annotations within the model. Therefore, the digital representation of the building and the data analytics are integrated, thus becoming operational to the users of the tool (Lu et al., 2019). When designing a digital twin, data of the performance of the building spaces and a digital model of the building are integrated in a display in order to become operational by the user of the tool.

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Valks et al. (2021b) investigated how dashboard design can contribute to decision making of university campuses. It was analysed how data with regards to the performance of a university building portfolio can be displayed in a dashboard and operationalised by campus decision makers. The research was conducted in a similar manner to the present research, by deploying the design science research framework by Hevner (2007). Aside from the many similarities of the present research, Valks et al. (2021b) focused on the display of the data in a dashboard without any building model integration. Additionally, they did not contextualise their smart tool within the concept of digital twins and they focused on university buildings instead of hospitals. However, the conceptual design of their dashboard (figure below) is notably based on the real estate management theory that was presented in some of the parts of section 3.1 and, thus relevant to the present design of the display of a digital twin (section 5.1).

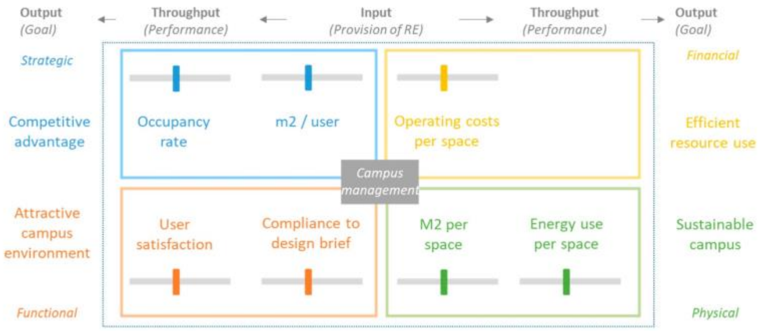
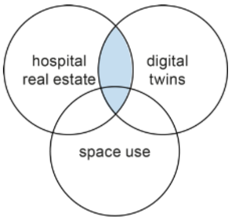


Figure 24: Conceptual design for structure of dashboards (Valks et al., 2021b).

3.3.8 Application layer

The application layer lies at the top of the system architecture of a digital twin. It is the implementation layer of the tool that corresponds to the interaction of the tool with its users (Lu t al., 2019). Researchers formulated a taxonomy of potential uses for a digital twin (Al-Sehrawy et al., 2021). They categorized the possible applications in four use groups, namely mirroring, analysing, communicating and controlling. Lu et al. (2019) mention energy management, space utilisation and failure prediction as examples of applications of a digital twin. In the following section, more applications will be identified.

3.4 Digital twins for hospital real estate



In this section of the literature review, the findings of eight publications are presented. The systematic approach of identifying those publications is analysed in section 2.1.1. The aim is to provide an overview of the recent research papers related with the topics of digital twins and hospital real estate. In the first section, an overview of the publications, their key technologies, tools and contributions is presented. In the following section, the displays of them is analysed, aiming to identify design principles for a digital twin.

3.4.1 Publications overview of digital twins for hospital real estate

The key technologies of the selected publications are mainly discrete event simulation, internet of things and several information systems that are deployed in hospitals. Discrete event simulation is a popular method to model and analyse healthcare provision services (Zeigler, 2014). It can be used to model and analyse the dynamic behaviour of a process which occurs in real life, such as the patient journey (Karakra et al., 2018). Internet of things is the cornerstone of Industry 4.0 that promotes the interconnectedness of data, which is essential in a digital twin for space use. The key algorithms and tools are further analysed in the two following sections.

Table 10: Overview of the publications related to digital twins for hospitals (source, author).

Reference	Key technologies	Key algorithms/tools	Key contribution
Karakra et al. (2018)	Discrete event simulation (DES), Healthcare information systems, Internet of Things (IoT), Pervasive computing	A digital twin of healthcare services based on patient journeys, using discrete event simulation with real-time input data from healthcare information systems, pervasive computing devices and IoT.	A proof-of-concept of a digital twin simulation model of patient journeys.
Karakra et al. (2019)	Discrete event simulation (DES), Internet of Things (IoT), Pervasive computing.	A digital twin of patient journeys and monitoring and simulation of possible events.	Three process levels of utilisation of a digital twin. Namely "construction and validation", "tracking and monitoring" and "future vision".
Karakra et al. (2020)	Discrete event simulation (DES), Internet of Things (IoT)	A digital twin of patient journeys and monitoring and simulation of possible events.	Two functionalities of digital twins. One for modelling existing patient journeys and one for predicting them. Both functionalities can analyse the required resources.
Liu et al. (2020)	Robotic Process Automation (RPA)	A digital twin of a hospital logistics system that is supported by robotic functions.	A framework for simulation and optimisation of a robotically supported logistics hospital system.
Peng et al. (2020)	Artificial intelligence, Internet of things (IoT), Building Management Systems	A digital twin created y integrating more than 20 management systems of a hospital building.	Results of a project case of a digital twin of for a Chinese hospital include increase in management satisfaction, less energy consumption and less facility repairs and faults.
Lu at al. (2021)	Blockchain	A network of digital twins that are interconnected through blockchain technologies.	A framework for optimisation of medical resources.
Song & Li (2022)	Internet of things (IoT), Building management Systems (BMS)	The development of a digital twin for healthcare facility management applied in a Chinese hospital ward.	A use case of a digital twin with applications related to facility management and analysis of real time data related to the use of spaces.
Zhong et al. (2022)	Medical information systems, Internet of Things (IoT), Discrete event simulation (DES)	A digital twin for simulation of patient journey and their corresponding resource requirement in intensive care units.	A framework for the development of a digital twin and its user interface based on patient journeys and the corresponding resource allocation.

3.4.2 Displays of digital twins for hospital real estate

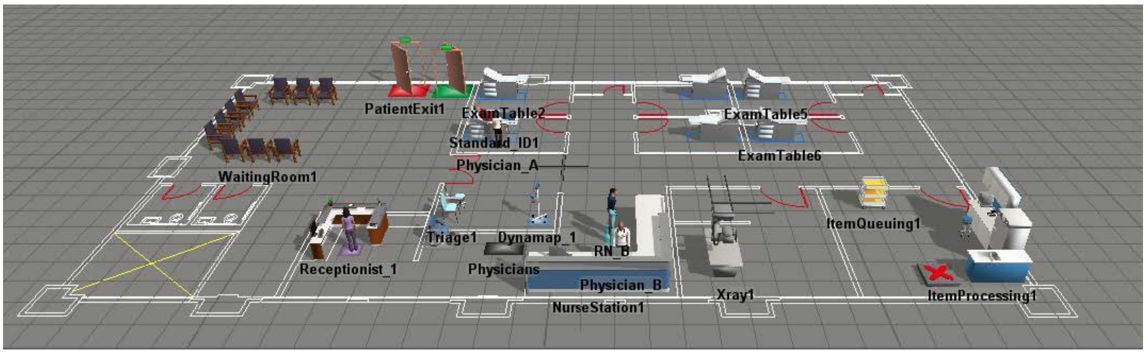


Figure 25: Display of a FlexSim simulation patient tracks (Karakra et al., 2018, p. 5).

The display of the digital twin of Karakra et al. (2018) was created through the software *FlexSim*. Its design is restricted to the functionality of the existing software and not customised for the use case. It offers a 3D overview of some hospital spaces and objects, which are accompanied with relevant annotations of rooms, items and people. However, in the specific example, the data of the functionality of the twin, such as a flowchart of the patient journey and graphs of its analysis, are only available through a different display. Thus, they are not integrated with the same building representation, which renders the utilisation of the twin dependent on alternating between the different displays.

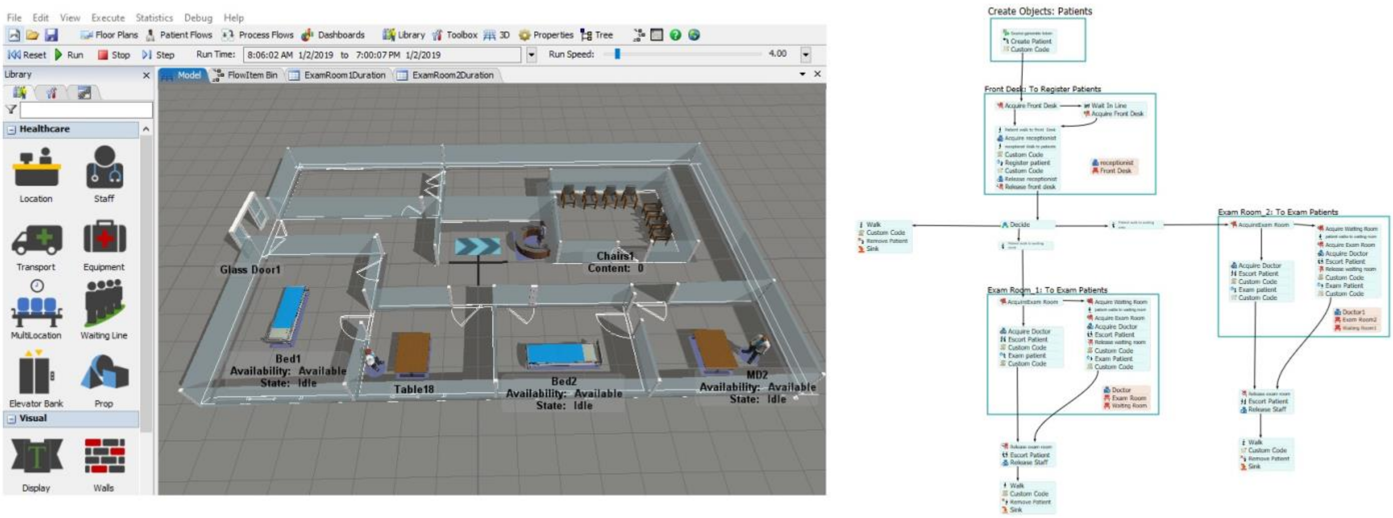


Figure 26: Display of a 3D design view and process flow (Karakra et al., 2020, p.68).

The publication of Karakra et al. (2020) is based on the same fundamental idea as the previous two. That is a digital twin that aims to model, analyse and potentially simulate a patient journey. However, in this publication, the model of the twin is elaborated further. It is designed again in *FlexSim*, like the one of Karakra et al. (2018), however a list of palettes and options for inputting data in the model is introduced and presented in a second window of the display, next to the building visualisation window. in the image above, the supportive window on the left offers options for modelling staff, transportation, equipment, etc.

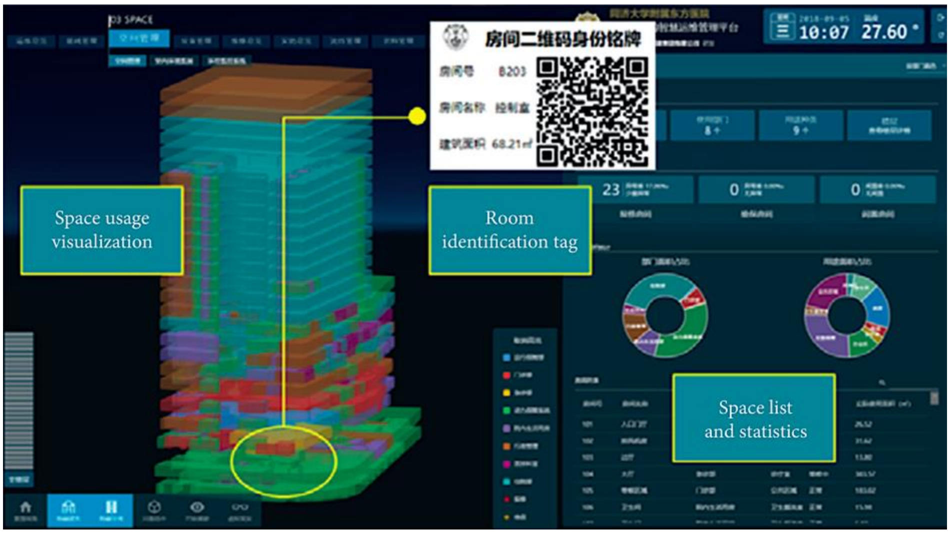


Figure 27: Display of a digital twin for space usage management (Pen et al, 2020, p.8).

Peng et al. (2020) analysed a use case of a digital twin that was created by integrating more than 20 building management systems. That lead to a digital twin with many functionalities. in order to support them, a display was created whereby building visualisation and data information were integrated in two different, yet adjacent windows. Coloured annotations on the building and graphs of the analysed data, rendered the display more comprehensible for the users.

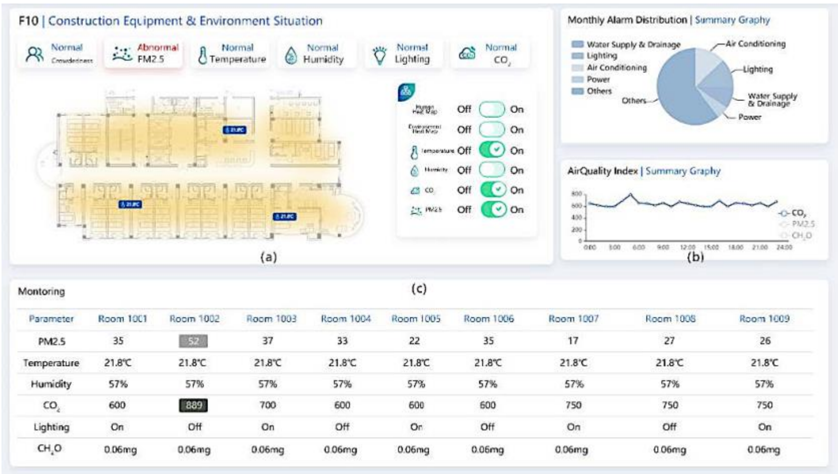


Figure 28: Display of digital twin, for environment management (Song & Li, 2022, p.1151).

Song & Li (2022) analysed a use case of a digital twin for healthcare facility management and space use analysis. The graphical user interface was developed through *Johnson Controls,* and, for the environment management use scenario, it has three main windows on the display. The upper left window offers a building visualisation with indications about the performance and choice of environment parameters. The window at the bottom of the screen visualises the performance data per category and room. And, finally, the upper right window visualises graphs whereby the previous data are operationalised. All of the three above examples of digital twin have in common that by combing a window for performance data and a building visualisation window, the display of the user interface is more comprehensive for the user of the twin.

The research of Zhong et al. (2022), is based on the analysis of the patient capacity and the relevant resource allocation that can be determined by simulating patient journeys. Their display is structured through different tabs, as seen on the figure below. In the first tab (a), the plan of a building is visualised and the patients, beds and the medical professionals are mapped based on real time sensor data. The second tab (b), called "logic" is a flow diagram that visualises the information structure that lies behind the monitoring process of the digital twin. An information diagram can be utilised to describe the information process that structures the data that become available on the display of a digital twin. In the next display (c), the input tab offers a series of parameters that define the simulation of the hospital users. The final three displays (d, e & f): unit output, data output and resources provide an overview of data analysis of the simulation that is generated by the digital twin. The displays of the previous three digital twins used tabs to organise the information and make it more operational for the user.

[knowledge base finding] →

Figure 29: Several displays of digital twin, based on a "variable tab selection (Zhong et al., 2022, p.9).

In the publications of Karakra et al. (2019), Liu et al. (2020) and Lu et al. (2021), there is no mention about a display or user interface of a digital twin.

3.5 Knowledge base conclusion

The conclusion of the knowledge base functions both as an answer to the research subquestion one [SQ1] and an input for the rigor cycle as described by Hevner (2007) (see section 2.1). Therefore, it aims to provide grounding theories that were generated from the academic literature review that can be utilised for the development of the design research (section 5). Upon the completion of the whole present research, thus after the design research, it is estimated that the final research output can be inserted once again to the rigor cycle and return to the knowledge base as an addition for the scientific community (Hevner, 2007).

Throughout sections 3.1, 3.2, 3.3 and 3.4, design and utilisation principles were identified and annotated based on the theory findings, aiming to formulate an answer to the following subquestion:

[SQ1]
"What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from the current academic literature?"

Thereafter, the following table is created summarising those findings. The environment findings are translated to design and utilisation principles. Adding to that, a system architecture (Lu et al., 2019) association is introduced in order to assess in which layer of the digital twin those principles correspond to. Since the design artefact is that of a display of a digital twin, the systems architecture layers that are identified are that of "data-model integration layer" and "application layer" the former related with design and the later with utilisation. In the next page, the conceptual framework that was introduced in section 1.5 is updated to include those findings.

Table 11: Summary of the design principles identified at the knowledge base (source: author).

ID	Knowledge base findings	Design and utilisation principles	System architecture	Section
1.1	"data from the primary processes of an organisation can be transformed to information about the performance of the real estate resources which in turn can be used for further decision making."	A digital twin can use data from primary processes as information about the real estate performance.	Data-model integration layer	3.1.3
1.2	"when the number of properties that are considered increases, the level of detail of the information system has to decrease in order to provide an operational amount of big quantity of information"	The amount of displayed information should be adjusted between adequate (minimum) and controllable (maximum) according to the level of influence of the potential decision that can be assisted.	Data-model integration layer	3.1.3
1.3	"Most of the dominions of the KPIs that were identified can be associated directly with a stakeholder perspective."	A set of KPIs can be introduced and grouped in the four real estate perspectives, determining potential choices of display of information for the users of the tool.	Data-model integration layer	3.1.4
1.4	"corporate real estate management aims for value creation through the administration of real estate resources with activities at a strategic, tactical and operational level."	A digital twin can be used to facilitate activities in a strategic, tactical and operational level.	application layer	3.1.5
1.5	"the interrelationship of space norms, management and utilisation and the feedback loop of determination and information can be transcribed to space use in hospital real estate management".	The design of a tool for space use in hospitals can provide information about the space norms, management and utilisation of the building resources.	Data-model integration layer	3.2.1

1.6	"an information system for space use can be designed to display information in temporal, occupant and spatial resolution."	A digital twin for space use can be designed to display information in temporal, occupant and spatial resolution.	Data-model integration layer	3.2.4
1.7	"when designing a digital twin, data of the performance of the building spaces and a digital model of the building are integrated in a display in order to become operational by the user of the tool"	By combining building visualisation and performance data, the display of the user interface is more comprehensive for the user of the twin	Data-model integration layer	3.3.7 3.4.2
1.8	The displays of the previous three digital twins used tabs to organise the information and make it more perational for the user.	Use tabs to toggle between different information options.	data-model integration layer	3.4.1

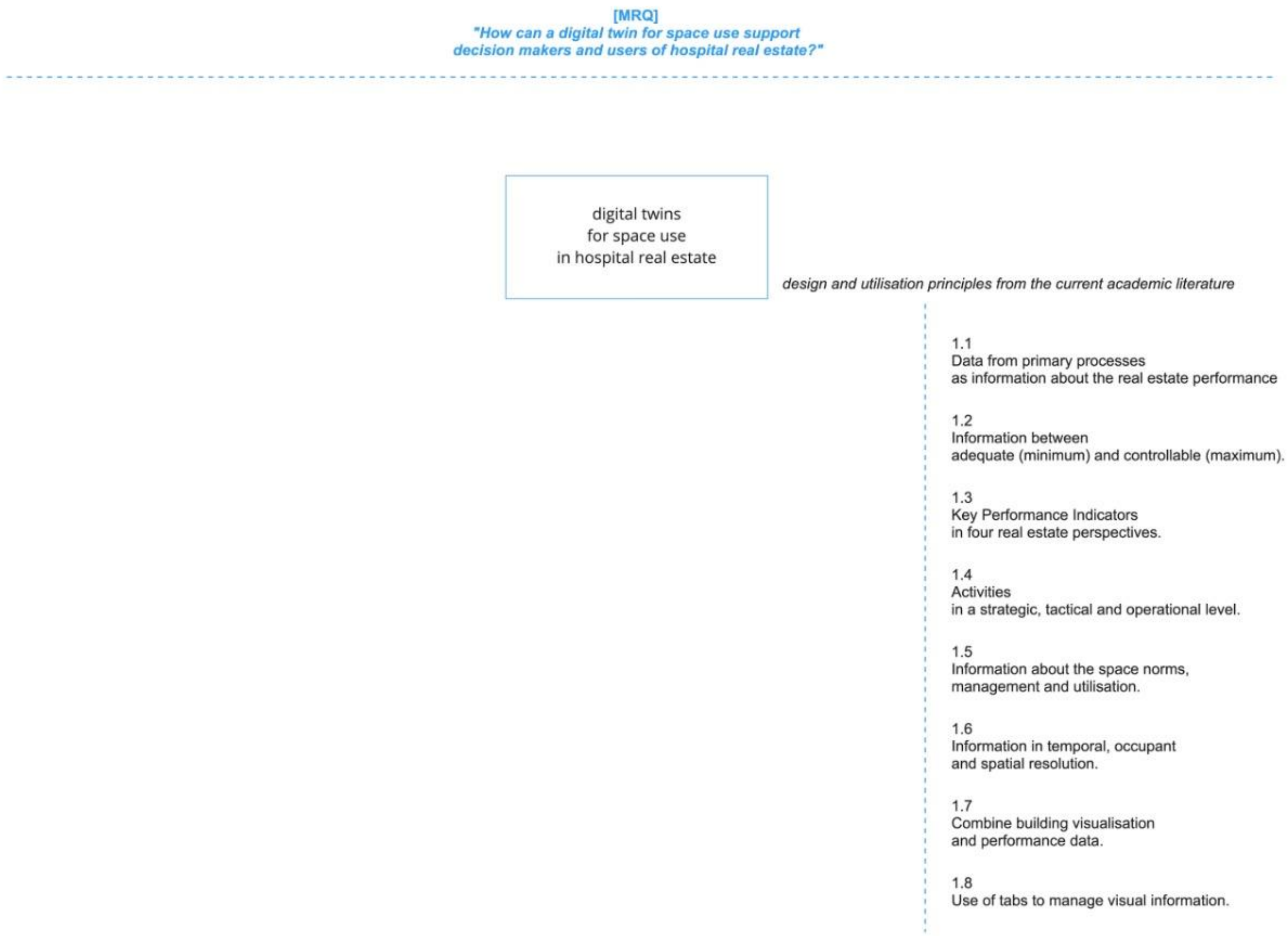


Figure 30:
Updated conceptual
framework based on [SQ1]
(source: author).

Chapter 4
Environment

The fourth chapter of the report analyses the attributes of the environment of the research. Starting with the organisational characteristics, the purpose is to understand the healthcare organisation that will provide the empirical data for the research analysis. In the real estate portfolio, the building assets of the organisation are presented. By exploring the information systems related to space use, it is aimed to analyse which relevant systems are currently deployed by the organisation. Eventually, by delineating the building documentation database of the organisation, it is aimed to trace how the building assets are administered digitally by the organisation.

4.1 Organizational characteristics

The Erasmus Medical Center (EMC) is a university medical center that operates in four main areas: healthcare services, higher education, scientific research and valorisation. The first three areas are common in most university hospitals since they combine the provision of medical services with educational and research activities. The fourth one has been growing in importance the recent years and aims to use the knowledge that is acquired through research for economic and social purposes (Erasmus MC, 2022a). Furthermore, the organisation has the three core values: **Responsible** by being held accountable for its operations, **interconnected** for facilitating connections that support improvement and innovations and **Enterprising** by being able to identify opportunities and anticipating them (Erasmus MC, 2022a).

4.1.1 The organisation's impact

In the image below, some indicative numbers of the users of the EMC are displayed, based on the annual report of 2021 (Erasmus MC, 2022c). More than sixteen thousand employees and slightly more than four thousand enrolled students are the frequent users and members of the EMC. To these numbers, almost six hundred fifty thousand annual outpatient visitors in 2021 reveal the high outreach of the organisation. Furthermore, a high patient satisfaction rating at 8,6 for polyclinic and clinic services is an indication of the importance that the EMC holds in offering medical services of exceptional quality.

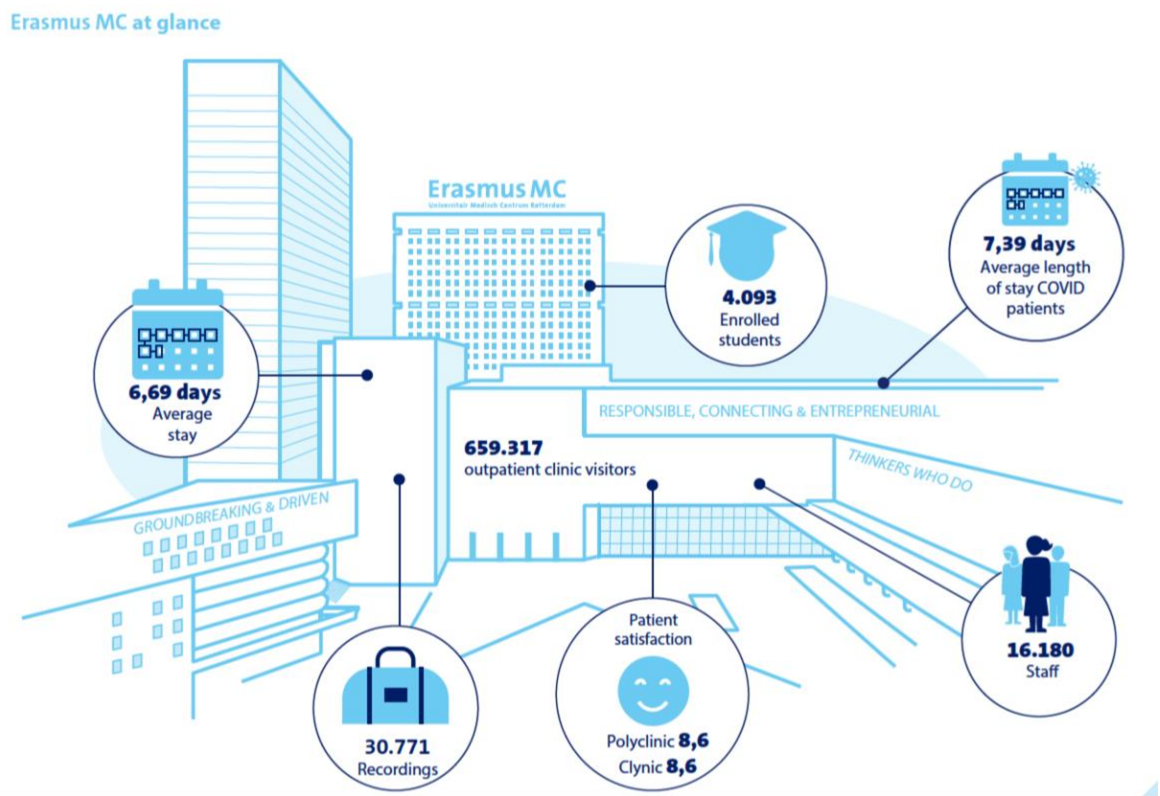


Figure 31: The EMC at glance on the annual report of 2021 (Erasmus MC, 2022c, p.2, translated).

4.1.2 Organisational structure

The approximate 16000 staff of the EMC are part of the 48 medical and scientific departments, out of which two main clusters can be identified, that of the Themes and that of the Service Company, as seen on the figure below (Erasmus MC, 2022a). The structure of the organogram for the allocation of staff is an indication of the high organisational complexity of the EMC. More specifically, the organisation is administered through a *Supervisory Board,* a *Board of Directors* and *Advisory Bodies*. The *Themes* cluster is made out of nine pillars each one corresponding to specific medical departments that function individually but also collaborating with one another for medical, research and educational purposes (Erasmus MC, 2022a).

[environment finding] →

The *Service Company* is the cluster with all the organisational pillars that provide products and services that support the entire the organisation (Erasmus MC, 2022c). The Information & technology pillar, for example, provides information services and support such as the maintenance of the digital patient record *HiX*, physical and digital security in the organisation (Erasmus MC, 2022c, E.10, 2021). The *Procurement and Facilities* pillar is responsible for the provision of a clean, hospitable and safe environment for the building users (Erasmus MC, 2022c, E6., 2021). This pillar has, therefore a significant contribution in the decision making related to the use of space in the hospital.

Adjacent to the two main organisational clusters of the EMC lies the pillar of *Programs* the leading organisational function is that of *Programma Integrale Bouw (PIB)*, which is responsible for the strategic and operational administration of the real estate portfolio of the organisation and the construction projects that this process may require. It is made from experts such as real estate asset managers, policy advisors, project managers, technical managers and building information managers (PC.1, 2021).

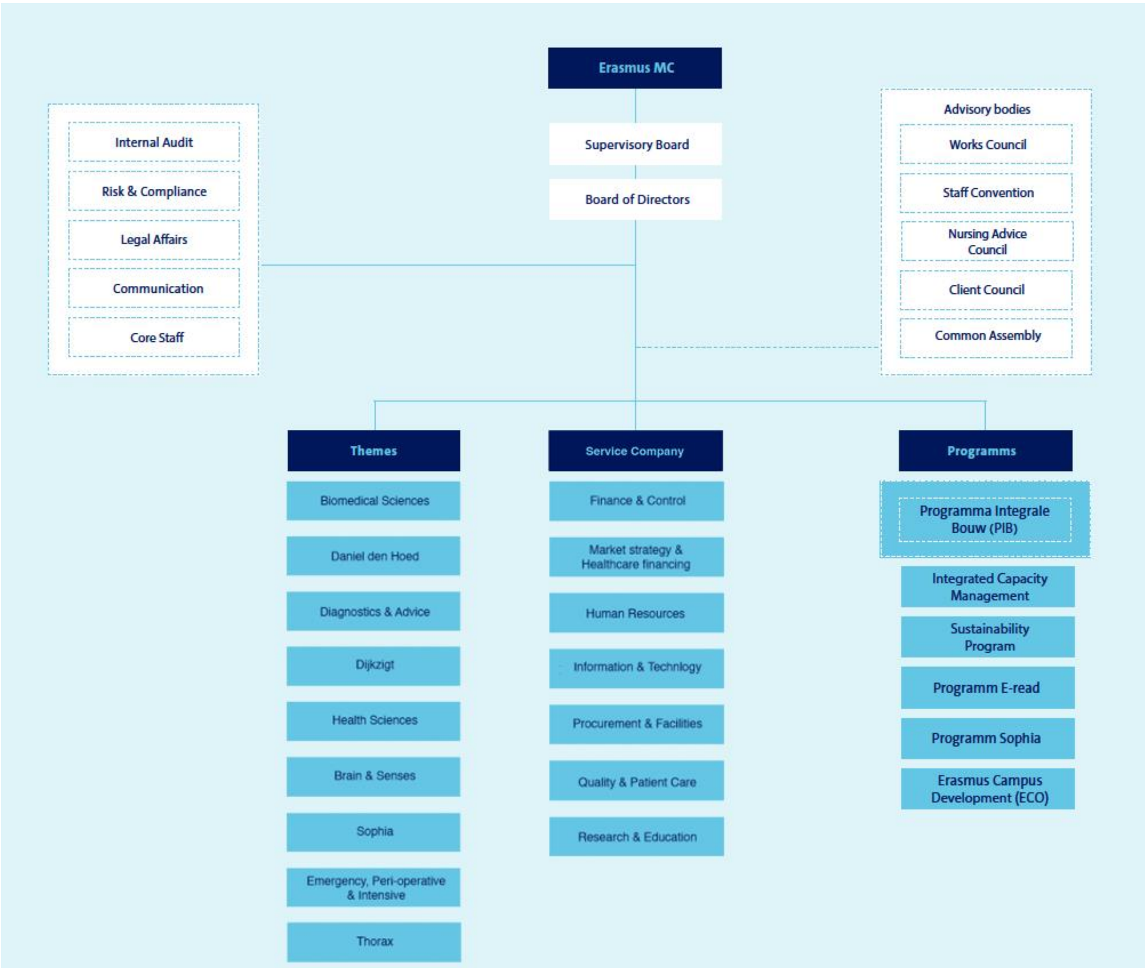


Figure 32:
The organogram of the Erasmus Medical center (Erasmus MC, 2022c, p.29, translated).

4.1.3 Organisational strategy

Every five years the EMC publishes a document named *Koers*, which delineates the strategic goals of the organisation for the following years (Erasmus MC, 2022a). Under the motto *Technology and dedication*, the current strategic document *Koers 23*, aims to analyse the strategic ambitions which combine the double themes of: people and technology, care and innovations, collaboration and impact (Erasmus MC, 2019).

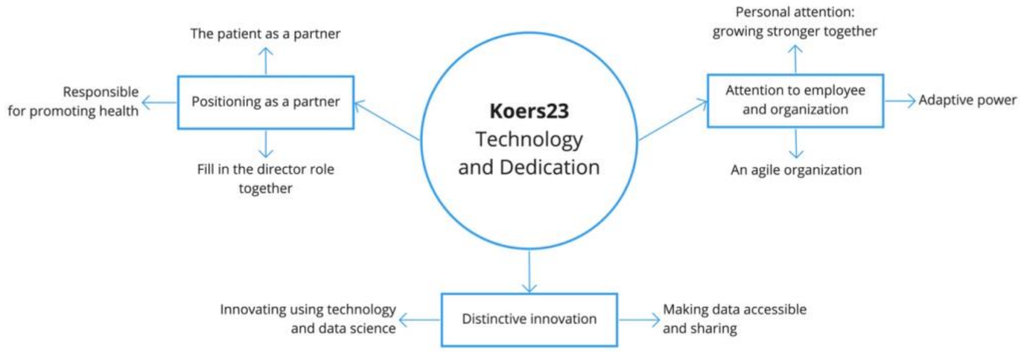


Figure 33:
Strategic ambitions
of Koers 23
(source: author,
based on Erasmus MC, 2019).

The first ambition of *Koers 23* is fostering the position of the organisation as a partner (Erasmus MC, 2019). Such an example is a patient-centred healthcare provision, the patient's feedback is deemed crucial and, thus, implemented for continuous improvement of the healthcare services. The second ambition is oriented towards the medical professionals, researchers, students and all the rest of the members that comprise the people of the organisation and aims to create the sense of appreciation, respect and responsibility within the EMC. The third ambition is called distinctive innovation and aspires to enhance the healthcare provision process through the deployment of innovative technology (Erasmus MC, 2019). The focus is placed in informed decision-making processes by using data at a medical and organisational level.

[environment finding] →

[environment finding] →

4.1.4 Sustainability objectives

The EMC considers crucial to contribute to the sustainability targets that are currently set by the United Nations as the "Seventeen Sustainable Development Goals" (17 SDGs) (Erasmus MC, 2022d). In particular, the organisation focuses on five of them. First, the *SDG 3: Good health and well-being*, by promoting a preventing approach to diseases and encouraging a healthy lifestyle. Second, the *SDG 4: Quality education* is being approached by offering equal opportunities for everyone, by organising public lectures and by educating on sustainable developments, sustainable lifestyles and social matters such as human rights and gender equality (Erasmus MC, 2022d). Additionally, the *SDG 10 Reduced inequalities* is pursued by facilitating an organisation that functions with the principles of diversity and inclusion across all its layers. The fourth goal is *SDG 12: Responsible consumption and production* is pursued by promoting sustainable consumption and production activities within the organisation (Erasmus MC, 2022d). By promoting a circular business model that encourages the reusability in material flows, EMC aims to reduce the waste that is being generated by its operations. Finally, the EMC aims to contribute to the *SDG 13: Climate action* which targets to combat the climate change and its relative impacts by reducing the carbon footprint of the organisation (Erasmus MC, 2022d). Controlling energy consumption is therefore essential in order to pursue the organisation's sustainability objectives. This is taken into account when changing a technical system, such as ventilation or lighting (E.2, 2021).

[environment finding] →

4.2 Real estate portfolio

In the section of the real estate portfolio of the EMC, an overview of the building assets of the EMC is presented. The first section presents the building complex at its present condition, accompanied with several key figures. The second section analyses the strategic goals for the real estate portfolio and the ongoing building programmes that are transforming the building complex. The third section deals with the sustainability measures that the organisation commits to with regards to its building portfolio.

Figure 34:
Bird's eye view
of the EMC building complex
(Erasmus MC, 2022d, p. 29)

4.2.1 The current real estate portfolio of EMC

The Erasmus Medical Center is accommodated by a building complex that is located at the center of Rotterdam, adjacent to two major green areas, the "Park" and the "Museum Park". The nearby metro station and the three surrounding avenues make it an easily accessible medical institution. The two towers (the newly built research tower and the medical faculty) are easily recognizable in the Rotterdam skyline. The several functions of the organization are accommodated in a similarly diverse and complex range of buildings. As seen on the image of the following page, the new buildings (Na-g) accommodate the new hospital functions at the center of the complex. The Sophia Children hospital (Sb-k) and a youth Psychiatry (Kp) are located at the northeast edge of the campus. Southeast lies the new building of the library (Eg) and adjacent to it is the medical faculty tower (Ee). At the southwest edge is a Psychiatry (Dp) and the "flexible shell" (Ba-e) which houses multiple functions of the campus. An office building (Gk) accommodates support functions at the northwest end of the complex. The table below offers some key figures with regards to the use of spaces of the hospital.

[environment finding] →

Real Estate	
Land owned and long-term leasehold	13 ha
Buildings and building parts	46
Gross floor area	~470,000 m^2
Core real estate	~403,000 m^2
Flexible shell	~52,000 m^2
Planned to be demolished in 5 to 10 years	~19,000 m^2
Services	
Rooms and corridors	19,554
Operating and intervention rooms	65
Medium and high care patient rooms (of which 604 are single-bed rooms)	699
Intensive care rooms (of which 87 are single-bed rooms)	95
Isolation rooms	125
General consultation and treatment rooms	976
Specific treatment rooms	276
Lab spaces	762
Office spaces	3,146
Meeting rooms	278
Classrooms and lecture halls	214

Table 12: Key figures of the EMC buildings (Erasmus MC & Programma Integrale Bouw, 2019, p. 26)

According to a healthcare real estate development consultant (E.1, 2021), a real estate management team ensures that the building assets are aligned with the organizational objectives of the hospital. In order to manage this real estate portfolio, the real estate decision makers are using performance indicators "in order "to translate long-term strategy into short term performance relatively easy" (Erasmus MC & Programma Integrale Bouw, 2019, p. 17). By benchmarking the threshold of a desired real estate performance, the decision makers can set clear targets, act on them and monitor the performance of their portfolio internally, but also in comparison to other organisations (Erasmus MC & Programma Integrale Bouw, 2019). For example, dashboards are developed to monitor the environments of the hospital (E.2, 2021).

[environment finding] →

The new building spaces provide a more flexible accommodation which leads to a more tight and efficient use of spaces. For example, some of the medical spaces are used by several specialties. By doing so, the spaces are used more efficiently as a result the utilisation of the spaces is increased, while the collaboration between the different medical departments is enhanced (Erasmus MC., 2018). Similarly, the office spaces, such as in the research tower support flexible workspaces, having a similar result of increased space efficiency (Erasmus MC., 2018). In order to support this flexibility information systems such as room reservation and occupancy monitoring are deployed by the organisation (E.3, 2021).

[environment finding] →

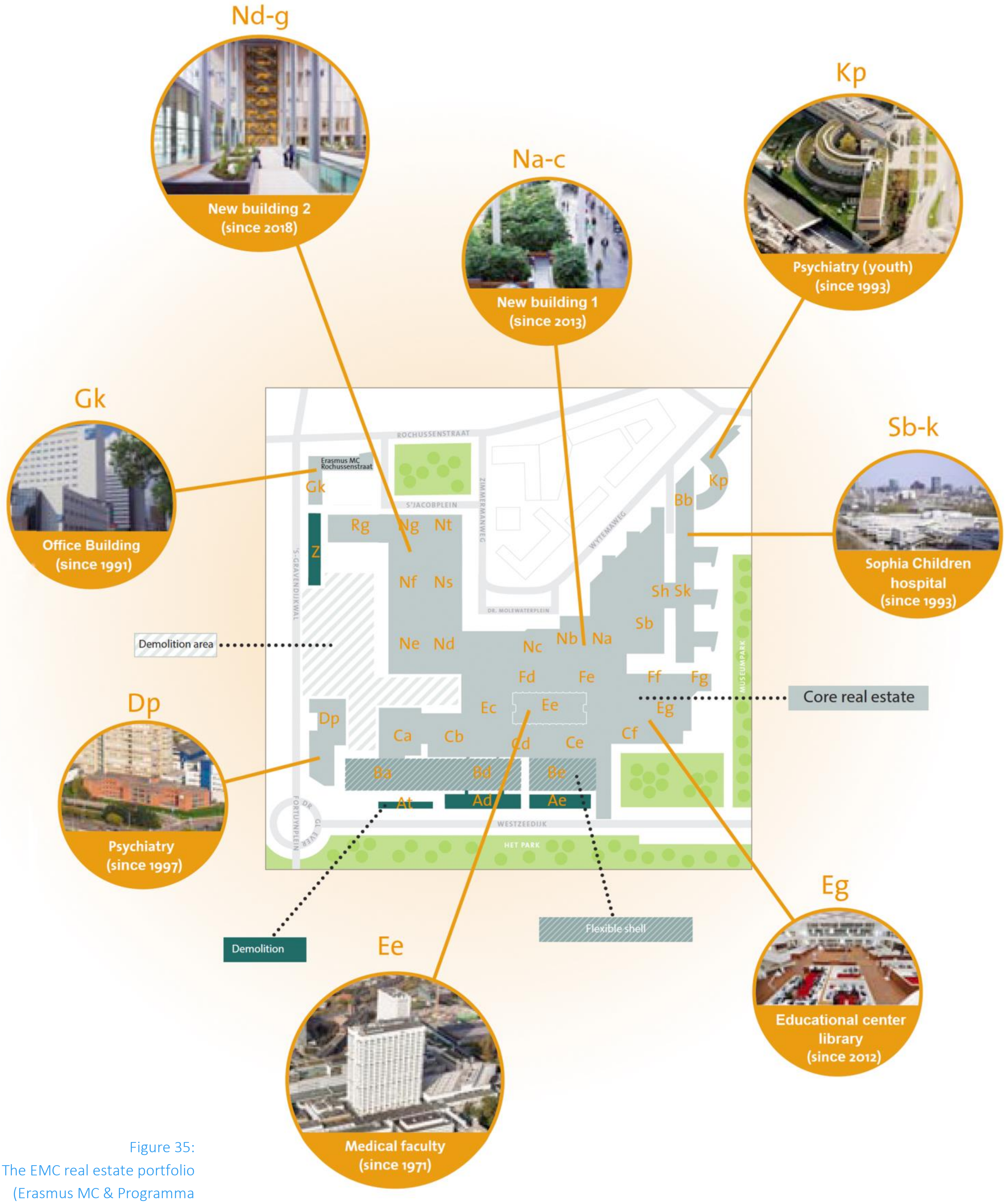


Figure 35:
The EMC real estate portfolio
(Erasmus MC & Programma
Integrale Bouw, 2019, p. 11)

4.2.2 From a hospital campus to a campus with a hospital

The strategic ambitions of the organisation are translated into real estate objectives in the strategic document *Vastgoed op koers 35* (E.1, 2021, Erasmus MC & Programma Integrale Bouw, 2019). This report outlines the desired alignment of the organisation's strategy with its real estate resources, aiming to future proof its building resources. More specifically the current report, Vastgoed op koers 35 (Erasmus MC & Programma Integrale Bouw, 2019) is structured around the central ambition of developing the organisation's real estate portfolio "from a hospital campus to a campus with a hospital" (Erasmus MC & Programma Integrale Bouw, 2019, p. 7).

Figure 36:
Top view of the development of the EMC campus (Erasmus MC, 2022c, p. 25)

The EMC is planning to develop real estate properties in the areas where the old ones will be demolished, with the intention of leasing space to healthcare related start-ups and research companies (Erasmus MC & Programma Integrale Bouw, 2019, E.4, 2021). The vision of the campus with a hospital entails an even more diverse range of healthcare related functionalities. It aims to facilitate the creation of a building complex whereby the existing functions will be placed together with entrepreneurial and research institutions in the healthcare field. Cooperation will be promoted through spatial but also functional proximity. Eventually the real estate portfolio will become even bigger and accommodate even more functionalities.

[environment finding] →

4.3 Information systems for space use

An exploration on the existing information systems of space use is realised at the EMC, with aim of analysing the available data that are related to the use to space, which can be introduced in a digital twin for space use. Several building professionals mentioned that there are many information systems in the hospital, which produce data related to the use of space (E.1, 2021, E.2, 2021, E.9, 2021). For example, a building management system (BMS), which collects data regarding the room environments of the rooms (E.5, 2021). Those data can be extracted and integrate in a digital twin for space use. Furthermore, several professionals who are positioned in various roles in departments of EMC, provided information on those systems. The data catalogue of the following two pages is the outcome of the information that was provided, which is an indication of the numerous space use data that can be leveraged for the creation of a digital twin. As mentions in section 3.3.4, data from implicit or explicit sensors can overlap thus offering more accuracy.

[environment finding] →

Two types of bottlenecks were identified in trying to integrate data related to the use of space. The first one is a managerial and is related with a "silo effect" (Tett, 2015) between the several departments of the EMC. Some departments use relevant data, such as capacity management from the medical departments (E.4, 2021, E.10, 2021) and logistics data from the facility management (E6. 2021), video camera data from the security department (E.7, 2021) and workplace occupancy monitoring from PIB (E.3, 2021). However, due to the high organisational complexity, these departments rarely collaborate in their lower levels, thus each one uses their own datasets (E.10, 2021). Also, some medical data types are permitted to be used by non-medical professionals, thus preventing real estate decision makers from accessing them (E.1, 2021). The other challenge is a technical one. Information systems use data types that are not compatible (E.2, 2021). The various software development companies (vendors) use their own principles with regards to the interoperability of their products, which renders the integration of data from different vendors an issue. A solution for that is the deployment of system integrators, however they are expensive (E.1, 2021).

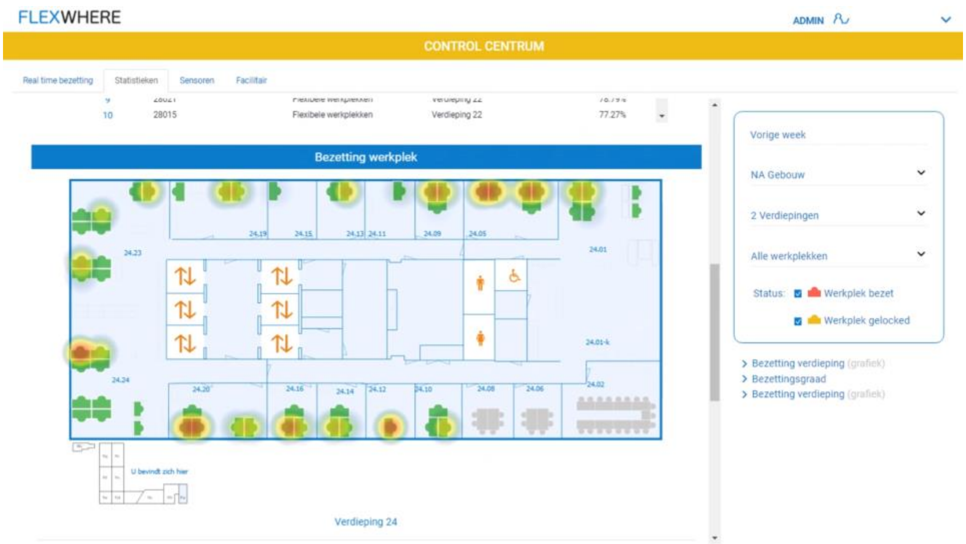


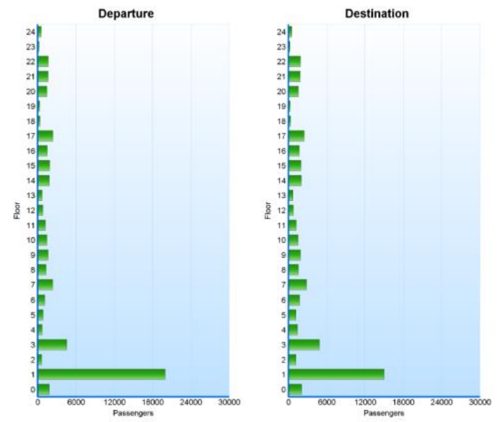
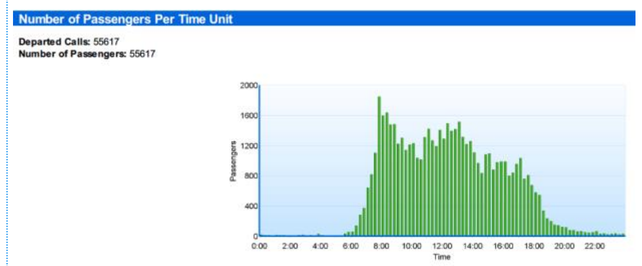
Figure 37: Display of information system for workplace occupancy monitoring (E.3,2021).

The EMC uses a software named *Flexwhare* for workplace occupancy monitoring purposes (E.3.2021). It is widely installed in the buildings of the new hospital (N buildings) and predominantly in the offices of the research tower (Na). It can be considered as a type of digital twin for space use, since a digital representation of a building space is displayed together with real time sensor data related to occupancy. However, the data are limited to that of space utilisation. Given the multifaceted definition of space use of the present research (section 3.2.1), the design of the next chapter seeks for a digital twin for space use that combines more types of data that would facilitate space utilisation, space management and decision making that defines the space norms of a hospital. Thus, a system like *Flexwhare*, can be integrated in it, however it is aimed to introduce more types of space use data.

ID	data	input sensor	type of sensing information	managed by	owned by	related to which building(s)	related to which people	stored at(in)	EMC department	information provided by	data input image	data output image
DC_1	Motion detector	PIR sensors	explicit	EMC/PIB	EMC	Na - Nt, recently renovated buildings or floors and operating theatres.	All users of the spaces	No storage	PIB	(PC.2, 2021)	DC_1_IN_A, DC_1_IN_B, DC_1_IN_C	-
DC_2	Air quality (CO2)	Elsys sensors	implicit	EMC/PIB	EMC	Na - Nt, recently renovated buildings or floors and operating theatres. In the larger rooms of the education center.	All users of the spaces	Cloud	PIB	(PC.2, 2021)	DC_2_IN	-
DC_3	Desk occupancy	PC-login	explicit	EMC/PIB	EMC, supported by Flexwhere	Na, Nc, Nd, Ne, Nf, Ng, Ns, Nt, Rg and Gk	All users of desks	SAAS	PIB	(PC.3, 2021)	-	DC_3_OUT_A, DC_3_OUT_B
DC_4	Lift movements	PC-login	implicit	EMC/PIB	KONE	Na t/m Rg & Ee	Administrator /PIB/ elevator mechanic	PC in Elevator machine room Nc E-Link Liftmanagement system	PIB	(PC.4, 2021)	-	DC_4_OUT_A, DC_4_OUT_B
DC_5	Room reservation sleeping	No sensor	-	Servicedesk	EMC	Ca	EMC employees	service portal	Procurement & Facility Management	(PC.5, 2021)	-	-
DC_6	Room reservation meeting	No sensor	-	Servicedesk	EMC	65 meeting rooms that are located across all EMC buildings	EMC users who have booking rights of rooms.	Outlook Exchange	Procurement & Facility Management	(PC.5, 2021)	-	DC_6_OUT
DC_7	Coffee machine utilisation data	Only coffee supplier has access	implicit	Coffee machine supplier (provision of the data to the EMC in a quarterly update)	Coffee machine supplier	All buildings of EMC	All users of EMC	Only coffee supplier has access	Procurement & Facility Management	(PC.6, 2021)	DC_7_IN	DC_7_OUT_A, DC_7_OUT_B
DC_8	Vending machine utilisation data	Only vending supplier has access	implicit	Vending machine supplier	Vending machine supplier	All buildings of EMC	All users of EMC	Only vending supplier has access	Procurement & Facility Management	(PC.6, 2021)	DC_8_IN	-
DC_9	Badget system for access	Card reader (EAL ATS)	implicit	Access management department	EMC	All buildings of EMC	Cardholders of EMC.	Afas/Oracle EBS	Procurement & Facility Management	(PC.7, 2021)	DC_9_IN	-
DC_10	Security cameras	Video cameras	implicit	Access management department	EMC	All buildings of EMC	All users of EMC	Griffid	Procurement & Facility Management	(PC.7, 2021)	DC_10_IN	-
DC_11	Parking utilisation light detector	PIR sensors	explicit	Access management department	EMC	Parking garages (Wytemaweg and Westzeedijk)	All users of EMC with parking access	No storage	Procurement & Facility Management	(PC.7, 2021)	-	DC_11_OUT
DC_12	Parking utilisation data A	Card reader (EAL ATS)	explicit	Access management department	EMC	Parking garages (Wytemaweg and Westzeedijk)	Cardholders of EMC whith parking access.	EAL ATS (for employees) and Skidata (for temporarily parkers:they are transfered daily at spreadsheets)In the future employees will also be at the Skidata.	Procurement & Facility Management	(PC.7, 2021)	-	DC_12_OUT_A, DC_12_OUT_B
DC_13	Parking utilisation data B	Card reader (EAL ATS)	explicit	Municipality of Rotterdam (does not provide data to the EMC). They use their own parking managemnt system.	Municipality of Rotterdam (does not provide data to the EMC, for safety reaons).	Garage Museumpark	Cardholders of EMC whith car access.	EAL ATS	Procurement & Facility Management	(PC.7, 2021)	-	-
DC_14	PC login with cards	Card reader	implicit	EMC/Informatie & Technologie (ICT services)	EMC	All buildings of EMC, however not all computers have the [C login card system	Users of the computers who have a card (usually the healthcare stuff).	(no information)	Procurement & Facility Management	(PC.7, 2021)	-	-
DC_15	Textile use data	Card reader (EAL ATS)	implicit	Textile deprtament	EMC	Nd and Ca	Cardholders of EMC.	(no information)	Procurement & Facility Management	(PC.7, 2021)	-	-
DC_16	Copy machine use data (multifunctionals)	Card reader	implicit	ICT	EMC	All buildings of EMC	Cardholders of EMC.	(no information)	Procurement & Facility Management	(PC.7, 2021)	DC_16_IN	-
DC_17	Locker access data	Card reader (EAL ATS)	implicit	Servicedesk	EMC	All buildings of EMC	Cardholders of EMC.	Oracle identity management ABS	Procurement & Facility Management	(PC.8, 2021)	DC_17_IN	-
DC_18	Pneumatic Tube System (eg for blood samples)	Card reader (EAL ATS)	implicit	EMC/Delivery Manager	Swisslog	Rg, Nt, Nf, Ns, Ne, Nd, Nc, Nb, Na, Eg, Dp, Ca, Ba, Bd, Ad, Be, S (buildings)	Cardholders of EMC (after following a training about the PTS)	EMC servers	PIB	(PC.9, 2021)	-	-

Table 13:
Data catalogue of information systems related to the use of space (source: author).

	DC_1_IN_A	DC_1_IN_B	DC_1_IN_C	DC_2_IN	DC_7_IN	DC_8_IN	DC_9_IN	DC_10_IN	DC_16_IN	DC_17_IN
input sensor photo										

ID	DC_3_OUT_A	DC_3_OUT_B	DC_4_OUT_A	DC_4_OUT_B
data output analysis				

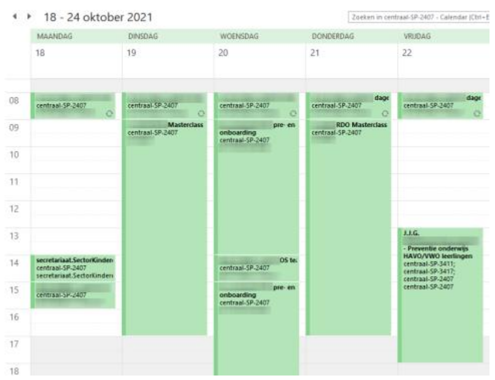
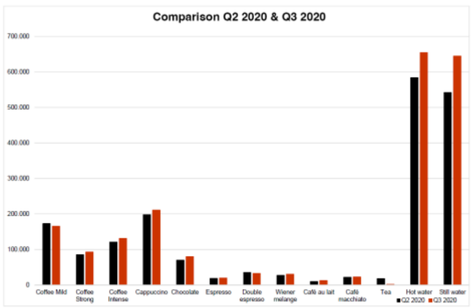
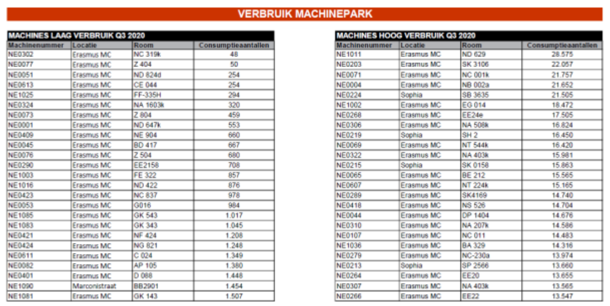
ID	DC_6_OUT	DC_7_OUT_A	DC_7_OUT_B	DC_12_OUT_B
data output analysis				

Table 14:
Photos of data inputs and data outputs
(source: author).

4.4 Building documentation databases

In an extensive interview, the BIM manager of the real estate department of the EMC provided a detailed elaboration on the building documentation databases that are currently deployed at the organisation (E.8, 2021). An overview of the file types and the related information can be seen on the table below. It should be noted that the most prevalent building documentation method takes *place* in *Planon*, a software type that uses spreadsheet type of information. This is the database that is most up-to date with the conditions of the buildings as well (E.4, 2021, E.5, 2021). The organization aims to gradually convert the building documentation into BIM files, specifically in Revit (E.8, 2021). However, given the complexity of the buildings and how old some of them are, this process is not an easy one and, therefore, it is implemented gradually.

ID	building	software	file type	type of documentation	comments
BD_1	all EMC buildings	Planon	spreadsheet type of database	all building systems (eg architectural and mechanic)	The most up-to-date database regarding building information. Most of the information has been entered manually. It is continuously being revised but they update it immediately, whenever a change is made.
BD_2	all EMC buildings	AutoCAD	2D CAD drawings	all building systems (eg architectural and mechanic)	They are separated per building and not connected so that they can be managed more efficiently.
BD_3	Na-Ng	AutoCAD	3D CAD drawings	only architectural	They were provided by the architect. They don't have a complete BIM model from the new hospital. When the contract was made (mid 2000) the BIM technology was not developed so much yet.
BD_4	Ca	Revit	BIM	all building systems (eg architectural and mechanic)	Every type of system, including architectural and mechanic.
BD_5	Fd, Fe, Ee, Cd, Ce, Ec (medical faculty)	Revit	BIM	only architectural	They were made to be used as input for the renovations. The architect has already started working with them.
BD_6	Sb, Sh, Sp, Sk, Bb, Kp (Sophia hospital for children and children psychiatry)	Revit	BIM	only architectural	They were made to be used as imput for the renovations. A small part also has mechanical an structural parts.
BD_7	Ad	Revit	BIM	architectural, electrical, plumbing	-
BD_8	Underground tunel (runs through all th ebuildings)	Revit	BIM	all building systems (eg architectural and mechanic)	Was made with a point cloud scanner and is documented with .ifc information
BD_9	Ventilation system at the rooftop of Eg (library)	Revit	BIM	mechanical	Were provided by the manufacturers.
BD_10	Elevators of Ee	Revit	BIM	mechanical	Were provided by the manufacturers.

Table 15:
Building documentation databases
(source: author).

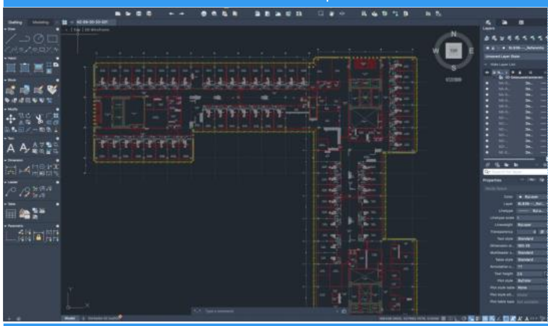
Furthermore, an overview of other building documentation practices was presented by the BIM manager, such as hospital spaces in virtual reality, 3D CAD files and photorealistic renders. The multitude and diversity of these building documentation methods, displays the intention of the organisation to deploy innovative ways of documenting their building assets. All these database findings are an indication of the extensive building documentation means that are deployed by the EMC.

[environment finding] →

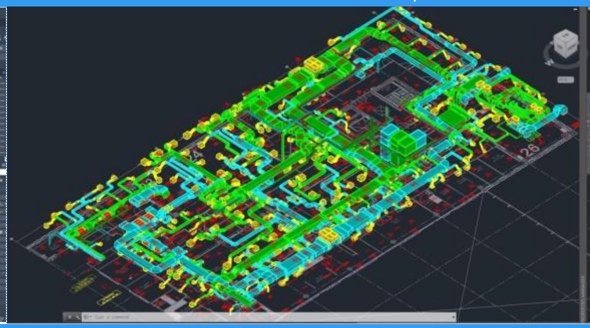
Space allocation in *Planon*

Type mapping: 'Afdeling' | Reference date: '01/09/2021'		
Afdeling	Aantallen	Netto oppervlak(meter²)
A100000.C200000.C3I0000.130431.1304312.5121, C. Inw.Geneesk.Sectie Transpl.	1	20.00
A100000.C200000.C3M0000.130453.5251.5251, C. MDL Secretariaat Ltx	1	20.00
A100000.C200000.C3T0000.C4T0300.C5T0305.3392, Polikliniek Rg-1 team 5	36	584.67
A100000.L200000.L3H0000.L4H0000.L5H0601.0062, SO: Voeding - Reiniging Centrum	1	5.86
A100000.L200000.L3H0000.L4H0300.L5H0300.0082, SO: Supply Chain - Pakketdienst	3	18.63
A100000.W2W0000.W3W0000.W4W0000.W5W0000.A006, Algemeen gedeeld gebruik	12	103.95
A100000.Z2Z0000.Z3Z0000.Z4Z0000.Z5Z0000.A005, Algemeen	24	668.52
Aantallen	78	1421.63

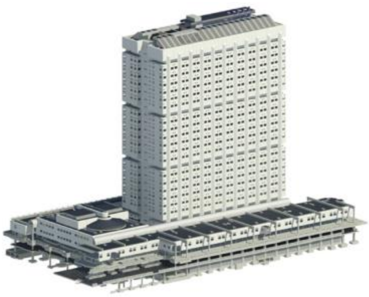
2D CAD floor plan



3D CAD with mechanical systems

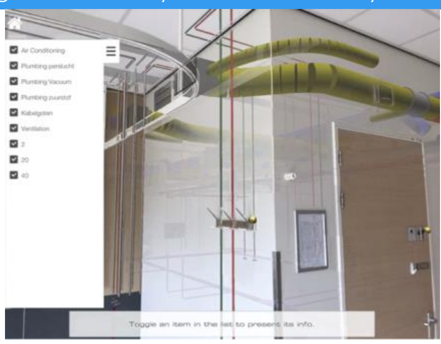


3D BIM faculty tower



3D render with terrain

Augmented Reality with mechanical systems



Virtual Reality of interior

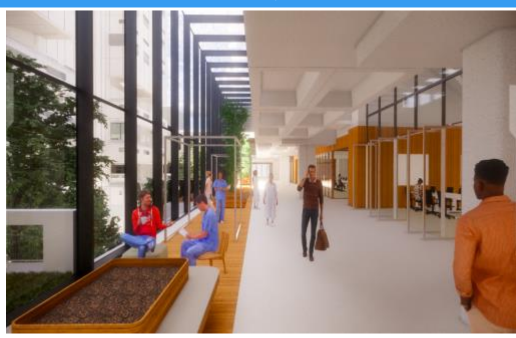


Table 16: Displays of building documentation software that are deployed by the EMC (E.8, 2021).

4.5 Environment conclusion

As was presented in section 2.1, the fourth chapter of the research delineates the environment of the design artefact and provides input for the relevance cycle of Hevner (2007). The relevance cycle uses information which is translated from the environment and converted to requirements for the design artefact. Additionally, the conclusion of the environment will formulate an answer to the second research subquestion:

[SQ2]
"What design and utilisation principles related to digital twins for space use in hospital real estate management can be extracted from a hospital case study?"

Throughout the fourth chapter, several case study findings are annotated, that are introduced in the table below and, therefore, translated in design and utilisation principles. By doing so, a connection can be established between the case study (the EMC hospital) and the identified principles. Similar to the conclusion of the third chapter, the principles are correlated with the layers of the system architecture of a digital twin that they correspond to. Many of the principles correspond to the application layer, which reflects the utilisation of the tool. Some other of the principles correspond to the Data-model integration layer, which is also related with the display of the user interface of the digital twin and, therefore they can be directly incorporated in the design development of the following chapter

ID	Environment findings	Design and utilisation principles	System architecture	Section
2.1	The structure of the organigram for the allocation of staff is an indication of the high organisational complexity of the EMC.	A design that will lead to different information provision, per user type.	Application layer	4.1.2
2.2	The feedback of the patients is deemed crucial and, therefore, implemented for continuous improvement of the healthcare services.	The digital twin can be used as a communication platform whereby the patients can provide feedback on their experience of the use of space	Application layer	4.1.3
2.3	The organisation aspires to enhance the healthcare provision process through the deployment of innovative technologies.	The digital twin can be used as a tool for healthcare process optimisation such as resource allocation and scheduling.	Application layer	4.1.3
2.4	Controlling energy consumption is essential in order to pursue the organisation's sustainability objectives.	A digital twin that can be used to monitor energy consumption.	Application layer	4.1.4
2.5	The several functions of the organization are accommodated in a similarly diverse and complex range of buildings.	A digital twin that can display information at a different building scale resolution.	Data-model integration layer	4.2.1
2.6	In order to manage this real estate portfolio, the real estate decision makers use performance indicators	Integration of performance indicators in the design of the digital twin.	Data-model integration layer	4.2.1
2.7	Information systems such as room reservation and occupancy monitoring are deployed by the organisation.	The digital twin can be used for room reservation and occupancy monitoring.	Application layer	4.2.1
2.8	The real estate portfolio will become even bigger and accommodate even more functionalities.	The utilised building model data can be updated when changes occur in the physical spaces.	Digital modelling and data complementary layer	4.2.2

2.9	Existing infrastructure of sensors.	The existing infrastructure of sensors can be leveraged by the digital twin.	Data acquisition layer	4.3
2.10	Existing building documentation dataset.	The existing building documentation dataset can be leveraged by the digital twin.	Digital modelling and data complementary layer	4.4

Table 17: Design and utilisation principles from the case study findings (source: author).

Below an updated version of the research conceptual framework presents the two principles from the hospital case study. It should be noted that some of the principles are partly overlapping or highly related such as "2.3: healthcare process optimisation such as resource allocation and scheduling" is partly overlapping with "1.1: Data from primary processes as information about the real estate performance. this is because healthcare provision is the primary process of the EMC organisation.

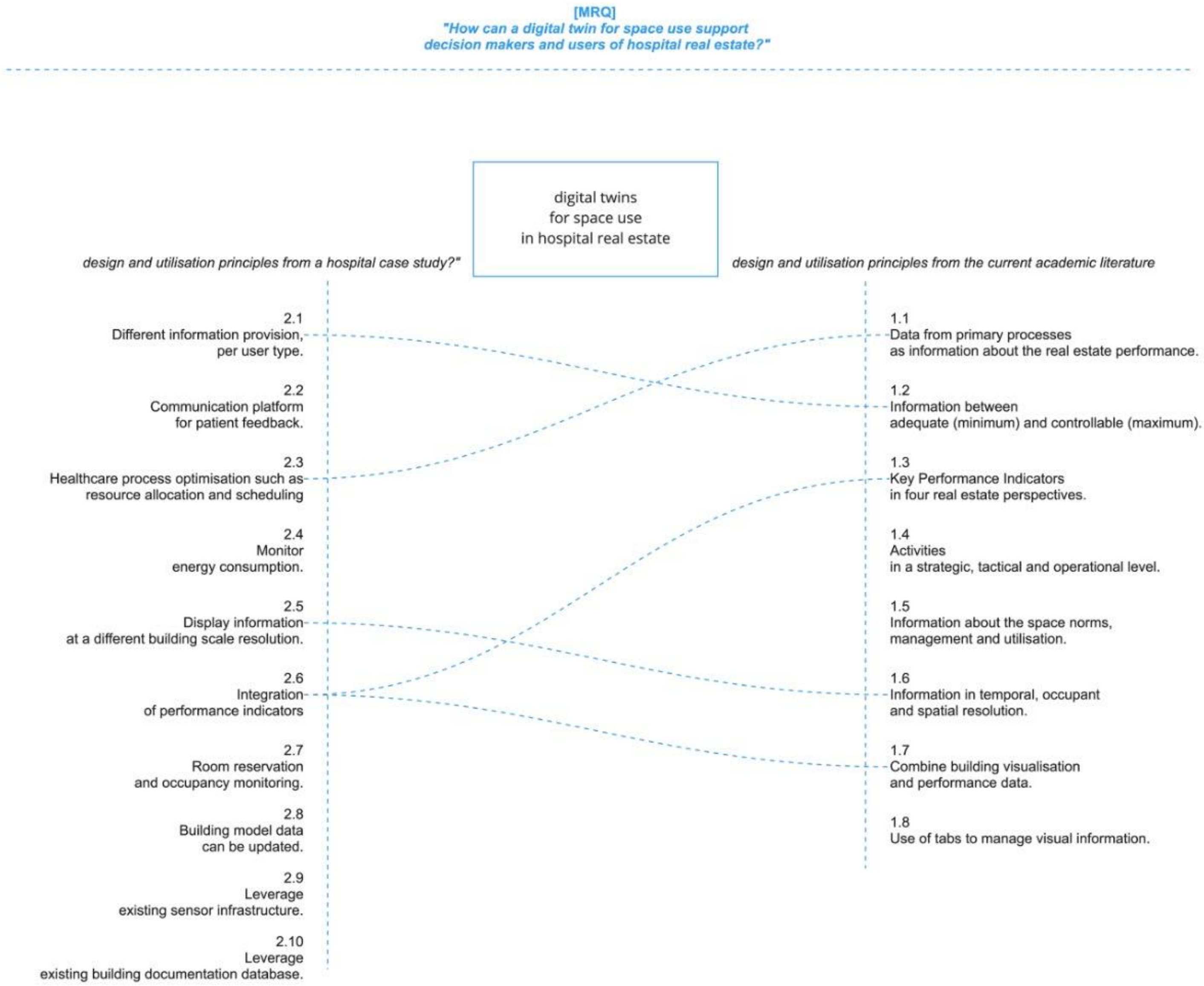


Figure 38: Updated conceptual framework based on [SQ2] (source: author).

Chapter 5
Design science research

In the design science research chapter, the research is conducted through a conceptual design development of a design artefact, that of a display of a digital twin. The design is elaborated from its overview to each respective windows and then it is evaluated through interviews from decision makers and users of hospital as was suggested in chapter 2.

5.1 Conceptual design development

The development of a conceptual design is the first step of the design science part of the present research. As was introduced in section 2.1 and based on the research approach introduced by Hevner (2007) the design cycle utilises input from the rigor cycle (section 3.5) and relevance cycle (section 4.5) in order to develop a design artefact. In this case, the design artefact is that of a display of a graphical user interface of a digital twin for space use and its complementary suggestion for information structure in the form of a diagram in some of its parts, that convey the relevant information structure that is required for its functionality.

5.1.1 The conceptual design overview

The conceptual design of the display of the user interface is based on the grouping of information in relevant windows as seen on the figure below. Each of the windows is designed in order to support a certain function of the user interface and in total make it an efficient tool. It is developed having as a utilisation scenario that of the real time display of the air quality in the rooms of the eighth floor of building Rg. The display is designed using a compartmentalisation logic, by dividing the screen into five windows. A time frame window, a building orientation window, a user profile window, a building visualisation window and a performance palettes window.

Figure 39:
The conceptual design of the display of the digital twin (Erasmus MC, 2022c, p. 25)

ID	Design and utilisation principles	time frame window	building orientation window	user profile window	building visualisation window	performance palettes window
1.1	Data from primary processes as information about the real estate performance.	-	-	indirect relationship	direct relationship	direct relationship
1.2	Information between adequate (minimum) and controllable (maximum).	indirect relationship	indirect relationship	-	direct relationship	-
1.3	Key Performance Indicators in four real estate perspectives.	-	-	indirect relationship	indirect relationship	direct relationship
1.4	Activities in a strategic, tactical and operational level.	-	-	direct relationship	indirect relationship	indirect relationship
1.5	Information about the space norms, management and utilisation.	-	-	-	direct relationship	indirect relationship
1.6	Information in temporal, occupant and spatial resolution.	direct relationship	direct relationship	-	indirect relationship	-
1.7	Combine building visualisation and performance data.	-	-	-	direct relationship	-
1.8	Use tabs to toggle between different options.	-	-	-	-	direct relationship
2.1	Different information provision, per user type.	-	-	direct relationship	indirect relationship	indirect relationship
2.2	Communication platform for patient feedback.	-	-	direct relationship	-	indirect relationship
2.3	Healthcare process optimisation such as resource allocation and scheduling.	indirect relationship	-	indirect relationship	-	direct relationship
2.4	Monitor energy consumption.	-	indirect relationship	-	direct relationship	direct relationship
2.5	Display information at a different building scale resolution.	-	direct relationship	-	indirect relationship	-
2.6	Integration of performance indicators	-	-	-	-	direct relationship
2.7	Room reservation and occupancy monitoring.	-	-	indirect relationship	indirect relationship	direct relationship
2.8	Building model data can be updated.	-	indirect relationship	-	direct relationship	-
2.9	Leverage existing sensor infrastructure.	direct relationship	-	-	indirect relationship	indirect relationship
2.10	Leverage existing building documentation database.	-	indirect relationship	-	direct relationship	-

Table 18: Relationships of design and utilisation principles with conceptual design (source: author).

In order to facilitate the design process, a matrix was created whereby the design and utilisation principles that were identified in section 3.5 and section 4.5 were crosschecked with the five window types. Direct, indirect or no relationship was approximated in order to ensure that the design artefact conforms to the principles of the previous chapters. It should be noted that the association is relative and intends to direct the design process. For example, the principle 1.2 "Information between adequate(minimum) and controllable (maximum) is directly related with the building visualisation window, since that is where it will be presented, however it is also indirectly related with the time frame and building orientation windows, since it the amount of information can be indirectly controlled by them.

5.1.2 The time frame window

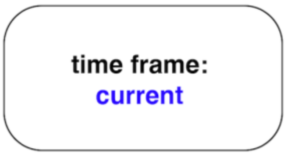


Figure 40:
Indicative design of the time frame window
(source: author).

The time frame window is related with time dimension of the data provision. It is created having in mind the principle 1.6, which requests information in time resolution. It generally iterates among past options, present (with the current option) and future (when the digital twin is used for simulation purposes).

selection time frame	description	information requirements
current	The current selection will lead to a real-time information display of the chosen indicators.	This choice will require the existence of real time sensor data that will be collected and displayed in the digital twin. Some time delays may occur, since the sensing and transferring of data oftentimes occurs with a minor delay.
day	The day selection will lead to the display of the information on a specific day. After the selection of the day option, the user will be prompted to insert the day information in the form of (DD/MM/YYY). This choice is useful to see information on a specific day in the past.	This selection will retrieve data from the database of the performance indicators and in the scenario, it is not averaged, it will be evened out for the day requirements.
month	The month selection is similar to the day selection. It will lead to an average performance within a month. After it is selected, the user will be prompted to insert the month in the form (MM/YYYY).	Similar to the day selection, an existence of a database is required for each of the performance.
quarter	The quarter selection functions the same way as the month and the day on the past. The user will be prompted to input the desired quarter in the form (QQ/YYYY). This selection is useful for a strategic overview of several performance indicators.	Similar to the day and the month selection, an existence of a database is required. Some processing of existing data may also be needed in order to create the quarterly average.
year	The year selection functions similarly to the quarter, month and day. the user will be prompted to input the year in the form (YYYY). This selection is useful for a strategic overview of several performance indicators.	Similar to the day, the month and the quarter selection, an existence of a database is required. Some processing of existing data may also be needed in order to create the quarterly average. It may not be easy to go back in many years, since some of the data may not be available.
simulation	The simulation selection is for the event of a simulation. This could be for the display of a patient journey or an optimisation suggestion based on certain requirements.	The requirements for this selection are the several algorithms that may be needed to perform the simulation event. For example, a geometric simulation algorithm may be needed for the patient journey. Or a linear programming algorithm may be needed for a simulation of optimised performance under certain boundary criteria.

Table 19:
Analysis
of the time frame window
(source: author).

5.1.3 The building orientation window

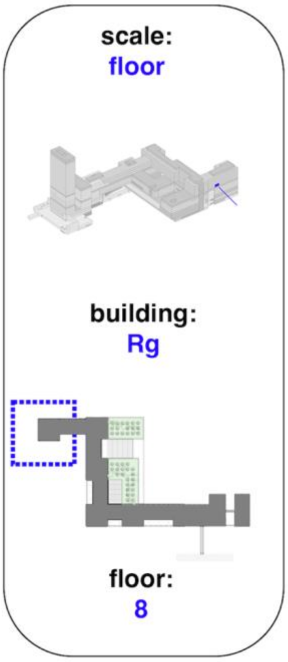
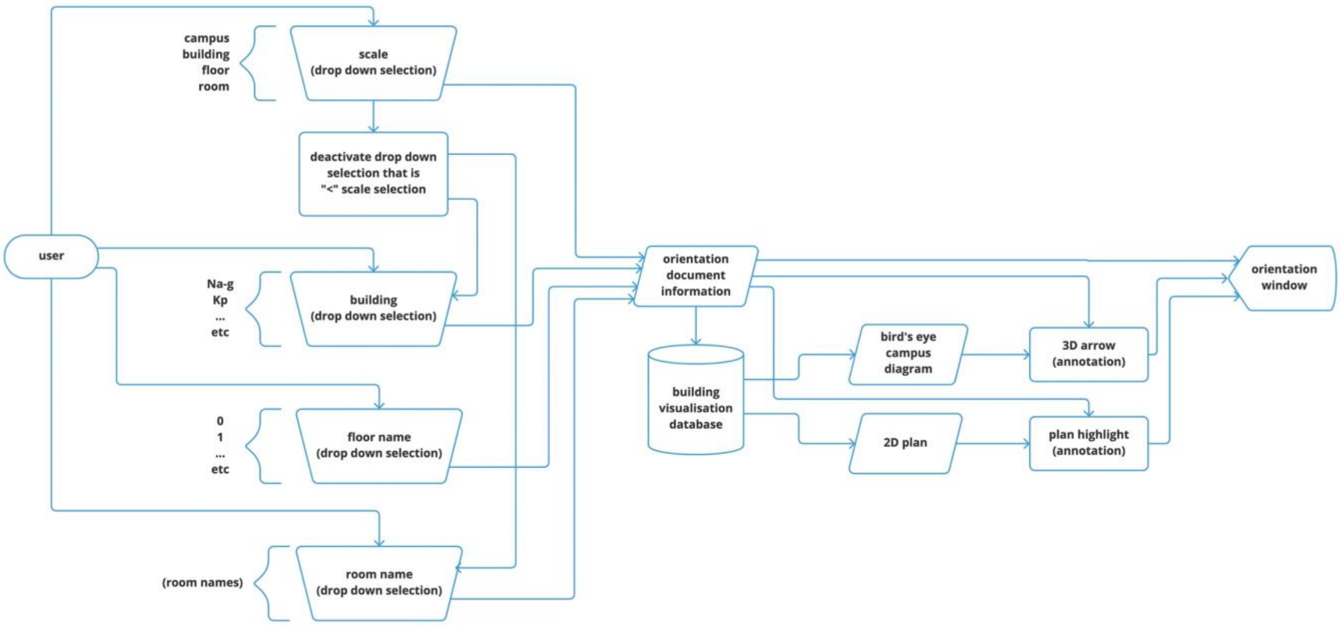


Figure 41: Indicative design of the building orientation window (source: author).

The functionality of the building orientation window is to assist in the navigation within the real estate portfolio and locate the size of the building information that can be displayed in the interface. It is created as an answer to the principle that requests a tool that can be applicable to many types of buildings that can comprise a real estate portfolio and to assist the user in navigating and locating the building visualisation within the campus. By choosing the "scale" option, the user has the ability to choose spatial resolution of the displayed information. Like in the time frame window and according to principle 1.6, information can be provided "in temporal, occupant and spatial resolution". the Information diagram below aims to present the information process behind the utilisation of the window. Annotation used commonly in information flowcharts was deployed. The annotation symbolism is also explained in Appendix 5.

Figure 42: Information diagram for the building orientation window (source: author).



selection	description	information requirements
scale		
campus	The campus selection leads to a display of the whole campus. In case it is chosen, the building selection group becomes inactive, since the building type cannot be selected. The floor selection group is still active, since the interface can offer a display of the whole campus at different floor levels.	This selection will require an overview of the whole building portfolio. In order to avoid the information overload, the building representation will be conducted with the appropriate low quality. That will be transferred to the scale of the performance displays, thus their information cannot be fragmented in many rooms, but averaged at a scale that would be applicable for the whole campus and within the screen real estate.

building	The building selection leads to a display of performance information of a whole building. In the scenario that it is selected, the user will have to choose the building name from a drop-down menu. The floor selection will be deactivated.	Similar to the campus selection, this selection require a model of the whole building. This information can be retrieved from the building visualisation window and the resolution will be adjusted accordingly.
floor	The floor selection will lead to a display of a floor resolution analysis. once it is selected, the user will be prompted to select a building and then a floor level. Like in the example of the conceptual design.	This selection will require a more detailed building documentation. Window and door openings will be visible. The plan of the building will be cropped to the borders of the building it will be showing, like in the example.
room	The room scale resolution will lead to the most detailed resolution. it can be used for example for environmental control by patients in the wards. Once it is selected an additional drop-down selection will appear, that of "room".	This selection requires the highest detail of building documentation. Furniture (like chairs, bedrooms, etc) and appliances (for example lights, or air conditioning devices) will be visible in the building display.
building		
Rg (example)	This selection navigates the user to one of the buildings of the campus.	It will require an information association of building names with the documentation files that can be retrieved from the building documentation database.
floor		
8 (example)	This selection navigates the user to one of the floors. The options of the floors in the drop down are adjusted based on the selection of the building above.	this selection requires associative information between buildings and floor names, before it will direct the system to the appropriate document.

Table 20: Analysis of the building orientation window (source: author).

5.1.4 The user profile window

The main task of the user profile window is to identify the user that sees the display. this is in order to filter out the available information that they will want to see and to avoid the information overload but also the types of information that are not publicly available. For example, the visitor selection will only be able to see a limited amount of information, mainly related with the available amenities that they can reach in their visit in the hospital. The patient can be connected with the medical database. Th decision maker will be able to see most of the available information on several types of performance in the hospital.

Figure 43: Indicative design of the user profile window (source: author).

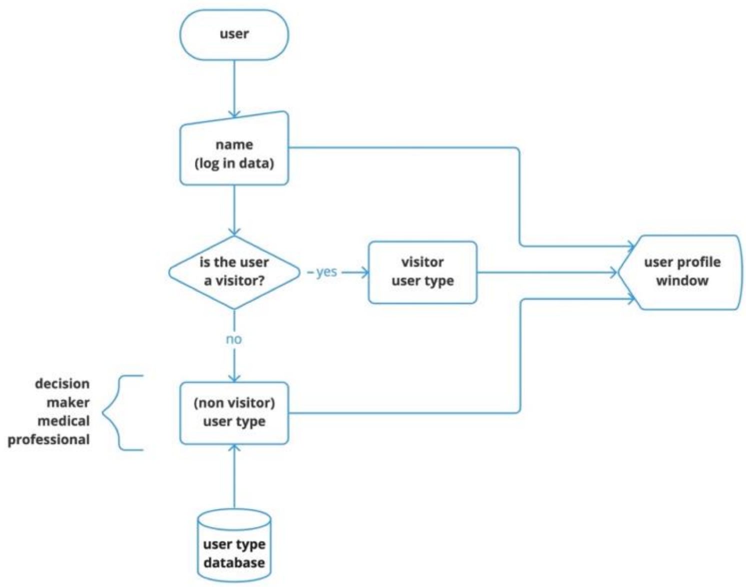


Figure 44: Information diagram of the user profile window (source: author).

selection name	description	information requirements
name & surname	The user types manually their name. In the scenario it is not a visitor, a window will pop up and prompt the user to input their personal password which will have already been provided by the hospital.	The user profile database will automatically connect the name with the user type it is associated with.
user profile type (automated)		
decision maker	Indicates the type of user.	This selection will have the maximum accessibility to information. however, they will not be provided with medical type of information.
support staff	Indicates the type of user.	This selection will have access to operational type of information, such as logistics or cleaning schedules, etc.
medical professional	Indicates the type of user.	This selection will retrieve data from a medical database and can be used to support the primary processes of the organisation.
patient	Indicates the type of user.	This selection will be connected with the medical database, however it will only be limited to the information associated with the specific patient.
visitor	Indicates the type of user.	This selection has the minimum accessibility to information.

Table 21: Analysis of the user profile window (source: author).

5.1.5 The building visualisation window

Figure 45: Indicative design of the building visualisation window (source: author).

The building visualisation window occupies the largest amount of screen real estate and is the main output window of the display of the digital twin.

Table 22: Analysis of the building visualisation window (source: author).

	description	information requirements
building visualisation		
(no selection)	The building visualisation will retrieve data from the building documentation database and simplify them for the display purposes of the digital twin. Additional annotations such as numbers, colours and text will be added and mapped on the budling in order to display the performance that it may lead to.	The information requirements for this window will derive from the building documentation database and the additional annotations will derive from processing of the performance information and mapping on the relative locations of the plan.

5.1.6 The performance palettes window

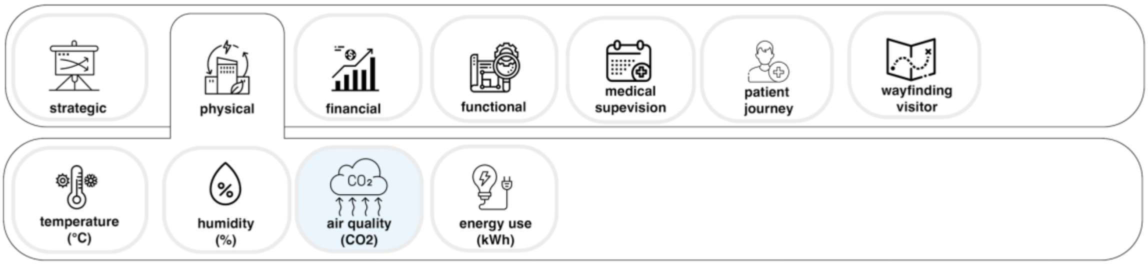


Figure 46: indicative design of the performance palettes window (source: author).

For the performance palettes window, the database choices of Valks et al. (2021b) on dashboard designs. The research group developed a design artefact of a dashboard based on clustering of the performances according to the four perspectives of den Heijer (2011). Additionally, three more options were added with the aim of rendering the digital twin useful for other types of potentials users. the medical supervision is intended for medical personnel, the patient journey for patients and the wayfinding visitor for visitors of the hospital who don't fall in any other of the categories.

Table 23: Analysis of the performance palettes window (source: author).

selection performance cluster	description	information requirements
strategic	The strategic performance cluster will provide information about the strategic perspective. In Valks et al. (2021b) that is space utilisation metrics. In the hospital case, that could be for example inpatient capacity.	Strategic information will be available through a combination of metrics. For example, capacity management database or facility related information such as amount of beds will be combined. Sensors which trace real time space use could be also deployed to offer information about occupancy.
physical	The physical performance cluster, which is used in the example as well, lead to a selection of performance indicators related with the indoor environments of the hospital. For example, temperature, humidity, energy use, etc will lie under this selection.	Data from this selection can be retrieved from sensors that are installed in several rooms of the hospital. Since environmental sensors are some of the most commons sensing types, this selection offers one of the biggest opportunities for data integration.
financial	The financial performance cluster will associate financial performance and spaces. For example, cost per bed or turnover per medical department information can be visualised on the digital building model.	The information requirements for this performance selection are predominantly related with financial statements and analyses. It is expected that this information can be available to decision makers of higher levels.
functional	The functional performance cluster associates information related with an attractive campus (Valks et al., 2021b). it can be used to assess feedback on the quality of spaces.	Information from a database that connects qualitative parameters with the space will be needed for this cluster. One possibility is to gather user feedback and map it in specific locations.
medical supervision	The medical supervision cluster is related with the support a digital twin can offer to the primary process of the organisation, which is the healthcare provision. A set of choices will be available such as patient monitoring, etc.	The information for this performance cluster will be available through medical information systems and, thus, it will be only accessible to medical personnel.
patient journey	The patient journey cluster aims to guide the patient throughout the hospital area to their appointment. Several functionalities may be added to support this process (see section 6.1.2).	Information will be retrieved partly from a medical database and it will be limited to the access a patient can have. Information about other options that could be related with the patient can be retrieved from other clusters.
wayfinding visitor	The wayfinding visitor is intended for use by visitors of the hospital who don't have a patient status. it will mainly provide an overview of the hospital's amenities and departments locations.	This performance cluster will require the less amount of information and will be the most accessible. No password will be needed since it will be associated with the user profile "visitor".

5.2 Conceptual design evaluation

The evaluation of the conceptual design was conducted through a set of interviews (section 2.1.3) from decision makers related to the hospital environment of the EMC. The first section of the evaluation analyses the feedback of the interviewees and underlines any potential changes that are suggested by them. The second section focuses on the utilisation of the tool and the ways that the interviewees suggest they could use the tool. The third section presents some potential opportunities and challenges that emerged through the interviewing process.

5.2.1 Feedback on the conceptual design of the display

All of the eight interviewees mentioned that the display layout is comprehensive.

"It feels intuitively right" (A5., 2021).

This is predominantly because of the similarity of the design with existing information management tools. The medical professional (A2, 2021) mentioned that they recognise the information that is being displayed on the conceptual model of the digital twin, because a lot of information is available already through different software. This renders the tool, according to them, practical because of the similarity with the existing tools. Another interviewee (A4., 2021) said that there is a right amount of information in the tool. Since the opening of the new hospital building (in 2008), a lot of new information systems were deployed of the hospital, as a result, they find it difficult to instantly think of new requirements for a tool (A2, 2021).

Several changes were proposed by the interviewees, as seen on the table below. It is noteworthy that rarely did the interviewees suggest the same change. However, they all shared some opinions about the improvement of the display. Some changes were directed towards annotation and graphics of the display (such as name highlights, customization of fond sizes, see environmental conditions in the surroundings of the hospital etc). Some others mentioned changes with regards to the contents of the tool. Those were changes in performance cluster types or addition of graphs. Only one removal was suggested, that of the financial cluster, since that information is available to a very limited amount of decision makers (A.3, 2021).

Table 24: Proposed changes of the display based on the interviewees (source: author).

Proposed change	Type of change	Suggested by
More indicators about mechanical systems (heating).	addition	A.1
Annotation on name and department of the room.	addition	A.1, A.4
Integrate the environment control of the inpatient rooms.	addition	A.2
Removal of the finances. They are not space related in the hospital.	removal	A.3
Have environmental conditions (weather, outside temperature) in the display.	addition	A.4
Have a more 3-dimensional view on the building plan.	addition	A.4
Annotation of technical areas in the plan (elevators, etc).	addition	A.4
The user can customize the information they can access.	addition	A.4
The user can customize the display options (font size, contrast, etc).	addition	A.5
A quality cluster can be added, focusing on qualitative metrics.	addition	A.6
Instead of "patient journey" integrate additional functionalities for patients (such as make orders or give feedback).	modification	A.6
Some graph would contribute to the information being more comprehensive.	addition	A.6
Add performance cluster related to the students and the educational part of the campus.	addition	A.6
Highlight the name of the room once the cursor hovers over it.	addition	A.7
Interrelate two or more types of performance information in the building visualisation window	addition	A.7

5.2.2 Utilisation of the tool

In the next part of the evaluation of the conceptual design, the interviewees were prompted to think of utilisation scenarios that they could carry out with this tool. The table below offers an overview of their statements accordingly.

utilisation scenarios	identified by	suggested user of DT	REM perspective	time frame	building scale resolution	management level
Wayfinding (patient, visitor, logistics)	A.1, A.2, A.4, A.5	all	functional	future	floor	operational
Information whether special care is needed for a specific room.	A.1, A.2	medical personnel	functional	present	floor	operational
Information on current use of a space.	A.1, A.4, A.6	decision makers	functional	present	campus-floor	operational
Information about the cleanliness of a room.	A.1, A.8	service employees	physical	present	floor	operational
Patient monitoring.	A.2	medical personnel	functional	present	floor-room	operational
Environment control (light, heat, ventilation) from inpatient rooms.	A.2, A.8	patient	physical	present	room	operational
Space allocation (especially in bed capacity).	A.3	decision maker	strategic	past	campus-room	tactical/strategic
Retrieve technical drawings from by clicking on a specific room	A.4	technical employee	physical	past	campus-room	operational
Provide notifications in case a space use is relocated to another place.	A.4, A.6	employees	strategic/physical	present	campus-floor	tactical
Information about utilisation and occupancy rates.	A.3, A.5, A.7	decision maker	strategic	past	campus-floor	tactical/strategic
Analysing potential patient journeys.	A.5, A.7	decision maker	functional	future	floor-campus	strategic
Medical room scheduling (such as operation rooms).	A.5	medical personnel	functional	future	room	operational
Forecast the use of space (capacity management) in relationship to medical data	A.7	decision makers	strategic/functional	future	room	tactical/strategic

Table 25: Proposed utilisation scenarios based on the interviewees (source: author).

The utilisation scenarios that were mentioned were directed predominantly to functionalities related with medical related topics (such as patient journey) or space utilisation, occupancy monitoring, etc. The first reason is because healthcare provision lies in the core of the organisation's operations. The latter is because of the need to deploy tools to assist in decision making of space allocation and management.

"One of the main problems in the EMC is deciding on where to place a space. This is because many departments have to be located in a limited amount of space" (A.7, 2021).

Similarly, many users compared the tool with Flexwhere (see section 4.3), so they proposed utilisation scenarios that they considered were missing from the software that is currently in use (A.6, 2021).

The scenarios were related with real estate management perspective (den Heijer ,2011), time frame, building scale resolution and management level (Glatte, 2021). It is noteworthy that all of their options could fit in the relationship with the scenarios. The only one missing was the financial perspective, which is possibly due to the fact that almost none of the interviewees were involved in financial decision making.

5.2.3 Feasibility of its deployment

As a final part of the evaluation interviews, the interviewees were prompted to discuss any potential opportunities or challenges that may arise in the deployment of such a tool. The table below offers an overview of the opportunities and challenges that were mentioned by the interviewees.

Opportunities	Suggested by	Perspective
An integration of systems could add value to the tool.	A.3, A.6, A.8	(all)
Many improvements in operational level.	A.3	physical/functional
Artificial intelligence operations can predict certain performances	A.5	technical
By using more input from the users of the buildings and the patients, the quality can be improved.	A.7	functional
Challenges	**Suggested by**	**Perspective**
Privacy related issues.	A.1, A.4, A.5, A.6, A.8	functional
Some types of available data may not be or rarely be used by some professionals, thus overburdening them with information.	A.2, A.7	functional
It is expensive to integrate all many types of data.	A.3, A.5, A.8	financial
Some information may not be reliable	A.4	technical
Some information systems by some companies are not easy to interconnect.	A.4, A.5, A.7	technical
Financially related data are difficult to become available to most users.	A.6	financial

Table 26: Proposed changes of the display based on the interviewees (source: author).

When assessing the potential opportunities and challenges, some of the interviewees responded that it all comes to the cost and benefit relationship of the deployment of such a tool.

"One question on should always ask with tools like this is: is it really worth all the investment? What added value will it create?" (A3, 2021).

The opportunities that were mentioned were related with technological potential of the tool, such as integration of various systems and automated operations with artificial intelligence. The other opportunities were related with the outcomes of the tools, such as operational process optimisation, in accordance with the design and utilisation principle 2.3 (see section 4.5). The other opportunity was the qualitative improvements from user feedback. This is in line with the design and utilisation principle 2.2 (section4.5). The identification of these two opportunities validated the design intentions.

When it comes to challenges, the privacy concerns was by far the most popular one. It was mentioned by five out of the eight interviewees. This underlines the importance of this matter. Other challenges were related with technical matters, such as the fact that many information systems are expensive to integrate (A.3, 2021, A.5, 2021, A.8, 2021) and, if not, very difficult to interconnect (A.4, 2021, A.5, 2021, A.7, 2021). Some other challenges were related with the information type, such as the financially related data and whether it would be useful to integrate them, since they will not be accessible by most users.

Finally, the business intelligence consultant directed the discussion towards the device that can run the digital twin software (A.5, 2021). It was suggested that an application version may be directed predominantly towards the visitors and the patients of the hospital, while a desktop version can be developed having in mind the decision makers. They mentioned that one should have in mind the ease of use (A5, 2021).

5.3 Design science research conclusion

By analysing the findings of the design science research, an answer can be formulated for the third research subquestion [SQ3], thus categorising the findings on the evaluation of the conceptual design of the display of the digital twin.

[SQ3]
"How can users interact with the information of a digital twin for space use in hospital real estate?"

All interviewees evaluated the display as a comprehensive, thus validating the principles through which it was designed. A time frame window, a building orientation window, a user profile window, a building visualisation window and a performance palettes window and their functionality all contribute to a synthesis of a display of a digital twin for space use in hospital real estate. Therefore, users can interact with the information of a digital twin for space use in hospital real estate:

Within a time frame window, whereby they can choose to see historical, current or simulation data. By doing so, they can be informed by the past performance of the real estate resources. They can interact with real time sensor data that provide current information about the spaces of a hospital. They can also access simulated information such as patient journey or optimisation processes.

Within a building orientation window, whereby they can be oriented within the hospital campus and navigate to the location that is currently analysed by the digital twin. Therefore, the building information can be filtered through size and the user can orient themselves in the documentation of a complex real estate portfolio.

Within a user profile window, whereby information can be filtered out and tailor-made with according to the user's role in the hospital. Thus, sensitive information such as medical or financial will only be available to medical professionals and decision makers who have the authority to access this information. Additionally, it can function as an information filter and prevent any potential information overload.

Within a building visualisation window, whereby data will be overlayed on a building model and provide the main operational information of the display. The user can see the data annotated on top of a digital building model and grasp an overview of the performance that they are accessing.

Within a performance palettes window, whereby the user will be able to choose the information that they want to see, related with the performance of the hospital real estate. This window is the main control of the information types that the user of the digital twin can access.

The specifications of each window can be adjusted for each organisation. However, the main concepts of the thematic windows will remain to guide the interaction of the users with the information. In the following page, an updated conceptual framework with the findings of the three subquestions is presented, which displays the relationships among them and substantiates the conceptual design.

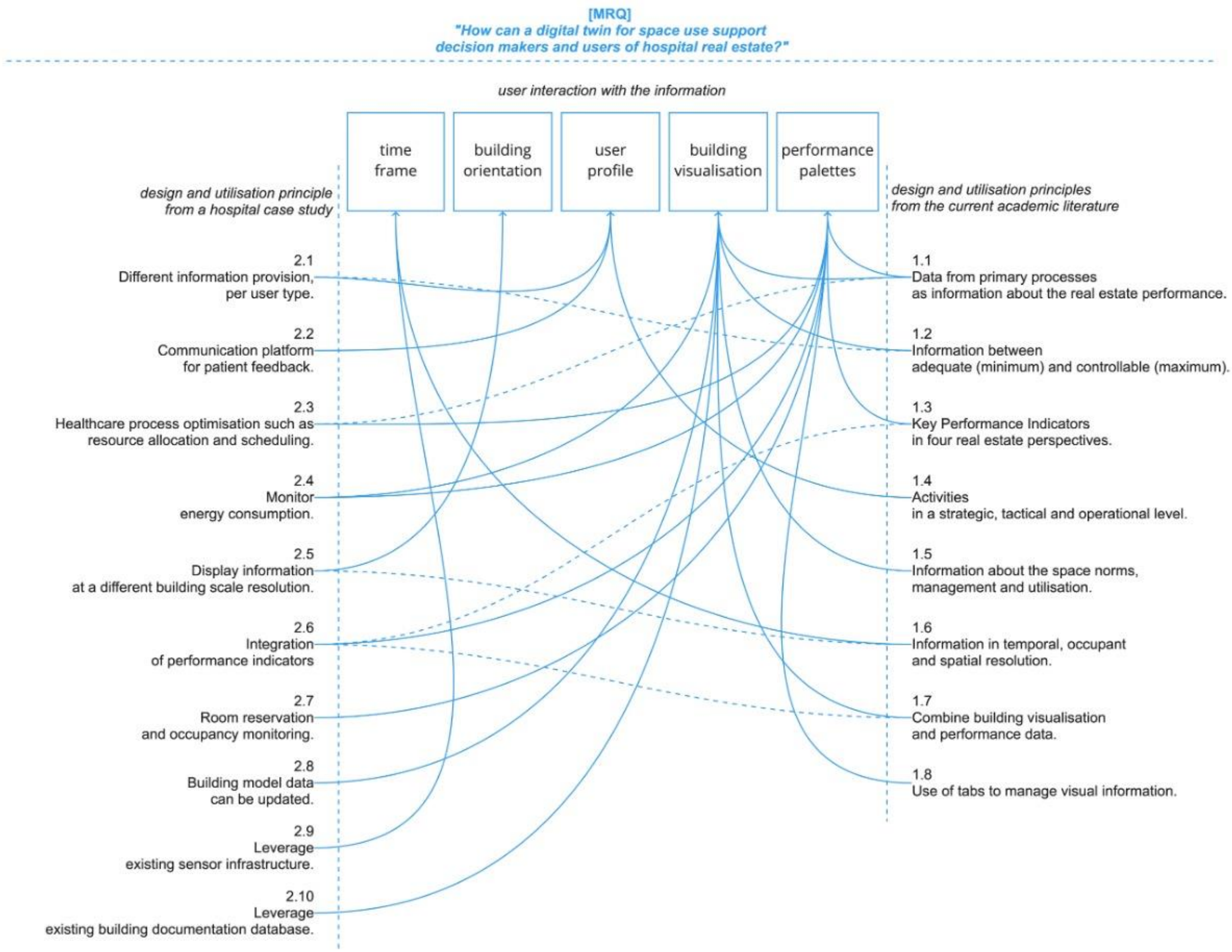


Figure 47:
Updated conceptual
framework based on [SQ3]
(source: author).

Chapter 6
Conclusions

The sixth and final chapter of the present report presents the conclusions of the graduation research. Starting with the discussion, section 6.1 elaborates on the limitations of the research and presents some further design suggestions. In section 6.2 the conclusion and the answer to the main question is presented. Finally, in section 6.3 some recommendations for practice and future research are presented.

6.1 Discussion

This section addresses two topics. In the limitations of the research, the reasons that restricted the research process and the outcomes are presented. In the further design suggestions, it is presented in the form of discussion a guide on how the iterations suggested by Hevner (2007) could occur. By designing the display for a different utilisation scenario and conducting an additional evaluation for this, some preliminary findings are presented.

6.1.1 Limitations of the research

One of the main limitations of the research, is the fact that it was conducted in a single case study. Only one hospital organisation was thus researched, thus lacking external empirical data. This may pose some limitations in the generalisation and theorisation of the research outcome (Blaikie & Priest, 2019). This is because the design research was developed specifically for the single case study and the evaluation came from decision makers and users who were already familiar with it. In a sense that would limit some aspects of the transferability to other healthcare organisations. For example, had the research been carried out in a smaller hospital with less diversity of functions, the findings are expected to be at a certain extend dissimilar.

Throughout the research process, the primary processes of the hospital had to be strictly respected. The ongoing pandemic COVID restrictions limited the availability of some of the interviewees and directed the research predominantly in the real estate management decision makers. Even though the focus is predominantly managerial and the interviewee selection is justified, more interviewees from the medical or user point of view could contribute to the research process.

The relatively nascent type of technology requires more development before it can be researched further. Digital twins as a technology are evolving quite rapidly in the last decade. This renders it a technology that is not mature enough and the constant technological advancements reveal even more functionalities and capacities for their deployment. As a result, they have not been yet widely adopted by the real estate sector, even though they have promising capabilities for assisting the relevant decision-making processes.

The anticipated timeframe for the research process was a limiting factor in the development and conduct of the research. Since it had to be fit within the educational requirements of a master programme, it had to be completed within the provisional time. Had this not been a limiting factor, additional research parameters could be introduced, such as more healthcare organisations, additional interviews or more design iterations of the digital twin.

A certain degree of researcher's bias may be apparent in the research. The limited experience of the researcher on similar technologies, on the managerial processes related with healthcare but also in the whole research process itself, may have led to some mistakes in the research choices. Had there been a longer exposure to similar types of research and bigger familiarity with these tools and processes, it is expected that the reliability of the research choices may have been better.

6.1.2 Further design suggestions

A recommendation for further research would be the development of further design suggestions. By utilising the design evaluation of the conceptual design (section 5.2), the display of the digital twin can be updated and recreated for certain utilisation scenarios. Thus, the design cycle of Hevner (2007) will conduct iterations. A suggestion would be to create an interface for each one of the three management focus utilisation scenarios (operational, tactical and strategic). By doing so, the design research can elaborate on how the decision makers and users of a digital twin would respond to different utilisation scenarios of the tool. Moreover, it can be assessed whether a design artefact would be developed more suitably for an individual building or service perspective (most suitable for an operational management focus) and for the portfolio perspective (mostly suitable for a strategic management focus) (Glatte, 2021).

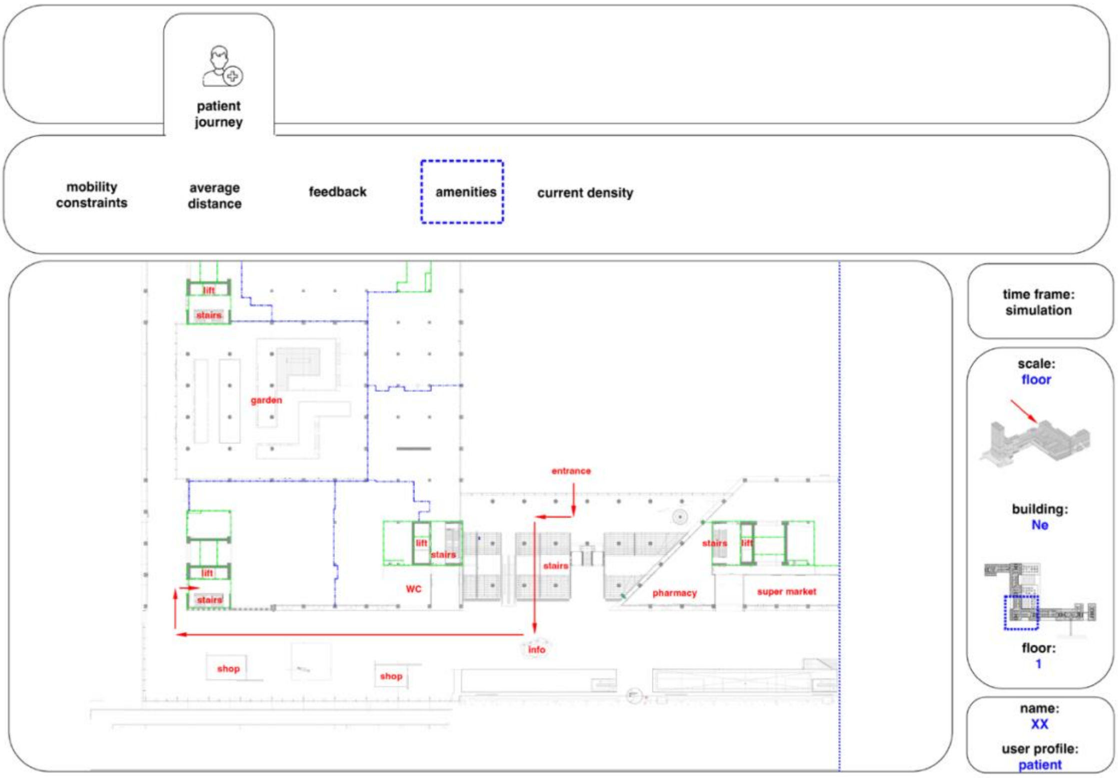


Figure 48: The display of the GUI according to a utilisation scenario of a patient journey (source: author)

An example was made using the patient journey as a utilisation scenario at operational level. As seen on the figure above, a design iteration was made on the display of the conceptual design (section 5.1). Only this time, the interface was adjusted for the requirements of a patient journey. The time frame window is displaying simulation, since it is a simulation event, therefore is not realised in a past time. The building orientation window is providing information on the orientation of the first floor of building Ne, which is the entrance and the beginning of the patient journey. The user profile window is displaying the name of the patient and the user profile *patient*. In this case, the patient would have used his name and his patient number and through the information system for medical records (for the scenario of EMC that would be HiX), their appointment with a specialist would be retrieved. The building visualisation window was recreated to display a suggested patient journey for a patient who enters the hospital and is directed to the second floor of the building Ne for examination with a specialist. A set of red arrows can direct them through the first floor in the shortest possible route for their destination.

On the performance palettes window, the palette *patient journey* is automatically locked as an option and, for the example, the performance indicator *amenities* is chosen. This indicator leads to a display of names of potential amenities that the patient can make use of in the hospital that are near their path. In this example those are the amenities of the first floor of building Ne, thus an info kiosk, two shops, WC facilities and a garden are displayed. Four other performance indicators can be chosen by the potential user of the display, as seen on the table below.

Table 27:
The performance indicators for the scenario of a patient journey (source: author).

selection performance indicators	description	information requirements
mobility constraints	The mobility constraints performance indicator leads to an option where the user (patient) can input their mobility constraints, for example use of wheelchair or crutches. By toggling this indicator on, the patient journey would be reconfigured in order to suggest routes that would not include stairs and but only lifts or other transportation means, so that the patient can overcome their mobility constraints in their journey.	This selection would require an indication of the mobility obstacles on each floor of the hospital, such as stairs or other types of difficult to access areas for people with mobility constraints. This information would be mapped on the building documentation and the algorithm that would define the patient journey would have to be reconfigured accordingly. Additionally, data from the medical database could be retrieved for the patient's mobility condition. This would automatically suggest the route that minimises the obstacles. Some privacy issues may arise however when it comes to the introduction of medical data to the system of the digital twin.
average distance	This indicator would display the total average distance towards the patient's destination. It could be available in order to inform the patient whether they would have to walk a high distance or not and to plan accordingly their time and effort in order to reach their destination.	This selection would require a geometric calculation of the distance in the patient journey. It can be applied on the building documentation files with regular algorithms, similar to ones use in the design process of a CAD drawing.
feedback	This indicator could be chosen by the user of the digital twin in order to give them the option to introduce feedback on a certain space, or amenity of the hospital. For example, after the use of a WC or upon the interaction with an entertaining artwork, the hospital visitor can share their opinion with the administrators of the digital twin. by doing so, the digital twin can function as a platform for interaction with the visitor and the decision makers of the hospital spaces.	This selection would provide a pop-up window, whereby the user can write their feedback on the chosen location of the building. It can be either private or public. Decision makers who will be overlooking this generated information would get a notification with the feedback, thus informing them on how the spaces of the hospital perform.
amenities	This indicator, like in the example of display would suggest several amenities that are available in the proximity of the patient's journey. Their aim is to inform the patient about the spaces that they can use and suggest to them several functions that lie upon their reach. It is proposed in order to minimise the complexity of the building functions and the building layouts of the campus.	This selection would require information about the amenities that are available within the proximity of the patient journey. It can be introduced as text information mapped accordingly on the location of the amenities on the building visualisation window.
current density	The current density window will indicate highly occupied areas. This choice is suggested as a tool for the assistance in the combat of pandemics such as the COVID19 and other highly transmissive viruses whereby a minimum distance is required.	Information can be retrieved from real time occupancy data of the spaces. Furthermore, information from medical systems could be used in order to indicate whether someone with a highly transmissive disease is present at a certain space. Privacy concerns will have to be dealt with in order to minimise any undesirable use of patient data.

An evaluation interview was conducted with a medical professional (B.1, 2022), that was interviewed as well in the first evaluation set of interviews (section 5.2). In the first interview the medical professional mentioned:

"*Especially the patient journey, I'm really enthusiastic about. Because a lot of patients cannot find the right department cannot find the right rooms. And the Erasmus is very big. So, I am enthusiastic about that, about the map thing*." (A2, 2021)

The aim of this interview was to assess how a medical professional who is familiar with the patient journey processes, but also the space of the hospital sees the display and what feedback they would provide to it.

Proposed change	Type of change	Suggested by
Use the logo of the shops in the respective amenities' location. That would make it more recognisable for them.	addition	B.1
Use a small figure in the indicators, for example a wheelchair in the mobility constraints that would make them more recognisable by the users.	addition	B.1
The density indicator could provide information about the waiting area that the patient may have to go to.	modification	B.1

Table 28: Proposed changes on the display of the patient journey scenario (source: author).

It should be noted that the interviewee (B.1, 2022) initially mentioned that a potential bias could be in the assessment of the display, because they are familiar with the spaces of the hospital, since they work there on an everyday basis. For a first-time visitor of the hospital that would be more difficult since they are not as familiar with the spaces as them. However, the interviewee assessed the readability of the display as being clear and comprehensible (B.1, 2022). They suggested some changes on the tool as seen on the table above and some opportunities and challenges in using it (table below). Finally, the interviewee mentioned that it is similar to some tools that are currently being developed by the organisation that display similar information (B.1, 2022), thus validating the relevance of the intentions of the organisation to develop a similar tool.

Opportunities	Suggested by	Perspective
The display of the retail amenities could work as an advertisement for the accommodated retail organisations; thus, a fee could be introduced.	B.1	financial
The visitors can be directed to specific paths, thus controlling the functional patient flow in the hospital.	B.1	functional
Less employees or volunteers will be required that are currently tasked to assist the patients in the wayfinding process.	B.1	functional/financial
Wayfinding can be easier in the campus, which is constantly becoming more complex.	B.1	functional/strategic
Challenges	**Identified by**	**Perspective**
There are many people who are not familiar with similar tools and may find it difficult to learn how to use one. An introduction can be used.	B.1	functional
Privacy concerns may arise, however there is already a specific department in the EMC that works on privacy related challenges on shareability of data.	B.1	functional
The tool will need to be adjusted for the different devices that will be using different operating systems and eventually varying screen real estate and user interfaces	B.1	functional
The employees will need to be trained on how to use the tool, since there are already many tools that are being used by the organisation.	B.1	functional

Table 29: Proposed opportunities and challenges of the patient journey scenario (source: author).

6.2 Conclusion

The answer to the main research question is a synthesis of the answers of the three subquestions. Therefore, it draws information from an overview of design and utilisation principles that were identified in the previous sections, together with the design development and evaluation process of the digital twin.

[MRQ]
"How can a digital twin for space use
support decision makers and users of hospital real estate?"

It can be concluded that by operationalising design and utilisation principles that are traced from a literature review, design and utilisation principles that can be identified in a hospital case study, a digital twin can be developed using as a display the synthesis of a time frame window, a building orientation window, a user profile window, a building visualisation window and a performance palettes window. The evaluation of the conceptual design of a display of a graphical user interface of a digital twin, by key stakeholders that represent decision makers and users of hospital real estate, validates the design choices. Furthermore, by extracting potential utilisation scenarios from the interviewees, it was noted that they all conveyed information relevant to the stakeholder perspectives (den Heijer, 2011), in three time dimensions, across all buildings scales and to pursue objectives of all three types of management focus (Glatte, 2021).

Therefore, aiming to answer the main research question, a digital twin can be used by different stakeholder perspectives, by providing historical, real time or simulation information at a room, floor, building or campus scale resolution to support operational, tactical and strategic utilisation processes. The stakeholder perspectives represent the diversity of the potential users of the digital twin but also the filtering of relevant information for its use. The historical, real time or simulation data refer to the time dimension of the utilised information. Historical data can be retrieved from databases and deployed for decision making that has a hindsight direction, the real time refers to sensor data that are collected from within the spaces of a hospital and provide the users an overview of the current performance of several aspects of the hospital. The simulation data types are related with data that can be generated by conducting simulations about the future performance of the hospital spaces, such as a patient journey. The room, floor, building or campus scale resolution refers to the scale outreach the information provision can have. By controlling the scale of the displayed information, a balance can be ensured between adequate (minimum) and controllable (maximum) amount of data. Finally, the operational, tactical and strategic utilisation processes refer to the fact that a digital twin for space use can support decision makers and users of hospital real estate in a plethora of utilisation scenarios, across all range of potential management focus.

6.3 Recommendations

The recommendations are divided in recommendations for practice and recommendations for further research. Those two groups of advice are based on several points that were identified throughout the whole research process. The former aim to advice real estate practitioners who deploy such tools in the decision-making process. The latter aim to advice future researchers who wish to conduct further research on the topic of digital twins for space use in hospital real estate.

6.3.1 Recommendations for practice

The first recommendation for practice is to facilitate cross-organisation collaboration to reduce the silo effect in data sharing. As it was pointed out in the hospital case study analysis, due to the high complexity and big scale of the medical center, the organisational structure was highly fragmented and as a result, several departments rarely collaborated with one another, especially at lower levels. However, two of these departments may have been deploying complementary data and therefore, miss the benefits from each other's data sharing.

The second recommendation is to develop information system infrastructure with integration in mind. The benefits of technologies enabled through internet of things are already widespread. However, many vendors for private reasons offer products that cannot be easily integrated in bigger systems. This makes system developers dependent on complex system integrators, which are often expensive.

Another suggestion is to streamline building documentation digitalisation process. The building documentation digitalisation means are constantly developing and offering more possibilities. However due to the high complexity of the hospital buildings but also the hindrances of the construction processes cause a mismatch between building documentation and reality. By deploying high standards in building digitalisation such as in building information modelling, this streamline can be facilitated.

The development of digital tools usually occurs from decision makers and development professionals sometimes without actively involving the perspective of the end users. For the digital twins for space use in hospitals it is suggested to involve both decision makers and users in tool development. By doing so, the opinion of the users can be considered, thus leading to a tool which can better support their needs.

It is suggested to acknowledge potential security issues and act upon any privacy concerns. Many research publications but also interviewees underlined the issue of privacy when it comes to sharing data in a tool like the digital twins. The utilised data should respect at all costs the users' privacy by filtering out identification information and other potentially sensitive data. Also, fostering the security of the system to prevent any data breaches or security violations that could occur on publicly accessible digital tools.

6.3.2 Recommendations for future research

It is suggested that future research on the same topic could be conducted in a comparative manner that would involve more hospital case studies. By doing so, the impact of the differences of the case studies in the development of digital twins can be compared. Eventually, organisational and building parameters can be assessed on the extend and the way that they can influence the requirements and the utilisation of a digital twin for space use. This is because the present research focused on a single organisation that is characterised by specific characteristics that dictated the design of the digital twin and thus the results of the research.

It is recommended to conduct further similar research on other types of real estate. Even though digital twins are likely to contribute in a more efficient manner of administering hospital real estate (see research context), it is expected that similar results can occur on other types of real estate. For example, research on the design of a digital twin for space use in retail real estate would yield results within the real estate management theory, however applicable to a different asset class.

Another recommendation would be that of the analysis of the perspective of the supply side in the development of such a tool. The present research studied the tool and the development of it from the perspective of the end user, being the decision makers and users of hospitals. A similar study could be carried out from the perspective of the developers of digital twins, such as software developers, information architects and other specialists who could participate in its development. Such research is expected to provide a more technical interpretation to the characteristics of digital twins.

While digital twins are still a nascent technology and there are not many use cases where these tools are already deployed, it is recommended to assess the impact of such tools in the future. This type of research is likely to shed light upon the usefulness and the potential bottlenecks a digital twin can create when it is in use. It would be interesting if this research would not be conducted under the framework of design research but probably in a quantitative or qualitative manner.

The present research focused on the application and the digital-model integration layer of the system architecture of a digital twin. Another recommendation for future research would be to focus on a different layer of the system architecture of a digital twin, for example the data acquisition layer. In that case, the leveraged data and the sensor inputs and networks could be analysed. By doing so, different parameters that determine the design and the utilisation of a digital twin can be analysed.

References

Adamenko, D., Kunnen, S., & Nagarajah, A. (2020, June). Comparative analysis of platforms for designing a digital twin. In Design, Simulation, Manufacturing: The Innovation Exchange (pp. 3-12). Springer, Cham.

Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. (2021). Digital twin as a service (DTaaS) in industry 4.0: an architecture reference model. *Advanced Engineering Informatics*, *47*, 101225.

Al-Sehrawy, R., Kumar, B., & Watson, R. (2021). A digital twin uses classification system for urban planning & city infrastructure management. *Journal of Information Technology in Construction (ITCON)*, *26*, 832-862.

Alvanchi, A., & Seyrfar, A. (2020). Improving facility management of public hospitals in Iran using building information modeling. Scientia Iranica, 27(6), 2817-2829.

Atkin, B., & Bildsten, L. (2017). A future for facility management. Construction Innovation.

Atkin, B., & Brooks, A. (2021). Total facility management.

Blaikie, N., & Priest, J. (2019). Designing social research: The logic of anticipation. John Wiley & Sons.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*, 103179.

Bryman, A. (2016). *Social research methods*. Oxford university press.

Bytheway, A. (2014). The information management body of knowledge. In Investing in Information (pp. 25-34). Springer, Cham.

Cayirli, T., & Veral, E. (2003). Outpatient scheduling in health care: a review of literature. *Production and operations management*, *12*(4), 519-549.

Christensen, K., Melfi, R., Nordman, B., Rosenblum, B., & Viera, R. (2014). Using existing network infrastructure to estimate building occupancy and control plugged-in devices in user workspaces. *International Journal of Communication Networks and Distributed Systems*, *12*(1), 4-29.

Collinson, A., Robertson, R., & Pitchford, J. (2019). Digital twinning in real estate Humanizing buildings with Industry 4.0. REflexions - Issue 9, 8–13.

Den Heijer, A. (2011). *Managing the University Campus: Information to support real estate decisions*. Eburon Uitgeverij BV.

Diez, K., & Lennerts, K. (2009). A process-oriented analysis of facility management services in hospitals as a basis for strategic planning. *Journal of Facilities Management*.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.

Edmunds, A., & Morris, A. (2000). The problem of information overload in business organisations: a review of the literature. *International journal of information management*, *20*(1), 17-28.

Erasmus MC. (2018). Oour new Erasmus MC. Erasmusmc.Nl. Retrieved June 27, 2022, from https://www.erasmusmc.nl/-/media/erasmusmc/pdf/2-themaoverstijgend/vastgoed/brochure-our-new-erasmusmc-english.pdf

Erasmus MC. (2019). *Koers23: Technologie & Toewijding*. https://www.erasmusmc.nl/-/media/erasmusmc/pdf/2-themaoverstijgend/koers-23-technologie-en-toewijding-nl.pdf

Erasmus MC & Programma Integrale Bouw. (2019). *Vastgoed op koers 35*. https://www.erasmusmc.nl/-/media/erasmusmc/pdf/2-themaoverstijgend/vastgoed/vastgoed-op-koers-35.pdf

Erasmus MC. (2022a). *Over Erasmus MC*. Erasmusmc.Nl. Retrieved March 18, 2022, from https://www.erasmusmc.nl/nl-nl/pages/over-erasmusmc

Erasmus MC. (2022b). *Vastgoed Erasmus MC*. Erasmusmc.Nl. Retrieved June 27, 2022, from https://www.erasmusmc.nl/nl-nl/patientenzorg/vastgoed-erasmus-mc

Erasmus MC. (2022c). *Jaarverslag 2021*. https://www.erasmusmc.nl/-/media/erasmusmc/pdf/2-themaoverstijgend/jaarverslag-2020.pdf

Erasmus MC. (2022d). *Duurzaamheidsverslag 2021*. *https://www.erasmusmc.nl/-/media/erasmusmc/pdf/2-themaoverstijgend/erasmusmc_duurzaamheidsverslag_2021_def.pdf*

Errandonea, I., Beltrán, S., & Arrizabalaga, S. (2020). Digital Twin for maintenance: A literature review. Computers in Industry, 123, 103316.

Few, S. (2006). Information dashboard design: The effective visual communication of data (Vol. 2). Sebastopol, CA: O'reilly.

Fleming, S., Apps, N., Harbon, P., & Baldock, C. (2012). Assessing space utilisation relative to key performance indicators–how well, not how much, space is used. Journal of Higher Education Policy and Management, 34(5), 503-515.

Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA* (p. 1818).

Glatte, T. (2021). *Corporate Real Estate Management*. Springer Fachmedien Wiesbaden.

Goble, E. (1960). Hospital planning starts with circulation. *Hospitals Clinics, and Health Centers*, 2.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behaviour in complex systems. In Transdisciplinary perspectives on complex systems (pp. 85-113). Springer, Cham.

Grigg, S. J., Garrett, S. K., & Miller, M. K. (2009). Helping a hospital shine: workflow and space utilization aid South Carolina residents. Industrial Engineer, 41(10), 24.

Halmetoja, E. (2022). The Role of Digital Twins and Their Application for the Built Environment. In *Industry 4.0 for the Built Environment* (pp. 415-442). Springer, Cham.

Haynes, B., & Nunnington, N. (2010). Corporate real estate asset management: strategy and implementation. Estates Gazette.

Haynes, B., Nunnington, N., & Eccles, T. (2017). Corporate real estate asset management: Strategy and implementation.

Hessel, M. (2004), "Standardprozessmodell fu¨r Klinische Pfade", in Greiling, M. (Ed.), Pfade durch das Klinische Prozessmanagement, Methodik und aktuelle Diskussionen, Verlag W. Kohlhammer, Stuttgart, pp. S.27-S.41.

Hevner, A. R. (2007). A three cycle view of design science research. Scandinavian journal of information systems, 19(2), 4.

Heywood, C., & Arkesteijn, M. (2017). Alignment and theory in corporate real estate alignment models. *International Journal of Strategic Property Management*, *21*(2), 144-158.

Jaakkola, H., & Thalheim, B. (2011). Architecture-driven modelling methodologies. In *Information Modelling and Knowledge Bases XXII* (pp. 97-116). IOS Press.

Jensen, P. A., & van der Voordt, T. (2016). *Facilities management and corporate real estate management as value drivers: how to manage and measure adding value*. Taylor & Francis.

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36-52.

Jylhä, T., Remøy, H., & Arkesteijn, M. (2019). Identification of changed paradigms in CRE research–a systematic literature review 2005-2015. Journal of Corporate Real Estate.

Karakra, A., Fontanili, F., Lamine, E., Lamothe, J., & Taweel, A. (2018, October). Pervasive computing integrated discrete event simulation for a hospital digital twin. In *2018 IEEE/ACS 15th international conference on computer systems and Applications (AICCSA)* (pp. 1-6). IEEE.

Karakra, A., Fontanili, F., Lamine, E., & Lamothe, J. (2019, May). HospiT'Win: a predictive simulation-based digital twin for patients pathways in hospital. In *2019 IEEE EMBS international conference on biomedical & health informatics (BHI)* (pp. 1-4). IEEE.

Karakra, A., Lamine, E., Fontanili, F., & Lamothe, J. (2020, September). HospiT'Win: a digital twin framework for patients' pathways real-time monitoring and hospital organizational resilience capacity enhancement. In *International workshop on innovative simulation for healthcare* (pp. 62-71). CAL-TEK Srl.

Khandal, D., & Jain, S. (2014). Li-fi (light fidelity): The future technology in wireless communication. *International Journal of Information & Computation Technology*, *4*(16), 1687-1694.

Klein, L., Li, N., & Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in construction*, *21*, 161-171.

Kritzinger W., Karner M., Traar G., Henjes J. & Sihn W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. IFACPapersOnLine, 51(11), 1016-1022.

Koch, C., Hansen, G. K., & Jacobsen, K. (2019). Missed opportunities: two case studies of digitalization of FM in hospitals. Facilities.

Krumm, P., Dewulf, G. and De Jonge, H. (2000), "What is corporate real estate?", in Dewulf, G., Krumm, P. and De Jonge, H. (Eds), Successful Corporate Real Estate Strategies, Arko Publishers, Nieuwegein, pp. 27-33.
Kunders, G. D. (2004). *Hospitals: facilities planning and management*. Tata McGraw-Hill Education.

Küsel, K. (2020). Model-Based System Engineering for Life Cycle Development of Digital Twins of Real Estate. INCOSE International Symposium, 30(1), 715–730. doi:10.1002/j.2334-5837.2020.00750.x

Lehr, W., & McKnight, L. W. (2003). Wireless internet access: 3G vs. WiFi?. *Telecommunications Policy*, *27*(5-6), 351-370.

Li, L., Yuan, J., Roper, K. O., & Zhou, Z. (2017a). A multi-stakeholder delphi study to determine key space management components for elderly facilities in China. *Sustainability*, *9*(9), 1565.

Li, L., Yuan, J., Ning, Y., Shao, Q., & Zhang, J. (2017b). Exploring space management goals in institutional care facilities in china. *Journal of Healthcare Engineering*, *2017*.

Li, L., & Benton, W. C. (2003). Hospital capacity management decisions: Emphasis on cost control and quality enhancement. European Journal of Operational Research, 146(3), 596-614.

Liu, W., Zhang, W., Dutta, B., Wu, Z., & Goh, M. (2020). Digital twinning for productivity improvement opportunities with robotic process automation: Case of greenfield hospital. *International Journal of Mechanical Engineering and Robotics Research*, *9*(2), 258-263.

Lohman, F. A. B. (1999). The Effectiveness of Management Information-A design approach to contribute to organizational control.

Lu, Q., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., & Heaton, J. (2019). Developing a dynamic digital twin at a building level: Using Cambridge campus as case study. In *International conference on smart infrastructure and construction 2019 (ICSIC) driving data-informed decision-making* (pp. 67-75). ICE Publishing.

Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., ... & Schooling, J. (2020a). Developing a digital twin at building and city levels: Case study of West Cambridge campus. *Journal of Management in Engineering*, *36*(3), 05020004.

Lu, Q., Chen, L., Li, S., & Pitt, M. (2020b). Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. Automation in Construction, 115, 103183.

Lu, Q., Ye, Z., Fang, Z., Meng, J., Pitt, M., Lin, J., ... & Chen, L. (2021). Creating an inter-hospital resilient network for pandemic response based on blockchain and dynamic digital twins. In *2021 Winter Simulation Conference (WSC)* (pp. 1-12). IEEE.

Mautz, R. (2012). Indoor Positioning Technologies. (Habilitation Thesis). ETH Zurich, Zurich.

Minior, S., Hanafin, N., & Bringhurst, F. R. (2004). Research Space Management-A Dynamic Process for Optimal Space Utilization and Strategic Planning. *Massachusetts General Hospital*.

Moatari-Kazerouni, A., Chinniah, Y., & Agard, B. (2015). Integration of occupational health and safety in the facility layout planning, part II: design of the kitchen of a hospital. *International journal of production research*, *53*(11), 3228-3242.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group*. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals of internal medicine, 151(4), 264-269.

Osgood, R.T. Jr. (2009), “Survey results and practical experience with the Fortune 1000”, CoreNet Global, Atlanta.

Pecoraro, F., Luzi, D., & Clemente, F. (2021). The efficiency in the ordinary hospital bed management: A comparative analysis in four European countries before the COVID-19 outbreak. Plos one, 16(3), e0248867.

Peng, Y., Zhang, M., Yu, F., Xu, J., & Gao, S. (2020). Digital twin hospital buildings: an exemplary case study through continuous lifecycle integration. *Advances in Civil Engineering*, *2020*.

Rodriguez-Labajos, L., Thomson, C., & O'Brien, G. (2016, September). Exploring the attributes and KPI's adopted by international healthcare providers to measure the performance of their estates at the strategic level. In *Proceedings of the 32nd Annual ARCOM Conference* (pp. 1213-1223). ARCOM.

Scarborough, H. , Piercey, . W. Douglas and Fralick, . Pamela C. (n.d.). hospital. Encyclopedia Britannica. https://www.britannica.com/science/hospital

Serraview. (2015). Managing Workplace Utilization. IoT & Other Technologies for Tracking Workplace Utilization. Retrieved from http://info.serraview.com/workplace-utilization-free-guide

Silva, B. N., Khan, M., & Han, K. (2018). Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustainable Cities and Society*, *38*, 697-713.

Simon, H. A. (1996). The sciences of the artificial. MIT press.

Sliteen, S., Boussabaine, H., & Catarina, O. (2011). Benchmarking operation and maintenance costs of French healthcare facilities. *Journal of Facilities Management*.

Song, Y., & Li, Y. Digital Twin Aided Healthcare Facility Management: A Case Study of Shanghai Tongji Hospital. In *Construction Research Congress 2022* (pp. 1145-1155).

Space Management Group. (2006). Space utilisation: practice, performance and guidelines. Retrieved from: http://www.smg.ac.uk/index.html

Starr, C. W., Saginor, J., & Worzala, E. (2020). The rise of PropTech: emerging industrial technologies and their impact on real estate. Journal of Property Investment & Finance.

Steins, K. (2017). Towards increased use of discrete-event simulation for hospital resource planning (Doctoral dissertation, Linköping University Electronic Press).

Tett, G. (2015). The Silo Effect: Why putting everything in its place isn't such a bright idea. Hachette UK.

Trivedi, D., & Badarla, V. (2019). Occupancy detection systems for indoor environments: A survey of approaches and methods. Indoor and Built Environment, 0(0), 1-17. doi:https://doi.org/10.1177/1420326X19875621

Valks, B., Arkesteijn, M. H., Den Heijer, A. C., & Putte, H. J. V. (2018). Smart campus tools–adding value to the university campus by measuring space use real-time. Journal of Corporate Real Estate.

Valks, B. (2021). Smart campus tools: Technologies to support campus users and campus managers. *A+ BE| Architecture and the Built Environment*, (18), 1-456.

Valks, B., Arkesteijn, M. H., Koutamanis, A., & den Heijer, A. C. (2021a). Towards a smart campus: supporting campus decisions with Internet of Things applications. Building Research & Information, 49(1), 1-20.

Valks, B., Arkesteijn, M., Koutamanis, A., & Den Heijer, A. (2021b). Towards smart campus management: Defining information requirements for decision making through dashboard design. *Buildings*, *11*(5), 201.

van der Voordt, D. J. M., Prevosth, J., & van der Zwart, J. (2012). Adding value by FM and CREM in Dutch hospitals. The added value of facilities management: concepts, findings and perspectives, 2012, blz. 205-222.

van der Zwart, J. (2014). Building for a better hospital: Value-adding management & design of healthcare real estate. TU Delft.

van der Zwart, J., Arkesteijn, M. H., & van der Voordt, D. J. M. (2009). Ways to study corporate real estate management in healthcare: an analytical framework. In Proceedings HaCIRIC.

van der Zwart, J., & van der Voordt, T. J. (2016). Adding value by hospital real estate: An exploration of Dutch practice. HERD: Health Environments Research & Design Journal, 9(2), 52-68.

Yang, X., & Ergan, S. (2014). Evaluation of visualization techniques for use by facility operators during monitoring tasks. Automation in Construction, 44, 103-118.

Yin, R. K. (2009). *Case Study Research: Design and Methods* (4th ed.). Thousand Oaks, CA: SAGE Publications.

Wauters, B (2005) The added value of facilities management: Benchmarking work processes. Facilities, 23(3/4), 142-151.

Wiggins, J. M. (2020). *Facilities manager's desk reference*. John Wiley & Sons.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., ... & Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific data*, *3*(1), 1-9.

Winch, G. M. (2010). *Managing construction projects*. John Wiley & Sons.

Zalacain. (n.d.). *Wayfinding consultancy for the biggest hospital in The Netherlands*. Retrieved June 12, 2022, from http://www.zalacain.com/projects/erasmus-mc

Zeigler, B. P. (2014, August). The role of Modeling and Simulation in coordination of health care. In *2014 4th International Conference On Simulation And Modeling Methodologies, Technologies And Applications (SIMULTECH)* (pp. IS-5). IEEE.

Zhong, X., Babaie Sarijaloo, F., Prakash, A., Park, J., Huang, C., Barwise, A., ... & Dong, Y. (2022). A multidisciplinary approach to the development of digital twin models of critical care delivery in intensive care units. *International Journal of Production Research*, 1-17.

Zijlstra, E., Mobach, M. P., Van Der Schans, C., & Hagedoorn, M. (2014). Facilities planning promoting efficient space use at hospital building. In *13th EuroFM Research Symposium* (pp. 366-377).

Zurmatai, J. (2020). Investigating the Performance of Smart Buildings and Intelligent Building Management System (BMS). Turkish Journal of Computer and Mathematics Education (TURCOMAT), 11(2), 726-734.

Towards digital twins for space use in hospital real estate.

Appendices

Appendix 1 - Interview protocol
Evaluating the conceptual design

Interviewer: Zisis Vomvas
Title: Towards digital twins of space use in hospital real estate
Interviewee: [name]
Organisation: Erasmus Medical Center
Role: [role of interviewee]

I. Introduction
Good morning/afternoon! Thank you again for giving me your time and allowing me to interview you today.

I am Zisis Vomvas, a student from TU Delft currently working on my graduation thesis entitled "Towards digital twins of space use in hospital real estate". As part of it, I focus on answering the research question: "How can a digital twin for space use support decision makers and users of hospital real estate?". In order to do so, a graphical user interface (GUI) of a digital twin is designed and assessed by key decision makers that influence space management in a hospital context. In this research project it is aimed to develop a list of specifications for a digital twin that can be utilized for the development of similar tools.

This is the first of two consecutive interview rounds. In this round, the aim is to evaluate the conceptual design of the GUI of a digital twin. The interview is structured around 4 themes:

1. Decision making processes related to the use of space in a hospitals
2. Evaluation of the current layout of GUI of the DT
3. Utilisation of the tool
4. Feasibility of its deployment.

All the information shared during this interview will remain anonymous and will only be used for the sole purpose of this research. Your informed consent has been collected as a proof that you have agreed to participate in the interview.

The following process will last approximately 50 to 60 minutes. As we go through the questions, feel free to stop me at any time, if you would like any clarifications or feel the need to take a break.

I would like to ask for your permission to record the interview. The recordings will be properly stored and anonymised with respect to your privacy.

[start recording]

The interview is now being recorded. Once again, I would like to ask for your confirmation thereof.
II. Questions
1. Background
    a. Could you briefly describe your **position in the hospital**?
    b. Can you explain a **typical workday** and some of the **daily tasks** and responsibilities that you perform at the hospital?
    c. What type of **information** do you consider important in order to perform these tasks?
    d. Could you tell me whether you use any **software or tool** to perform these tasks?
        i. Are you satisfied with this tool?
        ii. Are there any challenges when using this tool?

[present the GUI mock-up: explain the different windows, the different user profiles, the visual information of the building and the navigation windows and delve into the categories of the dashboard]

2. Evaluate the current **layout of GUI** of the DT.
    a. Is the layout of the tool, **comprehensive** to you?
    b. Do you understand the different **thematic areas** of each window?
        i. User profiles?
        ii. Scales?
        iii. Time frames?
        iv. Categories?
    c. Would you like to suggest any **changes** on the layout of the tool?

3. Utilisation of the tool
    a. Can you think of **conducting any of the previous tasks** with the help of this tool?
    b. Can you think of **any other everyday task** that could be assisted by using such a tool?
    c. Do you think there is some **type of information that is missing** and would be useful for your everyday tasks?
    d. Is there, maybe some **information** that would be **unnecessary** and superfluous?

4. Feasibility of deployment
    a. Could you identify any potential **opportunities** on using such a tool?
        i. Financial
        ii. Functional
        iii. Strategic
        iv. Physical
        v. User-oriented

b. Could you identify any potential **challenges** in deploying this tool?
   i. Financial
   ii. Technical
   iii. Related to privacy

III. Conclusion

The previous question marked the end of the planned part of the interview.

In case you would like to add something, feel free to do so. At this point you can ask any question that may have arisen to you throughout the interview.

I will now stop recording.

[stop recording]

As a next step, the recording will be transcribed and analysed. This is being done in to synthesise the interview findings in a systematic way that will form an input for the design development of the Digital Twin.

In the following January you will be contacted again for a second interview round. This will be conducted similarly, in order to evaluate the preliminary design of the GUI. This will have a more detailed form than the current one and will be updated based on the findings of the first interview.

I am sincerely thankful for your time and effort to participate in this interview. Your contribution is a valuable part of my research and can be used to improve the way tools that assist the decision making of hospital real estate are developed. The recording will be handled with all the necessary processes that will safeguard both the academic integrity and your individual rights as an interviewee.

The results of the research can become available to you once the graduation project is completed.

Appendix 2 - Interview introduction note

Dear [name of interviewee],

The following document is part of your invitation for your participation as an interviewee for my research entitled: "Towards digital twins of space use in hospital real estate". This research is conducted for my graduation project for my master studies in Management in the Built Environment at the faculty of Architecture at the Delft University of Technology. The aim of this research is to identify specifications for the deployment of digital twin technologies in the management of hospital real estate. This will be approached by designing a graphic user interface of such a tool and exploring its capabilities. The results will be in the form of specifications of digital twins that can be utilised by hospital real estate decision makers or developers of similar tools.

In order to do so, a selection of hospital stakeholders was made that represent the real estate management perspective (for example a real estate policy advisor) and the user perspective (for example a medical specialist). The design development is being carried out in parallel with the interview sessions and therefore, it is necessary to conduct two consecutive interview rounds oriented towards the assessment of the current design phase of the mock-up. The interviews will have a semi-structured form: they will be structured by specific topics of discussion whereby the interviewees can express their professional experience and opinion without being limited to a list of strictly predefined questions.

For the first round of the interviews, it is aimed to identify potential events and daily workflows of the interviewees that can be assisted by a digital twin for space use. The conceptual design of the mock-up will be presented, and the interviewees will be prompted to participate in a discussion on how the tool can be used. Furthermore, it is aimed to assess types of information that can be integrated in the digital twin. The results of the first round of interviews will be used as an input for the design development of the preliminary design. This part will be assessed in a similar manner in a second round of interviews. In this round, the same interviewees will be approached again to assess the mock-up, only this time it will be more developed, and the discussions will be directed to more specific aspects of its functionality. Similar to the first round, the output of the second round will be utilised to further develop the mock-up to its detailed design.

The duration of the interviews will be approximately 50 to 60 minutes. The first round will be conducted in December 2021 and the second in January, 2022. I would like to request your permission to record the interview and transcribe it accordingly. All the data will be anonymised and used for the sole purpose of research.

Finally, I would like to ask you to fill in and sign the Consent Form of the next page and email it back in a PDF version. The form will be signed on behalf of the researcher and returned to you.

If you have any questions about the research, you can always contact me at the following email: Z.Vomvas@student.tudelft.nl.

Kind regards,
Zisis Vomvas

Appendix 3 - Interview consent form

Interviewer : Zisis Vomvas
Research title : Towards digital twins of space use in hospital real estate.
Interviewee : [name of interviewee]

Please tick the appropriate boxes	Yes	No
1. Taking part in the study		
• I have read and understood the study information. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
• I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
• I understand that taking part in the study involves participating in a semi-structured interview by answering questions and providing information. The interview will be recorded and analysed only for research purposes. It will be anonymised and the recording will be destroyed when the research project is complete.	☐	☐
2. Use of the information in the study		
• I understand that information I provide will be used for an educational purpose by being incorporated in a graduation thesis report and its presentation at TU Delft.	☐	☐
• I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
• I agree that my information can be quoted in the research output and anonymised accordingly.	☐	☐
• I understand that in the scenario of the research being published, my identification as a participant will not be possible.	☐	☐
3. Future use and reuse of the information by others		
• I give permission for the information that will be provided through the interviews to be used for a thesis report. The report will published in the education repository of TU Delft and can be used for future research and learning.	☐	☐
4. Research output		
• I would like to be informed about the final output of this research. In that case, I would like the researcher to keep my contact information (email) and inform me about it at the end of the research.	☐	☐

Signatures

______________________ ____________________ _________
Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Zisis Vomvas ___________________ _________
Researcher name Signature Date

Study contact details for further information: Zisis Vomvas, Z.Vomvas@student.tudelft.nl

Appendix 4 - Interviews and Personal communications

Interviews

Interviewee E.1. (2021, 19 July). Interview about the hospital environment with a healthcare real estate development consultant (Z. Vomvas, Interviewer)

Interviewee E.2. (2021, 20 July). Interview about the hospital environment with a real estate business office manager (Z. Vomvas, Interviewer)

Interviewee E.3. (2021, 21 July). Interview about the hospital environment with a housing policy consultant (Z. Vomvas, Interviewer)

Interviewee E.4. (2021, 21 July). Interview about the hospital environment with a healthcare real estate property manager (Z. Vomvas, Interviewer)

Interviewee E.5. (2021, 22 July). Interview about the hospital environment with two technical consultants (Z. Vomvas, Interviewer)

Interviewee E.6. (2021, 29 July). Interview about the hospital environment with a facility management and procurement director (Z. Vomvas, Interviewer)

Interviewee E.7. (2021, 29 July). Interview about the hospital environment with a facility management director (Z. Vomvas, Interviewer)

Interviewee E.8. (2021, 13 September). Interview about the hospital environment with a BIM manager (Z. Vomvas, Interviewer)

Interviewee E.9. (2021, 28 September). Interview about the hospital environemnt with an energy and utility management consultant (Z. Vomvas, Interviewer)

Interviewee E.10. (2021, 29 September). Interview about the hospital environment with a business intelligence consultant (Z. Vomvas, Interviewer)

Interviewee A.1. (2021, 7 December). Interview with healthcare real estate information manager (Z. Vomvas, Interviewer)

Interviewee A.2. (2021, 16 December). Interview with medical professional (Z. Vomvas, Interviewer)

Interviewee A.3. (2021, 16 December). Interview with healthcare real estate development consultant (Z. Vomvas, Interviewer)

Interviewee A.4. (2021, 16 December). Interview with technical consultant (Z. Vomvas, Interviewer)

Interviewee A.5. (2021, 16 December). Interview with healthcare business intelligence consultant (Z. Vomvas, Interviewer)

Interviewee A.6. (2021, 17 December). Interview with healthcare real estate policy consultant (Z. Vomvas, Interviewer)

Interviewee A.7. (2021, 17 December). Interview with healthcare real estate policy consultant - sector manager (Z. Vomvas, Interviewer)

Interviewee A.8. (2022, 5 January). Interview with healthcare facility project manager (Z. Vomvas, Interviewer)

Interviewee B.1. (2022, 5 April). Interview with medical professional (Z. Vomvas, Interviewer)

Personal communications

Personal Communication 1. (July 5, 2021). Conversation with a healthcare real estate policy advisor and a healthcare real estate information manager (Z. Vomvas, Communicators)

Personal Communication 2. (September 14, 2021). Conversation with a technical automation consultant (Z.Vomvas, Communicator)

Personal Communication 3. (September 15, 2021). Conversation with a healthcare real estate policy consultant (Z.Vomvas, Communicator)

Personal Communication 4. (September 15, 2021). Conversation with a technical consultant (Z.Vomvas, Communicator)

Personal Communication 5. (October 17, 2021). Conversation with a facility manager (Z.Vomvas, Communicator)

Personal Communication 6. (October 18, 2021). Conversation with a contract manager (Z.Vomvas, Communicator)

Personal Communication 7. (October 22, 2021). Conversation with a facility manager (Z.Vomvas, Communicator)

Personal Communication 8. (October 25, 2021). Conversation with a facility management consultant (Z.Vomvas, Communicator)

Personal Communication 9. (October 25, 2021). Conversation with a technical consultant (Z.Vomvas, Communicator)

Appendix 5 - Information diagram annotation

In the information diagrams of sections 5.1.3 and 5.14 the below annotation protocol was used. This is a common practice for flowcharts that aim to describe information or process structures. The shape of each node is related to the type of data or process step that is used in a diagram.

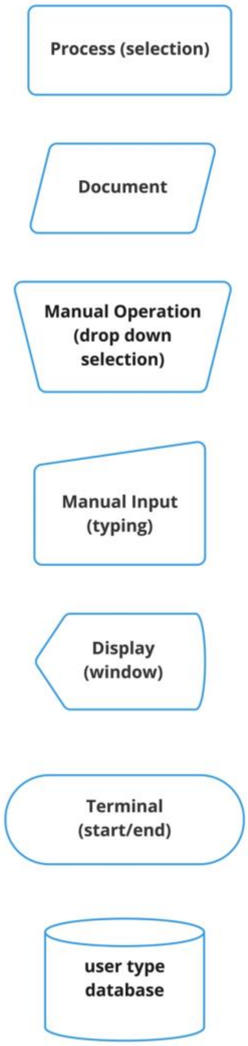


Figure 49: Annotation types of nodes in flowcharts (source: author)

Appendix 6 - Reflection

As a concluding part of the present report lies the reflection to the graduation process. Starting from a general overview on the process the researcher reflects on the research steps that were taken to complete the report. In the next section the research is positioned within the context of the whole master programme in order to identify its relationship with the rest of the master's educational curriculum. Next, the scientific relevance of the research approach and its potential transferability are discussed. Finally, some ethical issues and dilemmas that were identified are presented.

A.5.1 The research process

During the start of the graduation project, the researcher analysed corporate real estate management theories and technologies within the scope of industry 4.0. In an effort to reduce the extent of the research within the deliverables that would fit a graduation project, a choice was made to focus on hospitals, as a type of real estate with a highly public outreach. In a similar manner he delved into digital twins as a type of nascent technology that lies within the scope of industry 4.0 and offers promising applicability for the objectives of real estate managers.

While the research was developed in many phases and varying iterations, it was concluded that a framework applicable for design research would be a suitable frame for it. In particular the framework of Hevner (2007) could be applied in order to combine a literature review, an empirical approach and design research in an associative and cohesive way that would leverage the findings of a literature research and a case study for the design of a tool for decision makers. Eventually, the aim is for the design process to be theoretically grounded and connected with systematic research.

It is considered that the research approach has been effective, primarily due to the availability of the erasmus medical center and in particular the people who comprise the Programma Integrale Bouw (the department responsible for the building programs and projects at EMC). Regardless of the hindrances imposed by the pandemic, adequate information, interviews and empirical data were collected to deem the research feasible. Adding to this, the persistent and scrupulous, yet constructive feedback and guidance by the researcher's mentors, steered, motivated, and demarcated the graduation project.

The graduation research was developed in an iterative manner. For example, the literature review was continuously updated even after the collection of empirical data was complete. Regardless of the time requirements, this approach contributed to a more cohesive result whereby all its parts came along and worked complementary with one another. Since this graduation process was part of an education activity on its own, there has been a certain learning curve on the research process, which, had the research been conducted once again, would require less time to be complete.

A.5.2 Graduating in Management in the Built Environment

The research was conducted within the context of the main graduation lab of the master track management in the built environment of architecture. Lying in the convergence of a novel technology, that of digital twins and real estate management theories, the aim was to create a conceptual bridge between digitalisation and managerial theories of the built environment. By doing so, the technological capacities can be leveraged to facilitate administration objectives. The choice of mentors was in accordance with this approach, thus one focusing on real estate management and the other in information management.

Throughout the curriculum of the completed studies, the researcher was educated, among others, in theories of corporate (and public) real estate management, design and construction management and building information management. The scope of the present research was created by utilising parts of the aforementioned theories as a basis for its development. Therefore, the curriculum of the master track was used in a cumulative manner, leading to a synthetic approach for the concluding research project of his studies.

A.5.3 Research approach and relevance

The research can be divided in three parts. First, the literature review was carried out predominantly using a snowball approach, meaning that the researcher read, analysed and delved into publications in an arguably unsystematic way, however attaining an overview of the research concepts and terms that he would utilise. Later in the process the literature review became more systematic. That was because the concepts and the structure of the literature review became clearer.

Second, the case study was carried out in a single healthcare organisation. Strategic reports, personal communications, images and interviews shed a light on the processes and the systems that were utilised at the organisation, thus providing with empirical data. By doing so, the research was grounded through the industry's experience, making it relevant and applicable to professionals of hospital real estate.

Finally, the design development of the display of the digital twin was created as an output of the two previous steps and evaluated through eight industry experts whose workflow is related with hospital real estate management. Having an experience with information systems, the industry expert's opinions can be considered valuable for the assessment of the design artefact.

A.5.4 Research transferability

The aim of the graduation project is to suggest specifications for the development and utilisation of a digital twin for space use in hospitals. By doing so, healthcare organisations can be informed about what they can request from developers of similar tools and what practices they can conduct by deploying them. It is thus aimed to contribute to a better administration of healthcare building resources that can lead to a more efficient and higher quality healthcare provision. While the results were aimed to be generalised and applicable as much as possible to other organisations, the design of the artefact was based on the organisational characteristics and the real estate resources of the EMC. Therefore, any potential transferability of the research findings should consider the particularities of other organizations, the varying accommodation environments and the ways healthcare provision occurs.

A.5.5 Ethical issues and dilemmas

Throughout the research it has been aimed to conform to the ethical considerations that were elaborated in section 2.4. However, some issues can be acknowledged that occurred or may occur by the potential application of the results in practice. While conducting the research and collecting data from the hospital environment one of the main concerns was to interfere the least possible in the organisation's processes, even more so because of its role in dealing with the pandemic. As a result, the interviews occurred predominantly on non-medical personnel, but also any site visits in the buildings were limited to the absolutely necessary for the research. Finally, the design research results have been developed based on the characteristics of the EMC and its real estate portfolio, thus any potential applications by other organisations have to account for their respective differences in the way healthcare provision occurs and the built environments that it occurs at.