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Smart Commercial Buildings - Use Cases and Digital Twins

Smart Commercial Buildings -
Anwendungsfälle und Digitale
Zwillinge

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Abstract

In recent years, there has been intensive research on the Internet of Things (IoT), especially in the field of Industrial Internet of Things (IIoT). Building owners and tenants in commercial sectors are benefiting from this development. The efficiency and comfort of buildings have been improved by using various sensors and intelligent algorithms. Nonetheless, existing publications in the field of Smart Commercial Buildings (SCB) are limited. As the topic is becoming increasingly relevant for both, applying companies and providers of software and hardware solutions, this paper clarifies fundamental terms. It explains the terms Digital Twin (DT) and Digital Shadow (DS) in the context of SCBs. Furthermore, it reviews common use cases for SCBs. In order to identify those use cases, the method Grounded Requirements Engineering (GRE) is applied.

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1. Introduction

1.1. Motivation

The performance of buildings we use for commercial purposes has a critical impact on our resource consumption, the safety ratio and our well-being [Ver+19]. Currently, our building infrastructure accounts for more than one-third of global energy consumption [Joe+19]. This is not surprising, given that the population in industrialized countries spend the majority of their lives, up to 90 percent, indoors. Thereby, *Heating, Ventilation and Air Conditioning (HVAC)* systems account for a large portion of total energy consumption. In commercial buildings, HVAC account globally for around thirty-two percent of their total energy consumption. [LSR20]

Our comfort and health are also influenced by the buildings we spend time in. For instance, a Smart Building can help improve indoor air quality through monitoring and control measures by analyzing sensor data. This can especially contribute to well-being and health, as indoor air pollutant concentrations are higher than outdoor ones, while the effective air exchange there is much lower [Sar20].

Profit-oriented organizations have recognized the considerable savings and further benefits that can be realized through the intelligent control of buildings. For this reason, improving building's performance has increasingly been targeted by corporate optimization activities, in order to achieve economic, environmental and further corporate goals. A Smart Building used in a commercial or industrial context will be called *Smart Commercial Building (SCB)* in the following.

An SCB applies technologies based on *Internet of Things (IoT)*. It monitors and controls the building by using a complex network of electronic devices and (mostly) wireless media to transmit data. [Ver+19]

There are already numerous scientific publications on *Industrial Internet of Things (IIoT)*, the industrial application of IoT, and on Smart Homes, the IoT in private living spaces. However, there is a small amount of scientific publications that cover the combination of IIoT and Smart Homes. This intersection is referred to below as Smart Commercial Buildings and refers to the intelligent control of buildings intended for commercial applications. This thesis aims to close the gap between the terms of *Digital Twin (DT)* and *Digital Shadow (DS)* of an SCB and examines common use cases of SCB platforms.

In addition to the definitions of a DT and a DS, the result of this thesis is therefore a list of use cases and a respective use case description that can be used for defining requirements for software engineering.

1.2. Structure of this Thesis

In the course of this work, there will be a brief clarification of basics and terms necessary for understanding in Chapter 2. The motivation and research questions of this thesis will be presented in Chapter 3. Chapter 4 examines the differences between a Digital Twin and a Digital Shadow and finally proposes a formal definition of a DT of an SCB. In Chapter 5 common use cases are identified and described. Chapter 6 concludes this thesis by summarizing the main findings and giving suggestions for future research.

2. Background

2.1. The Internet of Things

The term IoT was first mentioned in 1999, but primarily gained global notoriety in 2014 when Google bought Smart Home electronics manufacturer Nest Labs for \$3.2 billion [Kar+19].

As [Sis+18] state in their work, there are several ways of defining IoT. This is caused by the fact that requirements and implementations of IoT depend on the respective application field and might differ. By a broad definition, IoT is the extension of computing power and network connectivity to sensors, devices, and other items, not typically referred to as individual computers. These so-called smart devices aim to reduce the need for human intervention. [Ros+15]

IoT is enabled by different hardware and software technologies that can be grouped in three categories. Those are devices that collect information (smart devices), technologies that enable those devices to process information and such that improve security and privacy [Pat+16].

It can be observed that IoT for private users is more human-centered, and the communication can consequently be described as machine-to-user interaction, while IoT in industrial environments (IIoT) typically interacts machine-to-machine [Sis+18]. This conclusion is also drawn by [Boy+18]. In their comprehensive publication, [Boy+18] examine the concept of IIoT and its relationship to related terms that are used by mistake as synonyms in business practice, such as *Cyber-physical system (CPS)* and Industry 4.0. They conclude that IIoT is a system, that includes cyber-physical assets, connected smart devices and other information technologies to enable intelligent, autonomous real-time processing in industrial environments to improve production value. IIoT exceeds the scope of a CPS and is characterized by the real-time character of its interactions with physical objects [Boy+18]. Real-time is a defined term and only used for a system that can deliver processing results within a deterministic, usually short period of time [Ges14].

Industry 4.0 is used as an umbrella term for technologies and concepts to further improve the German economy. It is necessary for Industry 4.0 to be able to monitor physical processes with the help of CPS and as a result, decentralized decisions can be made [Boy+18]. Based on similar considerations, [Sis+18] conclude that Industry 4.0 is the intersection of CPS and IIoT.

In order to implement IoT and IIoT, different architectures can be deployed [Ala+18]. Layered architectures similar to the ISO *Open Systems Interconnection (OSI)* 7-layer model are repeatedly proposed in scientific publications. Examples include the reference

architecture model for Industrie 4.0 (RAMI 4.0) [Hei+19], the 4-layer IoT architecture according to [Pat+16], the five-layer IoT architecture [Ala+18], and the *Industrial Internet Connectivity Framework (IICF)* of the industrial Internet consortium [Con17].

A large number of communication standards are used for the practical implementation of these layers. [LFD18], for example, identifies 123 standards and technologies, applied in the context of IIoT.

In addition to the industrial application field, there are other domains of IoT. [ARJ19] develop a taxonomy of IoT application fields based on their *Systematic Literature Review (SLR)* and show that these include health, environmental, smart city, commercial, industrial, and general aspects at the time of the study.

Smart buildings do not yet appear in the overview of 2019 but are considered as a separate future research direction by [ARJ19]. The following section provides basic information on this emerging application area.

2.2. The Application of IoT Technologies for Buildings

The definition of Smart Buildings is ambiguous in recent scientific publications. [Ver+19], for example, equates a Smart Building with a Smart Home, that is the exclusive application in the user's private area of use. Other authors use Smart Building as a generic term for digitalized buildings with different purposes [BG17; Kum+21]. Additionally, some other researchers add an explicit adjective to the term by what kind of building is meant. For example, [Cha+18; EF18] use the term SCB to refer to a building with meeting rooms [Cha+18] and [EF18] does not specify it further. [ARJ19] generally distinguishes between the IoT application domains commercial and industrial. Commercial IoT summarizes topics around shopping systems, including retail, and industrial IoT bundles traditional manufacturing applications. This work is more aligned with [Bar20]'s definition of SCBs to be commercial or industrial building projects in which IoT technologies are applied to improve tenants' and owners' comfort, safety and in general resource consumption.

3. Problem Statement

3.1. Research Questions

There is currently some ambiguity regarding the use of the terms Digital Shadows of Smart Buildings, Digital Twins of Smart Buildings, and Smart Building platforms when used in an industrial context. Proof for the ambiguity will be provided in the following chapters. This problem is also known from other application fields of IIoT. However, in those application fields, recent scientific publications address this problem by elaborating typical characteristics of the entities as one approach to clarify.

One aim of this thesis is to contribute to the clarification in the field of SCBs by considering the mentioned concepts. This will be done by transferring the results from a short literature research but also by comparing them with the results from qualitative expert interviews.

Furthermore, there is a notable quantitative difference in the amount of scientific publications on Smart Buildings in contrast to the already intensively researched application field of IIoT. There are currently no publications on a use case driven approach to implement an SCB platform.

For this reason, another aim of this work is to counter the lack of publications on use case driven software development approaches for Smart Buildings. Applying the well-known method of *Grounded Requirements Engineering (GRE)* common representative use cases of a SCB platform, are identified and described. Overall, the lack of transparency of terminology and methods for implementing an SCB platform will be addressed by answering the following *Research Question (RQ)*s:

- (RQ1) What is a Digital Twin and a Digital Shadow of a Smart Commercial Building?
- (RQ2) What are common use cases for a Smart Commercial Building Platform?

3.2. Scope

Not part of this work is the use of IoT technologies in Smart Homes, meaning in the private usage area. Also the integration of Smart Building into a smart city is out of scope of this paper. The research on existing suppliers is limited to those with software solutions on offer. Suppliers such as ABB [ABB22] and Infineon [inf22] advertise smart buildings, but mainly offer technical components for building automation. Providers with this focus were excluded from the scope of this thesis.

4. Digital Twin and Digital Shadow

In SCB platforms the physical building is mirrored by a DT. Therefore, it is necessary to precisely define the term DT before starting the software development for an SCB platform. Since the terms DT and DS are not clearly defined and distinguished from each other in literature [Bec+21], this chapter aims to find a definition for a DT of an SCB that reflects a DT's essential characteristics and enables differentiation from the DS. The findings of this chapter serve as a theoretical foundation for developing an SCB platform concept, in alignment with publications covering state of the art solutions.

In this thesis there will not be a discussion about setting up a blueprint for an SCB platform.

To complement the chapter, the definition is compared with the result of an expert interview (Appendix A). This comparison enables a valid and relevant conclusion regarding the definition of its accuracy.

4.1. Definition and General Characteristics of a Digital Twin

One of the initial definitions of a Digital Twin (DT) refers to one as an “integrated [...] simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so on to reflect the life of its flying twin” [GS12]. Although this definition is still frequently taken up today [Qi+21; SWB21; AR20; Ant21], the term DT is now used in a broader context. [Liu+21] examine 240 publications in their comprehensive review of DTs concepts, technologies, and industrial applications, and conclude that there is yet no formal or generally accepted definition of a DT. Although [Liu+21] conclude that the currently used concept of a DT is “general and ambiguous”, after examining 21 identified DT definitions, they state that the following aspects should generally be covered:

- Individual: The DT matches its individual physical twin exactly.
- High-fidelity: The DT can simulate the behavior of the physical twin as closely as possible over its lifecycle.
- Real-time: New technologies enable the DT to adapt and respond with low latency.
- Controllable: A change to one twin results in the same change to the other twin in each case. The physical and Digital Twins, therefore, control each other.

Especially the latter point differs from other interpretations, that see a DT as a mere virtual representation of a physical object (covering only the direction from the physical

world to a DT), and sometimes offering the option of simulation. Due the uncertainty in the use of the term DT, most publications claiming to implement a DT, but while taking a close look, they actually refer to a *Digital Model (DM)* or DS [Liu+21]. Therefore, the next chapter focuses on the definition of a DS to be able to distinguish between a DT and a DS.

4.2. Definition of a Digital Shadow

The term Digital Shadow originates in the privacy debate on risks of data traces, caused by actions performed online [LJ20]. These were referred to as Digital Shadows.

However, the meaning of this term has shifted. Especially in the context of IIoT a new meaning of DS has gained importance. By now term DS is established in the context of IIoT, however, there is a limited number of publications in the context of Smart Buildings [Cou+21]. For this reason, the following section draws on general explanations and definitions of a DS from the IIoT field of application.

DS in IIoT are seen as data sets on assets, processes, or a systems [Bre+21]. A DS' data structure is described differently in literature, but there is a consensus that a DS only contains data that is necessary for a specified purpose [LJ20; Bec+21; Bre+21]. Since DS are small, purpose-driven and lightweight data subsets of a DT they can be applied for aggregating and providing data in real-time scenarios rather than a DT itself [LJ20; Bec+21].

[Bre+21] suggest to implement what they call a DS Caster. This DS Caster is responsible for providing annotated and structured data for specific purposes – in other words for the aggregation of relevant data and providing them as DS. Since a DS Caster is implemented as generic functionality, it is necessary to implement DS templates, so-called DS Types, that contain meta information about DSs. A DS Caster is capable of processing requests and providing DS instances based on the requested DS Type.

In the following section, distinguishing features between DS and DT are explicitly discussed.

4.3. Distinction between Digital Twin and Digital Shadow

Since the in 4 lack of clarity and consensus concerning the term DT is not only found in literature but also among commercial providers for SCB platforms, the terms DM and DS will be clarified below. Apart from that, the distinction between the different models Digital Model, Digital Shadow, and Digital Twin is simplified by the decision tree elaborated by [Pro+21]. A simplified version is shown in Figure 4.1.

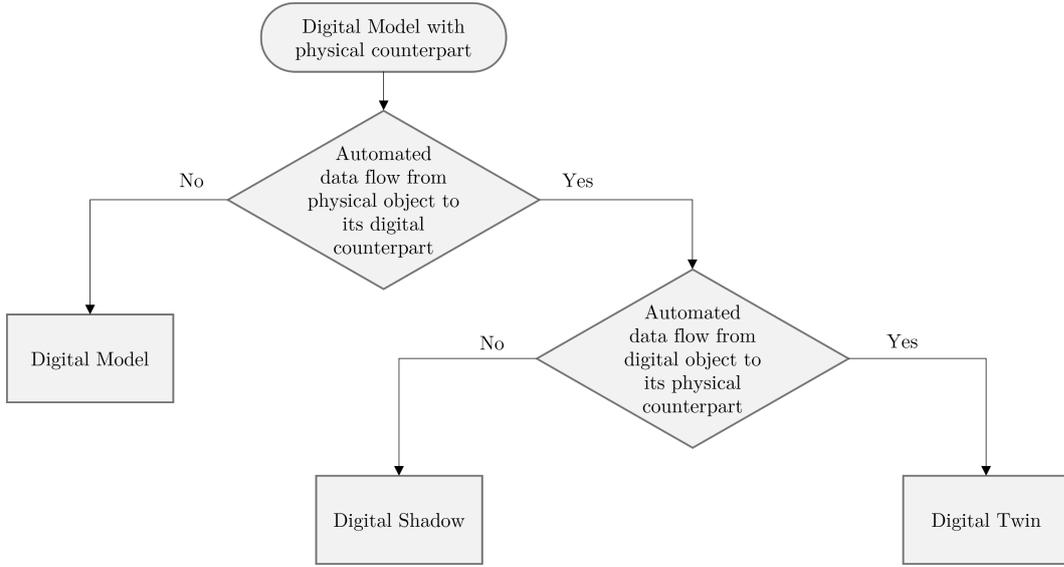


Figure 4.1.: Simplified decision tree of the Digital Twins subcategories according to [Pro+21]

While all mentioned terms describe a digital representation of a physical counterpart, a DM does not get updated automatically if its physical counterpart changes [Pro+21].

A DS is better integrated than a DM in the broadest sense. While a DM has no automated data flow, a DS serves as an accurate mirror image of the physical object and adapts to the changes automatically. The DS’s data sets and data traces must be just “sufficiently accurate” and aggregated from different data sources to fill the needs of the specific application or task [BHF18; Dal+20]. For this reason, before creating a DS, it is crucial to know how to select data, how detailed it should be, and what format it should be in [SDT18]. In addition to data from the CPS, the DS also contains context-describing metadata [Dal+20]. This metadata enables data evaluation and provision from different perspectives [Bre+21]. However, it is not possible for a DS to communicate reversely and control the physical object. This is reserved for the DT only.

In this work, an interpretation of DTs is used, including bidirectional control mechanisms and therefore is extending the virtual representation of a physical asset. Moreover, based on the results of [Dal+20], it is assumed that a DT consists of a set of DSs, and a set of further models and services (e.g. a DS Caster), the latter enables to interact with a DT and request data. This is an essential conclusion by the author of this thesis and used as a basis for the following chapters, neglecting deviating interpretations that can be found in literature. At this point, the terms DT and DS are clarified and clearly distinct.

4.4. Definition of a Digital Twin of a Smart Commercial Building

The number of publications on DTs in Smart Buildings is lower than in the manufacturing context, but there is also a lack of unity observed in what the DT includes, can be identified. [KRW19; KX18], for example, consider the DT of a Smart Building equivalent to a *Building Information Modeling (BIM)*, which cannot exercise control on its physical twin. This definition contradicts the previously established characteristics of a DT and it will therefore not be used. Nevertheless, it is important to clarify the term BIM which is indeed relevant for the next steps.

A BIM is a method to digitally represent the physical structure of a building with a high depth of information. This includes, for example, the geometry of units and components of the building and additional information such as technical properties. BIM contains a rather static set of data, as for instance the structure of the building. If the BIM is maintained and updated continuously over the entire life cycle, it can lead to an enormous reduction in effort, in particular by preventing redundant data entry. [Bor+15] BIM has become more mature in recent years and is not only used in the planning, design and construction phase but increasingly also in the operation and maintenance phase [LSR20].

Obviously, static building data is relevant for the representation of a real building. So, assuming that BIM model and DT are not identical, the question arises how BIM data can be integrated into the DT. [CFB20] focuses on this integration of a BIM model into the DT of a Smart Building. For this purpose, reference architecture is presented, which combines the dynamic data from sensors (like air quality or occupancy) and the static data of the BIM model in one database. There is a proposal on how to automate the translation of BIM software data, which according to the author is mostly in IFC standard, into a domain ontology. Doing so, she interprets the DT of a building as a set of data reflecting the state of a system, including BIM and sensor data. However, their interpretation of a DT cannot be adopted one-to-one for this work, as it does not sufficiently address controllability and related services, as typical characteristics of a DT. It can be inferred from this definition that data from the BIM must be integrated into the DT. For this reason, the DT of a Smart Building contains data about the dynamic state of the physical object, such as the room temperature, but also static data, such as the physical structure of the building. [CFB20]

Based on the identified characteristics of a DT, the identified need to integrate data from the BIM model, and the distinction made from the DS, the following definition of a DT is proposed for an SCB by the author of this thesis:

A Digital Twin of an SCB (*Digital Twin of a Smart Commercial Building (DT SCB)*) is a virtual representation of a building used for industrial or other commercial purposes. It is connected to its physical counterpart in such a way that there is an automated continuously bidirectional flow of data and control information between the virtual and physical object. A DT SCB monitors its individual physical twin precisely and adapts operational changes in real-time. Besides, it is able to integrate data of a BIM. In addition to dynamic and static data from different data sources, a Digital Twin also contains various controlling functionalities and services for providing Digital Shadows, which contain a use case specific section of data. A DT SCB can be maintained and constantly adjusted throughout the entire lifecycle.

4.5. Evaluation of the DT SCB's Definition and Discussion

To evaluate the proposed DT SCB definition, an expert interview was conducted to collect qualitative insides. The methodology for the interview is based on the guidelines of [RM16], who describe interviews as a qualitative method for empirical studies. A structured interview was conducted with questions that the author defined before the interview took place, considering the scope of this thesis and the in Chapter 3 mentioned research question. In contrast to an interview-based survey questionnaire, mostly open-ended questions were chosen as question type. The interview was conducted as a one-to-one conversation with a Ph.D degree in Human Computer Interaction and Ambient Intelligence (Appendix A).

A key finding of the interview is, the expert's describes of an DT SCB as a pure data model, that adapts to operational changes in the physical building. However, when questioned more closely, functionalities were explicitly mentioned as a possible content of the DT SCB. According to the expert, the direction of automatic data transmission between physical building and its Digital Twin depends on the application context. The interviewed expert states that the mere digital representation of a real object without any control functions can still be a DT SCB due to the fact of the broad definition of a DT. The expert sees a notable overlap between BIM and DT SCB. Anyhow, the equivalence only exists if dynamic sensory data is included in the BIM model. Furthermore, the expert sees the possibility and the trend of using the DT SCB over the entire life cycle.

Compared with the proposed definition of a DT SCB in the previous chapter, the interviewed expert does not assess all the characteristics as mentioned in the proposed definition as necessary and in addition, does not demand any new characteristics. As significant difference to previous findings he does not require the following three major points:

- The ability to control the physical twin
- Functions or methods that provide data
- Bidirectional data flow

While the expert leaves the interpretation to the application-specific context, the proposed definition selects an option, ensuring a clear distinction between the DT SCB and an DS.

4.6. Threats to Validity

In regard to validity, it is necessary to evaluate whether (in this work, the qualitative interview) is the right tool to measure exactly what it should measure or not [DB15]. A distinction can be made between four types of validity [DB15]: internal validity, external validity, statistical validity and construct validity. The chosen measure of conduction and qualitative interview is considered to be externally valid since the results are generalizable [DB15]. Due to the limited scope of this thesis only one interview was conducted. Considering the short period of time that DT SCB is implemented in building infrastructure, there is also a limited amount of academic experts available for qualitative interviews. Since only one expert interview was conducted for this qualitative approach, the informative value is limited. In order to obtain a more reliable result for future research, the survey should be conducted with a larger and more diverse amount of academic experts.

4.7. Summary

Within literature there is ambivalence in regard to DT SCBs as already described in section 4.3. Combining those scientific literature findings with the statements of the expert that led to the discussion in section 4.5, it can be concluded that expert and literature overlap and avoid agreeing on details within the definition of an DT SCB. Instead they depend the definition on the application context. This was not done in the proposed definition of a DT SCB. Instead, the findings of the previous chapters were consolidated and a specific definition was created on this basis

5. Common Use Cases of SCBs

In this chapter, RQ2 is addressed and common use cases for an SCB platform are identified. RQ2 is answered with a tabular listing of use cases. The identified use cases are the basis for determining the requirements of an SCB platform in following chapters.

Since the term use case is interpreted in different ways, in the beginning it will be explained what is understood by it in the context of this work and how comprehensive use case descriptions will be. The GRE method will be applied to identify use cases. Firstly, GRE will be introduced. Secondly, the deviant actions will be explained. Finally, the result of this GRE variant and thus the answer to RQ2 will be presented. This chapter results in 21 common use cases for SCB platforms. The use cases are assigned to eight use case categories. In addition, it is determined which business objectives are pursued per category.

5.1. Definition of the Term Use Case

Use case diagrams have proven to be beneficial for depicting behaviors and functionalities of software systems [AH22]. They improve the comprehensibility of requirements, and thus support *Requirements Engineering (RE)*, which is considered the most crucial phase in developing software, as it forms the foundation for future decisions [WLD15]. A use case is defined as a description of the sequences of interactions between a system and its actors, written in natural language. It can be used in various situations, such as describing work processes and as a basis for discussion. [Coc16]

A common understanding of a use case is that it expresses the functionality and the functional requirements of a system [Coc16; Alh02; 07; Sav+12]. [Alh02] state, that use cases are “unit[s] of behavior or functionality provided by an entity as a service to actors”. An actor is thereby understood to be a role outside of the use case entity, such as a human user or another system, that can interact with said entity. [WLD15] agree with this definition, but explicitly distinguish between the use case diagram, which is intended to visualize existing relationships and dependencies, and the tabular use case description, for more detailed information. Both are understood as part of the use case model, which the requirements analysis’ overall goal.

The use case description can vary in scope and level of detail. As [Sav+12] conclude in their work, the abstraction level of use cases depends on their purpose and stakeholders. For this work, it was necessary to establish an overview of the functional and behavioral requirements that should be addressed internally and through the user interface.

Use Case	Name: <i>Active phrase, that reveals the function (e.g., <verb><object>)</i>
Description	<i>Short summary of the system behavior, including the use cases' goal</i>
Primary actor	<i>Actor identified in Grounded Theory (GT) e.g., the main user</i>
Preconditions	<i>Conditions identified in GT, that must be fulfilled before start</i>
Trigger	<i>Actuating interaction after all preconditions are fulfilled</i>
Main success scenario	<i>Step-by-step specification of all individual actions of the interaction sequence which specifies the most frequent</i>
Associated use cases	<i>All associated use cases</i>

Table 5.1.: Template for use case description based on [WLD15]

In order to do so, the use case description based on [WLD15] has been limited to six attributes, that describe relevant activities (description, main success scenario), main users (primary actor) and relations to other use cases (preconditions, trigger, associated use cases). These appear to be essential for building the platform, as they can be used to conclude what data needs to be provided, in which form, and what other use cases need to be involved. The result is an abbreviated table for use case, as shown in Table 5.1.

5.2. Grounded Requirements Engineering (GRE)

Within the context of RE, various approaches have been established. Among them is GT, a social research method used for various RE activities, such as modeling abstract content and explaining for the relationship between concepts, and grounding use cases based on requirements elicitation [CB20]. Although there are several known approaches to use GT in requirements engineering [SB15; DLB18; Hal12], it appears that only [WLD15] transfers categories into use case specifications, using GRE.

By providing a structured method for developing use case specifications, GRE makes its results directly usable for an object-oriented or agile software development process, which in return is particularly suitable for the development of the planned platform. GRE is therefore selected as the preferred procedure to identify, categorize, and contextualize use cases.

The prerequisite for the application of GRE is fulfilled, because most of the requirements of the GRE method are met. Even if not obvious, the activities are observable in the investigated environment. While the traditional RE outputs a network of categories, GRE translates these categories into use cases that can be applied in the design phase of the software development process.

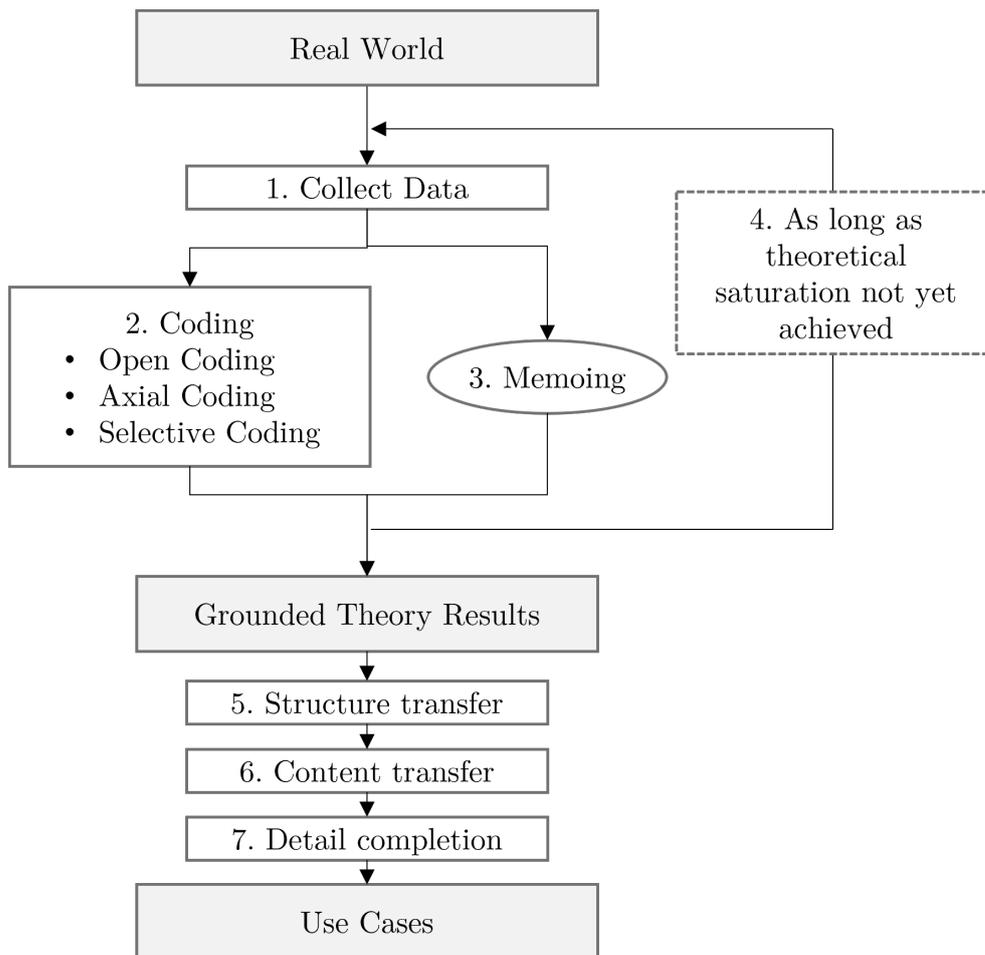


Figure 5.1.: GRE according to [WLD15]

[WLD15] describe GRE as an iterative process, consisting of two phases, each based on known methods from different fields. The complete procedure is shown in Figure 5.1.

In the first phase, the well-researched GT method is applied to get an abstract report of the real world, or more specifically, of user behavior and automation requirements. These should later be handled through the software system. The proposed GT approach according to [WLD15], as well as the deviations in the approach used in this work, are presented below:

1. Collect Data: Collecting data is usually done through investigations in direct contact with potential customers using methods such as interviews, questionnaires or watching users performing the task manually to identify their needs.
2. Coding: Examining the collected data is called coding. There are different types of coding.

- a) Open coding: The found activities, called concepts, are grouped under matching terms, called categories.
 - b) Axial coding: In axial coding, a hierarchical order is established among the categories.
 - c) Selective coding: In this step, the core statement is identified, to which all categories are related since it summarizes the central message of the GT.
3. Memoing: Memoing involves taking notes of the researcher's thoughts in order to reflect on the ideas that arise. For this work, use case diagrams were drawn to facilitate later hierarchical structuring.
 4. Repeat: As long as new data leads to new findings, steps 1-3 required to be repeated.

The result of this first phase is the GT result. In the second phase, the GT result, a network of categories, is translated into directly applicable use cases. This involves three steps:

5. Structure transfer: In the first phase, categories are turned into use cases by transferring basic information (such as identifier, name and description) in order to get a basic idea of the use case.
6. Content transfer: In this phase, the use cases are enriched with further information, like process information.
7. Detail completion: In the last phase, the perspective is shifted to a software perspective. For this reason, identified activities that should be digitalized are translated into software features.

For this work, some adjustments were made to the GRE method to adapt it to the preconditions of this work. Those are described in the next chapter.

5.3. Identification of SCB Use Cases applying GRE

In this work, the GRE method is adapted so that the results can be used to create software that is not based on current, possibly inefficient processes, but on the opportunities created by the use of new technologies. These technologies can significantly change the way a company works. There were no interviews conducted to identify use cases of Smart Building owners, nor are their employees observed while performing manual tasks. Instead, a different method is applied to obtain relevant use case data: The GRE approach is adjusted for the purpose of examining solutions that may not yet be known to the applying company, but a concept might already developed by SCB platform providers or suggested by academic case studies. As source of information for the use case descriptions, commercial SCB providers' web sites are chosen, as well as recent scientific publications on the corresponding use cases. Assuming that the commercial

vendors keep their offerings up to date and since the literature search is covering only on the current time period, both should represent the current state of the art.

For the identification of use cases, the features of the commercial vendors were analyzed. The research was continued until little further information was obtained per category and therefore theoretical saturation was approximately reached according to [WLD15]. The result was further narrowed down by considering only features that appeared at least twice. In order to find relevant commercial platforms, Google was used as a search engine. Figure 5.2 shows the search string, that was passed as search input. To ensure the neutrality of the result, personalized advertising and personalized search results, and personal default settings were disabled in advance.

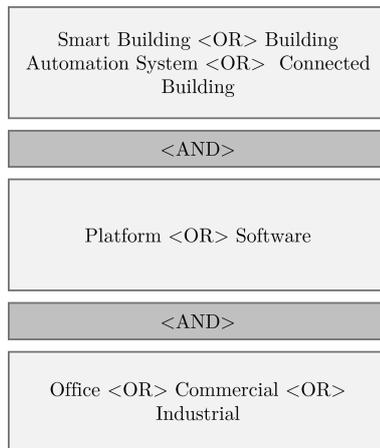


Figure 5.2.: Search term to find commercial SCB platform providers

The search results are filtered and the offers of the platform providers are examined more closely. The search was stopped when little further information was obtained per category, nor was the knowledge further refined for use cases. This happened after analyzing seven providers' solutions in detail. Thus, the point of theoretical saturation was reached according to [WLD15] and the search was stopped.

The use cases found were assigned to expressive designations and the absolute number of their occurrences was calculated. Only uniquely occurring results were omitted. Since the use cases varied in scope and were partially inclusive, a hierarchical structure was created.

Finally, eight categories and 21 associated use cases were identified. It is noticeable that a clear assignment to one category is not possible for any identified use case. This is indicated by arrows between categories and capabilities in Figure 5.3 and leads to the assumption that different use cases may require the implementation of the same capabilities. Since platform providers come up with fewer descriptions of small-step tasks on their websites and more of a listing of their features, a supplemental literature review was conducted to increase the depth of information. However, a description that includes a step-by-step specification of the activities of a use case was rarely found in

either type of source. Therefore, it is not only derived from feature descriptions but also from primary (case) studies or how a typical sequence of actions of a software solution for the respective use case could look like. The use cases are then assigned to use case categories. For each category, it is then determined which corporate goals are particularly relevant for it. The assignment of the company goals to the categories is done in order to simplify the recognition of possible target conflicts. This is considered later in this thesis. The decision whether a goal belongs to a category, is determined by asking the question “Does a use case of this category contribute to the achievement of the objective?”. When the answer is yes, the use case is considered for the relevant category.

5.4. Resulting SCB Use Cases

In this chapter, the identified use cases are listed in Table 5.2 and assigned to eight different categories in Figure 5.3.

Table 5.2 shows the interim result of the GRE method, particularly the covered use cases by SCB platforms of seven companies (Siemens AG, Johnson Controls plc, Eco Energy Insights Ltd., Envizi (an IBM company), Mapiq B.V., Bosch GmbH, Spacewell (Nemetschek SE)) that provide SCB platforms. The titles of the use cases can be found in the left-hand column. However, these terms also include use cases that are named differently by the provider but whose descriptions match those of the other providers. The right column indicates how often the use case occurred in total, considering the platforms of the mentioned SCB platform providers. Since the research question is to identify use cases that occur frequently, use cases that occurred only once were omitted for the later course.

The final result of the GRE method is the GT result, which is shown in Figure 5.3. It contains the identified use cases and the categories to which they are assigned by arrows. Categories found are listed on the left-hand side, use cases are listed on the right-hand side. Above the eight categories are icons with symbols for various corporate goals that are particularly relevant for the respective category. The different goals also illustrate the heterogeneity of the use cases found. It can be concluded that business objectives can be in conflict for different or even the same use case, e.g. improving sustainability while implementing a use case, which can lead to a cost disadvantage in the short term. This conflict of goals must be considered when developing an SCB platform, since different priorities can lead not only to different rules and thresholds, but also to a different functional scope of the use cases. For example, improving fire protection could focus on complying with legal requirements only.

Furthermore, the primary actors that perform operations for the respective use case differ. The following is a listing of the identified actors and a description of their role:

- (Operating) Accountant: Employee that provides (financial) information as a basis for decision-making by management.
- Control unit: A control unit can have a different scope in the actual implemen-

Use Case	Total amount
Simplify room booking	2
Simplify resource booking and tracking	2
Establish transparency about energy consumption	4
Recognize energy saving potential	5
Improve energy efficiency	5
Optimize on-site energy production and storage	1
Improve energy procurement	1
Improve lighting management (HCL)	4
Improve control of industrial refrigeration	1
Choose the best finance option	1
Optimize heating	5
Optimize ventilation	5
Optimize air conditioning	5
Improve air quality	2
Automate building access control	3
Manage video surveillance	2
Send mass notifications	1
Improve the evacuation process	1
Improve fire detection	3
Ensure fire suppression	1
Comply with healthcare regulations	2
Maintain in a predictive manner	3
Clean reactively and condition-oriented	2
Improve incident management	1
Implement indoor navigation	2
Virtualize data management	1
Building lifecycle management	1
Improve catering	1
Monitor carbon footprint	2
Optimize use of green energy	3
Comply with ESG regulations	3

Table 5.2.: Interim result of identified use cases

tations, depending on the respective IoT architecture. However, it is always the entity that decides on how to control devices or physical objects, such as windows or the aeration system. The control unit might be a simple base station that implements the control algorithm for devices, which is also called smart controller or (smart) device manager according to [Ver+19; Sam16] and is located between device and IoT gateway. However, especially for cloud-based software, IoT gateways are applied, which perform various tasks, such as *Network Address Translation (NAT)*, authentication and authorization. Those IoT gateways also

handle software requests that are addressed to devices in local networks, without a base station being connected in between. In this case, the control algorithm can be stored centrally in the cloud. [Nug+18]

- Employee: Any person employed by the company
- Energy manager: Employee of the energy management department, which is a subsystem of the quality management system. If not existing, an employee that has the responsibility to contribute to the company's goals by optimizing the use of energy [Kyc+19]
- Facility manager: Either contractor or internal employee responsible for administration, operation and maintenance activities related to the company's buildings [DGM17]
- Safety manager: Employee that prevents workplace hazards for company employees and promotes a safe work environment.
- Security service: Either contractor or internal employee that ensures the object protection of the building
- Sustainability manager: Employee who systematically implements the company's goals with regard to sustainability in internal processes. In particular, the reduction of CO_2 is part of his / her responsibility.
- Visitor: A person who is only in the building temporarily and is not an employee of the company, such as an applicant, a customer's purchaser, or a supplier's sales representative.
- Software: The set of computer programs, procedures, rules and data [18] that should be implemented for this use case.

In the following subsections, tabular use case descriptions of all 21 identified use cases are listed. The content of the use case descriptions is structured according to the template presented in section 5.1. The content of the use case description is based on features of SCB providers and recent scientific publications. As far as possible the information is summarized and consolidated. Features that are not clearly related to the respective use case have been neglected. If different solutions contradicted each other, the use case is aligned with the majority. In case of a tie, the more detailed case was chosen.

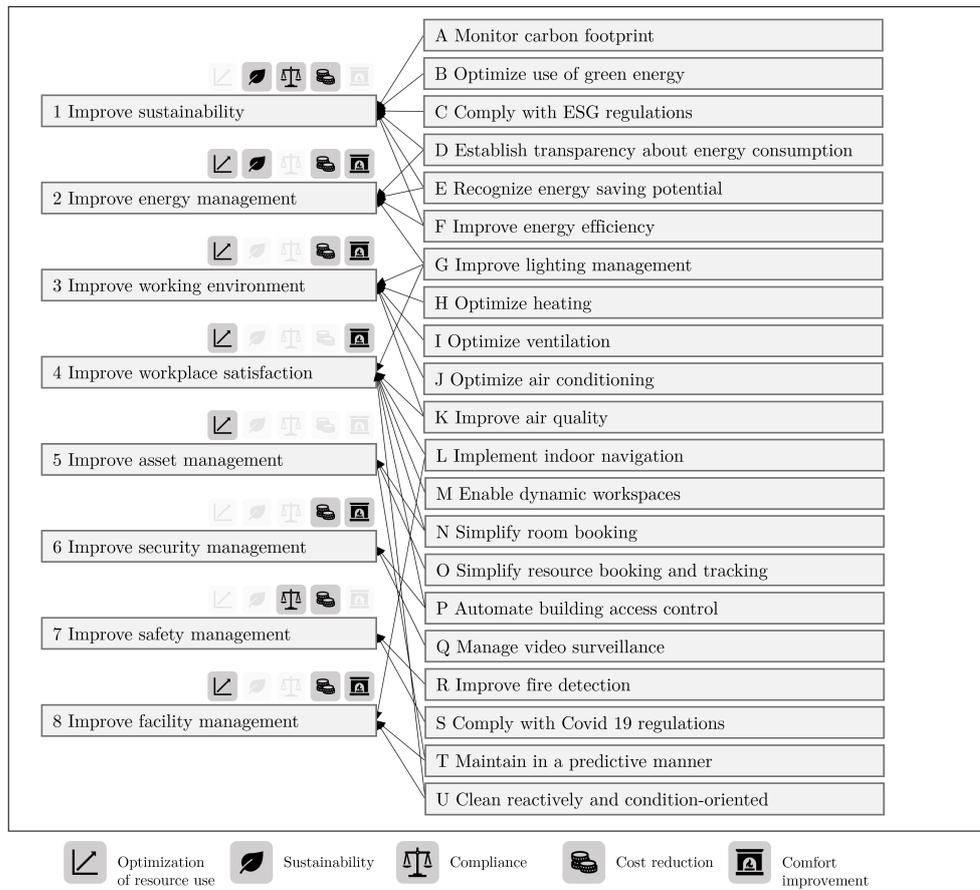


Figure 5.3.: Relevant use cases according to commercial platform providers

5.4.1. Monitor carbon footprint

This use case description is based on features from platforms of commercial vendors [Env22; Bos22]. Because CO_2 emissions in production are mainly caused by heating, cooling, lighting, or mechanical energy, there are various levers that can be used to save energy and thus CO_2 emissions. Examples include demand-driven control of systems and switch-off management in production. [Bos22; Env22] To ensure that these measures can be managed in a reasonable way, the CO_2 consumption in the company should be known and tracked. Setting decarbonization targets and a decarbonization strategy helps to set the proper focus for emission reduction. Optimally, the impact of projects with reduction measures can be tracked and the target achievement verified. The scope of CO_2 emission monitoring can also include emissions along the entire value chain. For example, [Bos22] offers options for developing the product portfolio in terms of energy efficiency. Since this is only done by this specific provider in the context of a Smart Building and goes far beyond its monitoring of it, it is not considered further here.

Use Case: A	Name: Monitor carbon footprint
Description	Greenhouse gas emissions are calculated and presented in a dashboard. It is possible to identify the worst CO_2 polluters within the company and set reduction targets, as well as track the development.
Primary actor	(Operating) Accountant, energy manager or sustainability manager
Preconditions	Consumption of energy and operating resources, business travels and energy sources used are known.
Trigger	Continuously tracking of data; preparation of official reporting, check compliance with legal <i>Environmental, Social and Governance (ESG)</i> requirements
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor calls data on the consumption of energy resources 2. Software calculates energy-related emissions 3. Software visualizes emission data (also of regulatory/legal limits) 4. Primary actor chooses suitable level of granularity 5. Primary actor sets decarbonization targets and tracks progress towards those emission reduction targets
Associated use cases	Optimize use of green energy, Comply with ESG regulations, Establish transparency about energy consumption, Recognize energy saving potential, Improve energy efficiency

Table 5.3.: Monitor carbon footprint

5.4.2. Optimize use of green energy

This use case is implemented as feature by commercial vendors [Joh22a; Env22; Bos22]. As newer energy distribution grids move toward using various sources of energy, the use of these energy sources must be optimized. While commercial providers mainly promote the flexibility of using different energy networks and storage capabilities [Sie; Joh22a; Env22; Bos22], the production of energy from renewable sources can be seen as a optimization problem. [Arn+16] propose a system capable of controlling energy flows inside a Smart Building by optimizing cost-revenues with a function that allows to buy energy at the lowest cost within a 24 hour slot.

Use Case: B	Name: Optimize use of green energy
Description	Optimize the renewable energy systems to cut carbon emissions.
Primary actor	Energy manager
Preconditions	Costs and revenue of energy prices are known and available via an interface
Trigger	None – is done continuously
Main success scenario	<ol style="list-style-type: none">1. Software monitors the generated energy2. Software monitors free and occupied storage capacities3. Software analyzes terms of cost and revenue4. Software calculates the optimization function5. Depending on the result, software recommends different actions and automatically triggers control units
Associated use cases	Monitor carbon footprint, Comply with ESG regulations, Establish transparency about energy consumption, Recognize energy saving potential, Improve energy efficiency

Table 5.4.: Optimize use of green energy

5.4.3. Comply with ESG regulations

Compliance with ESG regulations is supported by several commercial vendors [Eco22; Env22; Sie]. Their feature description is the basis for this use case description.

ESG are additional, non-financial indicators that are designed to measure and compare the social and environmental sustainability of a company. ESG has gained importance in recent years and must already be taken into account in accounting regulations [Dit22]. As ESG reporting increasingly becomes a relevant part of disclosure requirements for sustainability information, automatic data preparation and performance tracking over time (as done by [Env22]) for this purpose are also playing an increasingly important role.

Use Case: C	Name: Comply with ESG regulations
Description	The compliance with important ESG regulations is visualized in a dashboard.
Primary actor	(Operating) Accountant
Preconditions	Interface for importing information on regulations / Updated cockpit by provider
Trigger	Preparation of the annual financial statements
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor calls checklist of... <ul style="list-style-type: none"> • ...existing buildings • ...major renovations • ...new constructions 2. Software monitors policy compliance 3. Primary actor edits and saves policy compliance
Associated use cases	Monitor carbon footprint, Optimize use of green energy, Establish transparency about energy consumption, Recognize energy saving potential, Improve energy efficiency

Table 5.5.: Comply with ESG regulations

5.4.4. Establish transparency about energy consumption

Transparency about energy consumption is the basis for many other applications. [Bos22; Joh22a; Sie] explicitly mention this as a feature of their platform. For this reason, their published information is also the basis for this use case description.

This use case can vary in scope. While [Env22] taps the underlying data from electricity meters, utility bills and other sources and provides the data in a processed form, [Joh22a] promises a dashboard for energy consumption across the entire supply chain. [Sie] offers in comparison a rather slim tool, which provides a dashboard with the processed performance data in addition to the pure data collection of energy consumption data. In this use case, it is also conceivable that values are graphically displayed in a dashboard, which are described in this work in other use cases, such as CO_2 emission values and an energy profile analysis.

Use Case: D	Name: Establish transparency about energy consumption
Description	The energy consumption (in form of electricity, heat, fuel, gas) of various consuming devices and device groups (e.g. office lighting, production system, HVAC) are calculated and visually displayed. It is possible to identify the biggest energy consumer and show the consumption over time (e.g. hour, day, week) for individual consumers and groups.
Primary actor	Energy manager
Preconditions	Monitoring of energy consumption
Trigger	Preparation of official reporting; Search for highest energy consumer to reduce total energy consumption
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor calls data of energy consumption 2. Software calculates equipment downtime 3. Software visualizes energy profile analysis 4. Software performs plan-fact-analysis 5. Primary actor chooses suitable view / level of granularity
Associated use cases	Monitor carbon footprint, Optimize use of green energy, Comply with ESG regulations, Recognize energy saving potential, Improve energy efficiency, Improve lighting management, Optimize heating, Optimize ventilation, Optimize air conditioning, Improve air quality

Table 5.6.: Establish transparency about energy consumption

5.4.5. Recognize energy saving potential

Energy savings potential can be determined by calculating usage patterns. This approach is used by [Bos22; Eco22; Env22; Sie]. Therefore, the information from these operators therefore provides the basis for this use case description.

By evaluating energy consumption statistics in terms of consumption patterns, indications of important energy consumption sources and energy losses are obtained [Kyc+19]. For this purpose, consumption patterns and operating patterns of a fixed period are analyzed and the profiles are subsequently compared [Eco22]. To get the most accurate determination of actual usage patterns, additional data is often collected via IoT sensors or mobile devices, such as the number of attendant people, environmental variables, or the time of year [Kyc+19]. On this basis, potential savings are identified. A possible extension of this function is the active notification of the user through alerts, in which he or she is informed about energy consumption and energy usage patterns [Env22].

Use Case: E	Name: Recognize energy saving potential
Description	An intelligent algorithm is used to determine whether more energy is consumed than expected
Primary actor	Facility manager
Preconditions	None
Trigger	Detected anomaly in the consumption pattern of energy
Main success scenario	<ol style="list-style-type: none">1. Software calculates site usage patterns2. Software identifies the relationship between energy consumption patterns and operations patterns3. Primary actor receives alerts about energy waste
Associated use cases	Establish transparency about energy consumption, Improve energy efficiency

Table 5.7.: Recognize energy saving potential

5.4.6. Improve energy efficiency

Although, improving energy efficiency is a central topic of various suppliers, hardly any precise information on this topic is available on the suppliers' web presences. Therefore, in addition to general information according to [Bos22; Eco22; Env22; Sie], further information from the literature is also used.

This use case intendeds to ensure that the building infrastructure only consumes as much energy as is necessary. Energy losses due to inefficient chilled water and air distribution systems, for example, are to be prevented by optimizing them from the outset. [Sie; Eco22]

One possible calculation of energy efficiency is described in [Kyc+19]. The energy manager initiates a target function calculation (regression analysis) by defining possible predictors (independent variables) and having them confirmed by the subject matter expert. With the help of regression, it is possible to understand how the function value changes when the predictors are changed. Energy efficiency indicators can depend on various factors, such as technological and climatic factors. Since the most crucial energy efficiency indicator for industrial companies is the specific energy consumption per production unit, measurement data in production must also be considered via a predefined key.[Kyc+19]

Use Case: F	Name: Improve energy efficiency
Description	The energy consumption is optimized by controlling the proper parameters.
Primary actor	Energy manager
Preconditions	Energy consumption data is available
Trigger	Energy manager initiates calculation of the target function
Main success scenario	<ol style="list-style-type: none">1. Primary actor defines possible predictors for a target function calculation2. Domain expert confirms these predictors3. Software calculates key energy performance indicators4. Data analyst determines which time series values are dependent variables and which are predictors5. Selection of the type of the regression model (simple, multiple, linear, regression or nonlinear regression) by either a data analyst or the software, depending on the level of automation6. Software calculates regression coefficients7. If the result is not sufficient, primary actor goes back to step 18. Software visualizes suggested result
Associated use cases	Monitor carbon footprint, Optimize use of green energy, Comply with ESG regulations, Improve lighting management, Optimize heating, Optimize ventilation, Optimize air conditioning, Improve air quality

Table 5.8.: Improve energy efficiency

5.4.7. Improve lighting management

Commercial platform providers that offer automatic control of lighting in the building address the benefits rather than the actual implementation on their websites. Therefore, in addition to information from [Sie; Joh22a; Map22b; Bos22], input from scientific publications of recent years is used for this use case description. [Roo+15]’s proposed light control mechanism is triggered when a sensor detects a motion and compares target and actual brightness. If the current value is too low, lamps in a predefined radius are switched on.

Use Case: G	Name: Improve lighting management
Description	Improve management of artificial lighting taking into account the change of daylight during the day.
Primary actor	Employee (especially office worker), facility manager
Preconditions	None
Trigger	Detection of movement and deviation of actual and target values. This can be caused by the employees’ adjustment of the target values.
Main success scenario	<ol style="list-style-type: none"> 1. Sensors detect occupancy by detecting motion 2. Sensors detect the ambient light in a room 3. Software compares determined values with target values 4. Software instructs control units to adjust the lighting according to the determined values and in advance based on pattern recognition using machine learning
Associated use cases	Establish transparency about energy consumption, Recognize energy saving potential, Improve energy efficiency

Table 5.9.: Improve lighting management

5.4.8. Optimize heating

The commercial vendors examined do not elaborate at all on how the temperature in the building should be controlled [Sie; Env22; Map22b; Nem; Bos22]. For this reason, further information from primary studies is used.

Use Case: H	Name: Optimize heating
Description	Improve management of heating taking into account the change of the outdoor temperature during the day.
Primary actor	Employee (especially office worker), facility manager
Preconditions	None
Trigger	Continuous validation of parameters, and actions are initiated if actual and target values deviate from each other. This can be caused by parameter change by employees.
Main success scenario	<ol style="list-style-type: none">1. Sensors detect occupancy by detecting motion2. Sensors detect the current indoor and outdoor temperature3. The determined values are compared with the target values4. Heating is adjusted accordingly and in advance based on pattern recognition using machine learning
Associated use cases	Establish transparency about energy consumption, Recognize energy saving potential

Table 5.10.: Optimize heating

5.4.9. Optimize ventilation

Similar to the last use case (Optimize heating), there are hardly any detailed descriptions on the websites of commercial providers of how the platform controls ventilation. Although, there are scientific publications on the subject of HVAC [MUW15; ZSL15]. Therefore, these are used for background information for this use case description. [ZSL15] describes how to avoid over and under ventilation by calculating occupancy and using a so-called occupancy diversity factor that relies on deterministic and stochastic occupancy models.

Use Case: I	Name: Optimize ventilation
Description	Improve management of ventilation, considering the current air quality and occupancy rates
Primary actor	Employee (especially office worker), facility manager
Preconditions	None
Trigger	Continuous validation of parameters, actions are initiated if actual and target values deviate from each other. This can be caused by parameter change by employees.
Main success scenario	<ol style="list-style-type: none"> 1. Software tracks indoor environment, using sensors for temperature, humidity, illuminance, motion CO_2 2. Software calculates occupancy based on sensor data 3. Software compares calculated values with the target values 4. Software instructs control unit to adjust ventilation accordingly
Associated use cases	Establish transparency about energy consumption, Recognize energy saving potential, Improve air quality

Table 5.11.: Optimize ventilation

5.4.10. Optimize air conditioning

Features for this use case are mentioned by the same vendors as in the last two use cases (H: Optimize Heating and I: Optimize ventilation) [Sie; Env22; Map22b; Nem; Bos22]. Again, as with the previous use case (I: Optimize ventilation), the description on their websites is short and for this reason, supplementary literature is used [ZSL15].

Use Case: J	Name: Optimize air conditioning
Description	Improve management of air conditioning, considering the current air quality and occupancy rates
Primary actor	Employee (especially office worker), facility manager
Preconditions	None
Trigger	Actual and target values deviate from each other; parameter change by an employee
Main success scenario	<ol style="list-style-type: none">1. Track indoor environment, using sensors for temperature, humidity, illuminance, motion CO_22. Software calculates occupancy based on sensor data3. Software compares calculated values with target values4. Software instructs the control unit to adjust ventilation accordingly
Associated use cases	Establish transparency about energy consumption, Recognize energy saving potential, Improve air quality

Table 5.12.: Optimize air conditioning

5.4.11. Improve air quality

The air quality improvement is addressed by [Nem; Bos22]. However, [Nem] in particular elaborates on the health implications. Since the information provided by the providers is not sufficient for a use case description, further research is conducted.

Use Case: K	Name: Improve air quality
Description	The indoor air quality is monitored and improved by proper ventilation and opening windows in order to improve comfort and well-being of employees and visitors.
Primary actor	Control unit
Preconditions	None
Trigger	No trigger - Performed continuously
Main success scenario	<ol style="list-style-type: none"> 1. Software determine air quality (content of particulates or volatile gases such as carbon dioxide, sulfur dioxide, nitrogen dioxide) 2. Software predicts building use based on recognized patterns 3. Software evaluates data and decides (based on an if-then-else scenario) for or against action based on environmental readings and predicted events, e.g., open windows or start/stop adequate ventilation
Associated use cases	Recognize energy saving potential, Optimize ventilation, Optimize air conditioning, Implement indoor navigation, Comply with healthcare regulations

Table 5.13.: Improve air quality

5.4.12. Implement indoor navigation

Indoor navigation is mentioned by [Map22b; Nem] as a feature. Since the depth of information is not sufficient for the use case description, further research is conducted.

Use Case: L	Name: Implement indoor navigation
Description	Determination of the user's location and directions to a selectable destination.
Primary actor	Employee, visitor
Preconditions	The current 2D building plan/BIM model can be displayed abstracted in 2.5D (2D with floors) or 3D.
Trigger	Manually by user
Main success scenario	<ol style="list-style-type: none"> 1. On a three-dimensional map of the building, the current position is shown to the user 2. The user can select a navigation target to be guided to destinations, such as rooms or points of interest (e.g., coffee corner, work spaces, building entrance/exit can be selected) 3. The shortest route to the destination is calculated. 4. The guidance from the current location is started after user confirmation and displayed in the user interface 5. If points of interests are passed on the way, the user gets informed by location-based push notifications
Associated use cases	Enable dynamic workspaces, Comply with healthcare regulations

Table 5.14.: Implement indoor navigation

5.4.13. Enable dynamic workspaces

[Map22b; Nem] offer flexible office capacity management. The use case description is predominantly based on the information [Nem] provided.

Use Case: M	Name: Enable dynamic workspaces
Description	Office capacity is managed flexibly, and employees are distributed evenly throughout the building.
Primary actor	Employee
Preconditions	Workplaces are recorded as bookable resources
Trigger	Booking process is initiated by the employee
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor request overview of available office capacities in their shifts 2. Software proposes a workplace 3. Primary actor confirms or return to step 2 4. Software unlocks workplace automatically at the end of shift
Associated use cases	Implement indoor navigation, Simplify room booking, Simplify resource booking and tracking, Automate building access control, Comply with healthcare regulations, Maintain in a predictive manner, Clean reactively and condition-oriented

Table 5.15.: Enable dynamic workspaces

5.4.14. Simplify room booking

A simplified room booking is provided by [Map22b; Nem] on their websites but is not described further.

Use Case: N	Name: Simplify room booking
Description	The user can search for and book a suitable meeting room for his or her needs.
Primary actor	Employee
Preconditions	None
Trigger	Employee initiates booking process
Main success scenario	<ol style="list-style-type: none">1. Primary actor searches for and books suitable meeting room for his or her needs2. Primary actor enters data such as number of people, time, equipment of the meeting, etc.3. Software displays available and suitable rooms4. Primary actor confirms booking of suitable room.5. Software blocks this room automatically for the selected time period
Associated use cases	Enable dynamic workspaces, Comply with healthcare regulations, Maintain in a predictive manner, Clean reactively and condition-oriented

Table 5.16.: Simplify room booking

5.4.15. Simplify resource booking and tracking

This use case description is based on feature descriptions of [Joh22a; Nem]. [Nem] describes a drag and drop function to assign furniture to rooms and users. [Joh22a] describes a real-time asset tracking where the state of the assets is tracked over lifecycle.

Use Case: O	Name: Simplify resource booking and tracking
Description	The user can search for resources and book a suitable one for his or her needs.
Primary actor	Employee
Preconditions	None
Trigger	Employee initiates booking process
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor searches for and books suitable resource 2. Primary actor specifies the period of time and the number of required resources 3. Software displays available and suitable resources 4. Primary actor confirms booking 5. Software blocks resource automatically for the selected time period 6. Software approves access to the storage location automatically, if necessary
Associated use cases	Enable dynamic workspaces

Table 5.17.: Simplify resource booking and tracking

5.4.16. Automate building access control

This use case description is based on implementations of [Sie; Bos22; Map22b]

Use Case: P	Name: Automate building access control
Description	Regulate automatically who enters the building complex physically
Primary actor	Security service
Preconditions	None
Trigger	Employees or visitors want to enter the building area
Main success scenario	<ol style="list-style-type: none"> 1. Primary actor defines roles in order to allow access to specific areas of the company 2. Employee or visitor requests access 3. Software matches role of the initial user with access rules for the area 4. Software allows or denies access
Associated use cases	Enable dynamic workspaces

Table 5.18.: Automate building access control

5.4.17. Manage video surveillance

This use case description is based on the video surveillance features of [Sie; Bos22] While [Bos22] does not disclose any information about the fact that video surveillance is part of their platform, [Sie22] describes their solution Siemens Siveillance Video as a single management interface that simultaneously monitors multiple security cameras .

Use Case: Q	Name: Manage video surveillance
Description	Use video analytics to monitor an increasing number of video channels, as manual monitoring occasionally fails
Primary actor	Security service
Preconditions	None
Trigger	None - Continuous data analytics
Main success scenario	<ol style="list-style-type: none"> 1. Software applies video analytics to detect security breaches and threats 2. Software flags suspicious incidents 3. Software notifies primary actor by alarm in case of suspicious incidents
Associated use cases	Improve fire detection, Comply with healthcare regulations

Table 5.19.: Manage video surveillance

5.4.18. Improve fire detection

This use case description is based on [Joh22a]’s explanations of fire detection, testing and maintenance of sensors, internet-based diagnostic services and alerts. The capabilities mentioned were selected in particular because they overlap with those of other providers [Sie; Bos22].

Use Case: R	Name: Improve fire detection
Description	Testing and maintenance of sensors for fire detections is simpler and more cost-effective
Primary actor	Safety manager
Preconditions	
Trigger	Continuous monitoring of the devices
Main success scenario	<ol style="list-style-type: none">1. Software monitors devices for fire detection continuously and electronically2. Software tests sensors centrally and automatically3. Software alerts the primary actor when fire detectors are non functional, for example due to debris4. Software takes environmental data (such as common contaminants in the air) into account to reduce the chance of false alarms
Associated use cases	Manage video surveillance

Table 5.20.: Improve fire detection

5.4.19. Comply with healthcare regulations

This use case description is based on the functions of [Map22b; Joh22a] for compliance with person caps in the context of the pandemic situation. [Map22c] enables the user to set a maximum number of people for a building. [Joh22b] states without providing further information that business operations can continue smoothly if an employee tests positive for Covid -19. Since the two use cases do not have functions that overlap, some were selected by both vendors that complement each other.

Use Case: S	Name: Comply with healthcare regulations
Description	Compliance with rules developed during the Covid-19 pandemic is simplified by allowing security personnel to adjust the parameters for the number of people allowed per room, and automatically integrating the results into the room and work space booking tool
Primary actor	Employee, safety manager
Preconditions	New and updated regulations are continuously implemented
Trigger	Room or workplace booking
Main success scenario	<ol style="list-style-type: none"> 1. Safety manager adjust parameters to the currently valid laws and regulations 2. Software ensures that the number of permitted persons is not exceeded when booking rooms and reserving workstations 3. If an employee subsequently tests positive, he or she can communicate this via a feedback function 4. Other meeting participants are informed immediately via an e-mail alert function
Associated use cases	Enable dynamic workspaces, Simplify room booking, Clean reactively and condition-oriented

Table 5.21.: Comply with healthcare regulations

5.4.20. Maintain in a Predictive Manner

[Sie; Eco22] offer only little information about the implementation of the predictive maintenance tool on their website. The work assistant maintenance app from [Nem] is designed to help technicians perform their tasks by providing work orders, locations on a map, maintenance activities and material accounting information [Nem22a]. Since this description is not yet sufficient for deriving a use case, additional reference is made to the work of [Cou+21]. In their literature review they investigate how a Digital Twin combined with *Extended Reality (XR)* technologies can improve the maintenance of a building. XR includes extended reality technologies such as augmented reality, mixed reality and virtual reality. After considering more than 242 publications, they conclude that locating and navigating to defects is just one way to use XR for predictive maintenance. Others include visual annotation, simplified inspection by providing relevant information, and asset identification. For example, with *Augmented Reality (AR)* and *Mixed Reality (MR)* devices, 3D models can visually overlay their physical counterpart and provide data relevant to maintenance. Overall, the DT is the most common model type in facility management [Cou+21]. [Cou+21] describe in their work also how predictive maintenance can be used to improve building inspection planning. This is started after the last inspection and damage assessment is completed. By applying predictive algorithms such as machine learning, linear regression, and neural networks to a BIM-based DT, the remaining life of assets and emerging defects in buildings can be detected. By better predicting emerging defects, proactive maintenance can be performed.

Use Case: T	Name: Maintain in a predictive manner
Description	Intelligent evaluations detect in advance when an error is likely to occur and maintenance measures are initiated beforehand
Primary actor	Facility manager
Preconditions	Data quality is sufficient for model generation
Trigger	Machine learning algorithm suggests maintenance measures
Main success scenario	<ol style="list-style-type: none"> 1. Software monitors sensors on equipment and assets continuously 2. Software applies machine learning to calculate how likely equipment failure is to occur based on past fault detection data 3. If Software detects patterns that indicate a high probability of error, maintenance measures are initiated
Associated use cases	Improve lighting management, Optimize heating, Optimize ventilation, Optimize air conditioning, Enable dynamic workspaces, Simplify room booking

Table 5.22.: Maintain in a predictive manner

5.4.21. Clean reactive and condition-oriented

This use case description is based on features from [Map22b; Nem]. [Map22b]’s platform solution evaluates data of desk sensors to check if a desk is or was occupied and should be cleaned [Map22a]. [Nem] offers the possibility of distributing demand-oriented cleaning schedules in the in-house app. However, sensors in this case are used in a different way, for example as door count sensors at the bathroom or motion sensors in meeting rooms. The possibility to report a need manually is provided by a ticket system. [Nem22b] For this use case, both the sensor and the manual reporting option were considered, since both provide information about the current cleanliness status of the facility.

Use Case: U	Name: Clean reactive and condition-oriented
Description	User feedback options and traffic tracking can improve the cleanliness of office spaces and restrooms without increasing costs in the long term. Cleaning is no longer done at regular intervals, but depending on the condition.
Primary actor	Employee
Preconditions	Booking tool or manual user feedback
Trigger	User feedback or critical sensor values
Main success scenario	<ol style="list-style-type: none"> 1. Evaluate data of sensors in a room and the dynamic workplace tool to get information about the utilization of the room 2. The user operates a feedback panel to confirm that the room is clean or to report a problem 3. The cleaning schedules are adjusted accordingly 4. The cleaning person actuates a switch or touches buttons to confirm that the cleaning is done
Associated use cases	Enable dynamic work spaces, Simplify room booking, Comply with healthcare regulations

Table 5.23.: Clean reactive and condition-oriented

5.5. Discussion

The application of the adjusted GRE method in this thesis results in an open-use case list without a claim for completeness. Nevertheless, the list reflects common use cases of SCB platforms. Therefore, it can be said that RQ2 has been answered to a certain extent, covering common use cases from different subject areas in an adequate granularity.

The use case descriptions enable software developers to derive requirements regarding behaviors and functionalities for the SCB platform. The most important information of the use case descriptions is listed in the main success scenario section as a sequence of steps.

Categorizing the use cases aims to provide a better overview and enables the assignment of common business objectives. The latter simplifies the consideration of conflicting goals in the implementation, creating a better overview. Contrary to expectations, the use cases could not be assigned to one category.

Since in this work follows a use case-oriented approach, GRE is suitable in the context of GT in RE. However, there are further reasons for using it. GRE not only offers the possibility to categorize use cases, but applying GT also makes it possible to understand the relationships between them [WLD15].

GRE could also be interesting concerning the efforts to further automate the software development process by combining model-driven development and requirements engineering. The requirements could be represented as use cases, described with modeling languages such as UML, and be used as basis for code generation. [LIA10]

However, due to the limited scope of this work and the fact that empirical values outside the requirements analysis are missing so far, this topic is not considered further at this point.

5.6. Threats to Validity

A major threat to the validity of GRE is that domain knowledge must be available in advance in order to select proper data. In order to reduce the risk of missing domain knowledge for this thesis, the research was started after a preparation phase. Another weakness of the GRE approach described by [WLD15] is that it only considers processes and activities that are already done, which diminishes the importance of GRE results. This was counteracted in the previous chapters by examining recommended practices from recent scientific publications instead of manual processes currently being performed. As a result, new ideas were taken into account. However, one could argue against this approach that the findings in the above-mentioned use case scenarios do not necessarily fit specific needs of a company that is the focus of consideration, when applying this procedure in practice. Consequently the use cases and use case descriptions from the previous chapters are suitable as a basis for building an exemplary SCB platform, but their implementation does not necessarily make sense for all companies. Besides use case enumeration is an open list that does not claim to be complete. For some companies, additional use cases might make sense, or some might not. In addition, features of

providers were examined. To be able to apply GRE, it is assumed that user requirements can be derived from vendor features. This assumption implies that platform providers know their customers and their requirements well. However, non-transparent customer requirements can lead to feature developments that miss market requirements. This could lead to a bias in the results of the GRE and therefore a bias in this work's results. As a countermeasure, feature search results were only selected for further consideration, if they were mentioned by at least two providers.

5.7. Summary

In this chapter GRE is applied in order to determine common use cases of SCB platforms. A categorized list of use cases is derived of the results and the identified use cases and primary actors are described more detailed. Although the research question could be answered, the enumeration of use cases is not a closed list, but an insight into a more complex issue, valid only for a limited period of time. Nevertheless, the use case descriptions can be used to derive requirements for an SCB platform. Furthermore, the developed adapted GRE approach can be repeated and applied to other circumstances to describe further use cases.

6. Conclusion

6.1. Summary

In this thesis, the terms DT and DS in the context of SCBs are defined and distinguished from each other. The proposed definition of a DT SCB is evaluated by an expert interview. It has been shown that the detailed scope of the proposed DT SCB definition is necessary in order to ensure an exact differentiation between both terms. In addition to clarifying these terms, common use cases of an SCB platform were identified and described in a form suitable as a basis for further use in software engineering. For this purpose, the GRE method was adapted and applied. For this reason both research questions have been answered sufficiently. This thesis contributes to fill the gap in research on terminology of Smart Commercial Buildings. The result of this work can serve as a basis to create a blueprint of an SCB platform, based on a use case oriented approach. It also shows that use cases of an SCB are diverse, have different requirements, and can contribute to the achievement of different goals.

The procedure could be applied on other IoT application fields as well.

6.2. Future Work

The results of this work lead to further questions that have not yet been answered. First, it could be interesting to examine which functional and non-functional requirements for an SCB platform result from the identified use cases. The use case description could be used as a basis for this. Furthermore, it might be possible to determine commonalities between use cases, which can contribute to the implementation of reusable code, i.e., shared functions. The knowledge gained about the terms Digital Twin and Digital Shadow could also be useful in order to build an SCB platform. Further work could develop a systematic approach to translate use cases directly into DSs that can be invoked and deployed by an intelligent platform.

A. Expert Interview on Smart Commercial Buildings and their Digital Twin

Date: 03.03.2022
Name: Dr. Ing. Kai Kasugai (Hereafter abbreviated with KK)
Current Position: Head of Research and Development, Formitas AG
About: Dr. Kasugai is a graduate engineer in architecture and completed his PhD at RWTH Aachen University in the field of Human Computer Interaction and Ambient Intelligence, focusing on prototypes of room assisting technology. Formitas AG, for which he currently works for, is a leading company for digitalization construction industry whose portfolio includes Building Information Modeling (BIM), Digital Transformation and Virtual & AR.

1. What do you consider to be the Digital Twin of a Smart Commercial Building?
KK: A Digital Twin is a data model that describes an abstract building. It is also a geometric representation of the building with any level of detail.
2. Is a building represented by multiple Digital Twin s, or just one?
KK: This depends on the use case and thus on the context. A Digital Twin can be very large and even represent an entire city area.
3. Is a Digital Twin only a collection of data or can it also contain functionalities?
KK: The Digital Twin is primarily a data model. Functionalities are more of a platform topic. But that also depends on the use case.
4. What is the direction of data flow between digital and physical twin?
KK: The definition of Digital Twin is very broad. It is possible to have a Digital Twin with bidirectional data flow and control capabilities of the physical twin, but also scenarios of Digital Twins as a sensory representation are possible.
5. In which stage of a building's existence is a Digital Twin used?
KK: A Digital Twin can be created even before the physical object, i.e. the building. It is possible that it will not be used after construction phase. However, the trend is for use to continue over the lifecycle of the building.

6. Is the BIM model part of the Digital Twin or is the data integrated?

KK: The BIM model and the Digital Twin tend to be the same. The BIM model should include sensory technology.

7. What current developments do you notice in the field of use cases for Smart Commercial Buildings? Are there any new use cases?

KK: Smart Commercial Buildings are no longer only used for building design but also in facility management. Recently, more use cases have been implemented as part of New Work, supporting for example flexible working hours and workplaces. Life cycle analysis for e.g. the carbon footprint of the building is also becoming more important.

8. In your experience, what are the expectations of users for Smart Commercial Buildings?

KK: The Digital Twin of a Smart Commercial Building should primarily support use cases. In contrast, shadow data sets, which are not continuous in the data flow, should be avoided. Data of the Digital Twin, which is available in a Smart Commercial Building platform, should be based on a single source of truth.

Bibliography

- [07] *Conceptual Modeling of Information Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007. ISBN: 978-3-540-39389-4. DOI: 10.1007/978-3-540-39390-0 (cit. on p. 13).
- [18] *Standard Glossary of Software Engineering*. 2018. URL: <https://ieeexplore.ieee.org/servlet/opac?punumber=2238> (cit. on p. 20).
- [ABB22] ABB. 2022. URL: <https://new.abb.com/buildings/smarter-building/automation> (visited on 05/26/2022) (cit. on p. 5).
- [AH22] A. Albaghajati and J. Hassine. “A use case driven approach to game modeling.” In: *Requirements Engineering 27.1* (2022), pp. 83–116. ISSN: 0947-3602. DOI: 10.1007/s00766-021-00362-4 (cit. on p. 13).
- [Ala+18] Z. Alansari et al. “Internet of Things: Infrastructure, Architecture, Security and Privacy.” In: *2018 International Conference on Computing, Electronics & Communications Engineering (iCCECE)*. IEEE, 2018, pp. 150–155. ISBN: 978-1-5386-4904-6. DOI: 10.1109/iCCECOME.2018.8658516 (cit. on pp. 3, 4).
- [Alh02] S. S. Alhir, ed. *Guide to Applying the UML*. New York, NY: Springer New York, 2002. ISBN: 978-1-4684-9293-4. DOI: 10.1007/b97223 (cit. on p. 13).
- [Ant21] L. Ante. “Digital twin technology for smart manufacturing and industry 4.0: A bibliometric analysis of the intellectual structure of the research discourse.” In: *Manufacturing Letters 27* (2021), pp. 96–102. ISSN: 22138463. DOI: 10.1016/j.mfglet.2021.01.003 (cit. on p. 7).
- [AR20] M. E. Auer and K. Ram B. *Cyber-physical Systems and Digital Twins*. Vol. 80. Cham: Springer International Publishing, 2020. ISBN: 978-3-030-23161-3. DOI: 10.1007/978-3-030-23162-0 (cit. on p. 7).
- [ARJ19] P. Asghari, A. M. Rahmani, and H. H. S. Javadi. “Internet of Things applications: A systematic review.” In: *Computer Networks 148* (2019), pp. 241–261. ISSN: 13891286. DOI: 10.1016/j.comnet.2018.12.008 (cit. on p. 4).
- [Arn+16] D. Arnone et al. “Energy management of multi-carrier smart buildings for integrating local renewable energy systems.” In: *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*. IEEE, 2016, pp. 845–850. ISBN: 978-1-5090-3388-1. DOI: 10.1109/ICRERA.2016.7884455 (cit. on p. 24).

- [Bar20] O. Barker. “Realizing the Promise of the Internet of Things in Smart Buildings.” In: *Computer* 53.2 (2020), pp. 76–79. ISSN: 0018-9162. DOI: 10.1109/MC.2019.2952419 (cit. on p. 4).
- [Bec+21] F. Becker et al. “A Conceptual Model for Digital Shadows in Industry and Its Application.” In: *Conceptual Modeling*. Ed. by A. Ghose et al. Cham: Springer International Publishing, 2021, pp. 271–281. ISBN: 978-3-030-89022-3 (cit. on pp. 7, 8).
- [BG17] M. R. Bashir and A. Q. Gill. “IoT enabled smart buildings: A systematic review.” In: *2017 Intelligent Systems Conference (IntelliSys)*. IEEE, 2017, pp. 151–159. ISBN: 978-1-5090-6435-9. DOI: 10.1109/IntelliSys.2017.8324283 (cit. on p. 4).
- [BHF18] T. Bauernhansl, S. Hartleif, and T. Felix. “Der Digitale Schatten*/The Digital Shadow.” In: *wt Werkstattstechnik online* 108.03 (2018), pp. 132–136. ISSN: 1436-4980. DOI: 10.37544/1436-4980-2018-03-28 (cit. on p. 9).
- [Bor+15] A. Borrmann et al. *Building Information Modeling*. Wiesbaden: Springer Fachmedien Wiesbaden, 2015. ISBN: 978-3-658-05605-6. DOI: 10.1007/978-3-658-05606-3 (cit. on p. 10).
- [Bos22] Bosch Sicherheitssysteme GmbH. *Smart Buildings: How buildings become intelligent*. 2022. URL: <https://www.boschbuildingsolutions.com/xc/en/news-and-stories/smart-buildings/> (visited on 06/04/2022) (cit. on pp. 22, 24, 26, 28, 29, 31, 32, 34, 35, 40–42).
- [Boy+18] H. Boyes et al. “The industrial internet of things (IIoT): An analysis framework.” In: *Computers in Industry* 101 (2018), pp. 1–12. ISSN: 01663615. DOI: 10.1016/j.compind.2018.04.015 (cit. on p. 3).
- [Bre+21] C. Brecher et al. “Gaining IIoT insights by leveraging ontology-based modelling of raw data and Digital Shadows.” In: *2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*. IEEE, 2021, pp. 231–236. ISBN: 978-1-7281-6207-2. DOI: 10.1109/ICPS49255.2021.9468116 (cit. on pp. 8, 9).
- [CB20] R. Chitchyan and C. Bird. “Theory as a Source of Software Requirements.” In: *2020 IEEE 28th International Requirements Engineering Conference (RE)*. IEEE, 2020, pp. 227–237. ISBN: 978-1-7281-7438-9. DOI: 10.1109/RE48521.2020.00033 (cit. on p. 14).
- [CFB20] Z. Chevallier, B. Finance, and B. C. Boulakia. “A Reference Architecture for Smart Building Digital Twin.” In: *SeDiT@ESWC*. 2020 (cit. on p. 10).
- [Cha+18] B. Chai et al. “Optimal Meeting Scheduling in Smart Commercial Building for Energy Cost Reduction.” In: *IEEE Transactions on Smart Grid* 9.4 (2018), pp. 3060–3069. ISSN: 1949-3053. DOI: 10.1109/TSG.2016.2625313 (cit. on p. 4).

- [Coc16] A. Cockburn. *Writing effective use cases*. 27. print. The agile software development series. Boston: Addison-Wesley, 2016. ISBN: 0201702258 (cit. on p. 13).
- [Con17] I. I. Consortium. *The Industrial Internet of Things Volume G5: Connectivity Framework*. 2017. URL: https://www.iiconsortium.org/pdf/IIC_PUB_G5_V1.0_PB_20170228.pdf (visited on 06/04/2022) (cit. on p. 4).
- [Cou+21] C. Coupry et al. “BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings: A Literature Review.” In: *Applied Sciences* 11.15 (2021), p. 6810. DOI: 10.3390/app11156810 (cit. on pp. 8, 44).
- [Dal+20] M. Dalibor et al. “Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits.” In: *Conceptual Modeling*. Ed. by G. Dobbie et al. Vol. 12400. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2020, pp. 377–387. ISBN: 978-3-030-62521-4. DOI: 10.1007/978-3-030-62522-1{\textunderscore}28 (cit. on p. 9).
- [DB15] N. Döring and J. Bortz. *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften: In den Sozial- und Humanwissenschaften*. 5 Aufl. Springer-Lehrbuch. [s.l.]: Springer, 2015. ISBN: 978-3-642-41088-8. DOI: 10.1007/978-3-642-41089-5 (cit. on p. 12).
- [DGM17] M. Dastbaz, C. Gorse, and A. Moncaster. *Building Information Modelling, Building Performance, Design and Smart Construction*. Cham: Springer International Publishing, 2017. ISBN: 978-3-319-50345-5. DOI: 10.1007/978-3-319-50346-2 (cit. on p. 20).
- [Dit22] C. D. Ditlev-Simonsen. “Sustainability and Finance: Environment, Social, and Governance (ESG).” In: *A Guide to Sustainable Corporate Responsibility*. Ed. by C. D. Ditlev-Simonsen. Cham: Springer International Publishing, 2022, pp. 189–206. ISBN: 978-3-030-88202-0. DOI: 10.1007/978-3-030-88203-7{\textunderscore}9 (cit. on p. 25).
- [DLB18] J.-L. Dupree, E. Lank, and D. M. Berry. “A case study of using grounded analysis as a requirement engineering method: Identifying personas that specify privacy and security tool users.” In: *Science of Computer Programming* 152 (2018), pp. 1–37. ISSN: 01676423. DOI: 10.1016/j.scico.2017.08.010 (cit. on p. 14).
- [Eco22] EcoEnergy Insights. *The Best Predictive Analytics Platform*. 2022. URL: <https://ecoenergyinsights.com/> (visited on 06/04/2022) (cit. on pp. 25, 28, 29, 44).
- [EF18] M. El-Shafie and L. Fakeih. “The smart environment of commercial buildings.” In: *2018 15th Learning and Technology Conference (L&T)*. IEEE, 2018, pp. 161–166. ISBN: 978-1-5386-4817-9. DOI: 10.1109/LT.2018.8368501 (cit. on p. 4).

- [Env22] Envinzi. *ESG & sustainability software for every stage of your decarbonization journey*. 2022. URL: <https://envizi.com/solutions/> (cit. on pp. 22, 24–26, 28, 29, 32, 34).
- [Ges14] R. Gessler. *Entwicklung Eingebetteter Systeme*. Wiesbaden: Springer Fachmedien Wiesbaden, 2014. ISBN: 978-3-8348-1317-6. DOI: 10.1007/978-3-8348-2080-8 (cit. on p. 3).
- [GS12] E. Glaessgen and D. Stargel. “The Digital Twin Paradigm for Future NASA and U.S. 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*. Reston, Virginia: American Institute of Aeronautics and Astronautics, 2012. ISBN: 978-1-60086-937-2. DOI: 10.2514/6.2012-1818 (cit. on p. 7).
- [Hal12] M. Halaweh. “Using grounded theory as a method for system requirements analysis.” In: *JISTEM - Journal of Information Systems and Technology Management (Online)* 9.1 (Apr. 2012), pp. 23–38. DOI: 10.4301/S1807-17752012000100003. URL: <https://www.revistas.usp.br/jistem/article/view/45586> (cit. on p. 14).
- [Hei+19] R. Heidel et al. *Industrie 4.0: The reference architecture model RAMI 4.0 and the Industrie 4.0 component*. 1st edition. Berlin et al.: Beuth Verlag GmbH and VDE Verlag GmbH, 2019. ISBN: 9783800749904 (cit. on p. 4).
- [inf22] infineon. 2022. URL: <https://www.infineon.com/cms/de/applications/industrial/smart-building/#hvac> (visited on 05/26/2022) (cit. on p. 5).
- [Joe+19] R. L. Joench et al. “A Short Review on Smart Building Energy Resource Optimization.” In: *2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia)*. IEEE, 2019, pp. 440–445. ISBN: 978-1-5386-7434-5. DOI: 10.1109/GTDAsia.2019.8715982 (cit. on p. 1).
- [Joh22a] Johnson Controls International plc. *Smart Buildings Demand Smart Controls: Intelligent Solutions for Every Facility*. 2022. URL: <https://www.johnsoncontrols.com/building-automation-and-controls> (visited on 06/04/2022) (cit. on pp. 24, 26, 31, 39, 42, 43).
- [Joh22b] Johnson Controls International plc. *Uncover Space Utilization, Safety and Security Opportunities*. 2022. URL: <https://www.johnsoncontrols.com/openblue/openblue-location-manager> (visited on 06/04/2022) (cit. on p. 43).
- [Kar+19] A. Karmakar et al. “Industrial Internet of Things: A Review.” In: *2019 International Conference on Opto-Electronics and Applied Optics (Optronix)*. IEEE, 2019, pp. 1–6. ISBN: 978-1-7281-0070-8. DOI: 10.1109/OPTRONIX.2019.8862436 (cit. on p. 3).
- [KRW19] S. Kaewunruen, P. Rungskunroch, and J. Welsh. “A Digital-Twin Evaluation of Net Zero Energy Building for Existing Buildings.” In: *Sustainability* 11.1 (2019), p. 159. DOI: 10.3390/su11010159 (cit. on p. 10).

- [Kum+21] A. Kumar et al. “Secure and energy-efficient smart building architecture with emerging technology IoT.” In: *Computer Communications* 176 (2021), pp. 207–217. ISSN: 01403664. DOI: 10.1016/j.comcom.2021.06.003 (cit. on p. 4).
- [KX18] S. Kaewunruen and N. Xu. “Digital Twin for Sustainability Evaluation of Railway Station Buildings.” In: *Frontiers in Built Environment* 4 (2018). DOI: 10.3389/fbuil.2018.00077 (cit. on p. 10).
- [Kyc+19] A. Kychkin et al. “IoT-Based Energy Management Assistant Architecture Design.” In: *2019 IEEE 21st Conference on Business Informatics (CBI)*. IEEE, 2019, pp. 522–530. ISBN: 978-1-7281-0650-2. DOI: 10.1109/CBI.2019.00067 (cit. on pp. 20, 28, 29).
- [LFD18] Y. Liao, E. de Freitas Rocha Loures, and F. Deschamps. “Industrial Internet of Things: A Systematic Literature Review and Insights.” In: *IEEE Internet of Things Journal* 5.6 (2018), pp. 4515–4525. DOI: 10.1109/JIOT.2018.2834151 (cit. on p. 4).
- [LIA10] G. Loniewski, E. Insfran, and S. Abrahão. “A Systematic Review of the Use of Requirements Engineering Techniques in Model-Driven Development.” In: *Model Driven Engineering Languages and Systems*. Ed. by D. C. Petriu, N. Rouquette, and Ø. Haugen. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 213–227. ISBN: 978-3-642-16129-2 (cit. on p. 47).
- [Liu+21] M. Liu et al. “Review of digital twin about concepts, technologies, and industrial applications.” In: *Journal of Manufacturing Systems* 58 (2021), pp. 346–361. ISSN: 02786125. DOI: 10.1016/j.jmsy.2020.06.017 (cit. on pp. 7, 8).
- [LJ20] M. Liebenberg and M. Jarke. “Information Systems Engineering with Digital Shadows: Concept and Case Studies.” In: *Advanced Information Systems Engineering*. Ed. by S. Dustdar et al. Cham: Springer International Publishing, 2020, pp. 70–84. ISBN: 978-3-030-49435-3 (cit. on p. 8).
- [LSR20] A. Latifah, S. H. Supangkat, and A. Ramelan. “Smart Building: A Literature Review.” In: *2020 International Conference on ICT for Smart Society (ICISS)*. IEEE, 2020, pp. 1–6. ISBN: 978-1-6654-0420-4. DOI: 10.1109/ICISS50791.2020.9307552 (cit. on pp. 1, 10).
- [Map22a] Mapiq. *3 trends for Facility management in 2021*. 2022. URL: <https://www.mapiq.com/articles/facility-management-in-2021-3-trends> (visited on 06/04/2022) (cit. on p. 46).
- [Map22b] Mapiq. *One platform, major opportunities*. 2022. URL: <https://www.mapiq.com/platform> (visited on 06/04/2022) (cit. on pp. 31, 32, 34, 36–38, 40, 43, 46).
- [Map22c] Mapiq. *Open your doors for a new chapter of work*. 2022. URL: <https://www.mapiq.com/return-to-the-office> (visited on 06/04/2022) (cit. on p. 43).

- [MUW15] U. Manandhar, A. Ukil, and D. Wang. “Building HVAC load profiling using EnergyPlus.” In: *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*. IEEE, 2015, pp. 1–6. ISBN: 978-1-5090-1238-1. DOI: 10.1109/ISGT-Asia.2015.7386983 (cit. on p. 33).
- [Nem] Nemetschek SE. *Erschließen Sie das volle Potenzial Ihrer Gebäude*. URL: <https://spacewell.com/de/> (visited on 06/04/2022) (cit. on pp. 32, 34–39, 44, 46).
- [Nem22a] Nemetschek SE. *Work Assistant maintenance app*. 2022. URL: <https://spacewell.com/solutions/asset-maintenance-management/maintenance-app/> (visited on 06/04/2022) (cit. on p. 44).
- [Nem22b] NemetschekSE. *3 trends for Facility management in 2021*. 2022. URL: <https://www.mapiq.com/articles/facility-management-in-2021-3-trends> (visited on 06/04/2022) (cit. on p. 46).
- [Nug+18] A. Nugur et al. “Design and Development of an IoT Gateway for Smart Building Applications.” In: *IEEE Internet of Things Journal* (2018), pp. 1–1. DOI: 10.1109/JIOT.2018.2885652 (cit. on p. 20).
- [Pat+16] K. Patel et al. “Internet of Things-IOT: Definition, Characteristics, Architecture, Enabling Technologies, Application & Future Challenges.” In: (May 2016) (cit. on pp. 3, 4).
- [Pro+21] G. Pronost et al. “Towards a Framework for the Classification of Digital Twins and their Applications.” In: *2021 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*. IEEE, 2021, pp. 1–7. ISBN: 978-1-6654-4963-2. DOI: 10.1109/ICE/ITMC52061.2021.9570114 (cit. on pp. 8, 9).
- [Qi+21] Q. Qi et al. “Enabling technologies and tools for digital twin.” In: *Journal of Manufacturing Systems* 58 (2021), pp. 3–21. ISSN: 02786125. DOI: 10.1016/j.jmsy.2019.10.001 (cit. on p. 7).
- [RM16] C. Robson and K. McCartan. *Real world research*. Fourth edition. Chichester: John Wiley & Sons, 2016. ISBN: 9781118745236 (cit. on p. 11).
- [Roo+15] M. H. Roohi et al. “Design and implementaion of smart building lighting system.” In: *2015 International Congress on Electric Industry Automation (ICEIA 2015)*. IEEE, 2015, pp. 7–10. ISBN: 978-1-4799-1788-4. DOI: 10.1109/ICEIA.2015.7165838 (cit. on p. 31).
- [Ros+15] K. A. Rose et al. “Proposed best modeling practices for assessing the effects of ecosystem restoration on fish.” In: *Ecological Modelling* 300 (2015), pp. 12–29. ISSN: 03043800. DOI: 10.1016/j.ecolmodel.2014.12.020 (cit. on p. 3).
- [Sam16] S. Samuel. “A review of connectivity challenges in IoT-smart home.” In: Mar. 2016, pp. 1–4. DOI: 10.1109/ICBDSC.2016.7460395 (cit. on p. 19).
- [Sar20] D. E. Saraga. “Special Issue on Indoor Air Quality.” In: *Applied Sciences* 10.4 (2020), p. 1501. DOI: 10.3390/app10041501 (cit. on p. 1).

- [Sav+12] D. Savic et al. “Use Case Specification at Different Levels of Abstraction.” In: *2012 Eighth International Conference on the Quality of Information and Communications Technology*. IEEE, 2012, pp. 187–192. ISBN: 978-1-4673-2345-1. DOI: 10.1109/QUATIC.2012.64 (cit. on p. 13).
- [SB15] R. Sharma and K. K. Biswas. “Functional Requirements Categorization - Grounded Theory Approach.” In: *Proceedings of the 10th International Conference on Evaluation of Novel Approaches to Software Engineering*. SCITEPRESS - Science and Technology Publications, 2015, pp. 301–307. ISBN: 978-989-758-100-7. DOI: 10.5220/0005472103010307 (cit. on p. 14).
- [SDT18] G. Schuh, C. Dolle, and C. Tonnes. “Methodology for the derivation of a digital shadow for engineering management.” In: *2018 IEEE Technology and Engineering Management Conference (TEMSCON)*. IEEE, 2018, pp. 1–6. ISBN: 978-1-5386-2047-2. DOI: 10.1109/TEMSCON.2018.8488412 (cit. on p. 9).
- [Sie] Siemens AG. *Building technology*. URL: <https://new.siemens.com/global/en/products/buildings.html> (visited on 06/04/2022) (cit. on pp. 24–26, 28, 29, 31, 32, 34, 40–42, 44).
- [Sie22] Siemens AG. *Video Surveillance*. 2022. URL: <https://new.siemens.com/uk/en/products/buildingtechnologies/security/video-surveillance.html> (visited on 06/04/2022) (cit. on p. 41).
- [Sis+18] E. Sisinni et al. “Industrial Internet of Things: Challenges, Opportunities, and Directions.” In: *IEEE Transactions on Industrial Informatics* 14.11 (2018), pp. 4724–4734. ISSN: 1551-3203. DOI: 10.1109/TII.2018.2852491 (cit. on p. 3).
- [SWB21] S. Singh, M. Weeber, and K.-P. Birke. “Advancing digital twin implementation: a toolbox for modelling and simulation.” In: *Procedia CIRP* 99 (2021), pp. 567–572. ISSN: 22128271. DOI: 10.1016/j.procir.2021.03.078 (cit. on p. 7).
- [Ver+19] A. Verma et al. “Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review.” In: *IEEE Sensors Journal* 19.20 (2019), pp. 9036–9046. ISSN: 1530-437X. DOI: 10.1109/JSEN.2019.2922409 (cit. on pp. 1, 4, 19).
- [WLD15] D. Würfel, R. Lutz, and S. Diehl. “Grounded Requirements Engineering: An Approach to Use Case Driven Requirements Engineering.” In: *Journal of Systems and Software* 117 (Oct. 2015). DOI: 10.1016/j.jss.2015.10.024 (cit. on pp. 13–15, 17, 47).
- [ZSL15] J. Zhang, B.-C. Seet, and T. Lie. “Building Information Modelling for Smart Built Environments.” In: *Buildings* 5.1 (2015), pp. 100–115. DOI: 10.3390/buildings5010100 (cit. on pp. 33, 34).

Glossary

AR Augmented Reality

BIM Building Information Modeling

CPS Cyber-physical system

DM Digital Model

DS Digital Shadow

DT Digital Twin

DT SCB Digital Twin of a Smart Commercial Building

ESG Environmental, Social and Governance

GRE Grounded Requirements Engineering

GT Grounded Theory

HVAC Heating, Ventilation and Air Conditioning

IICF Industrial Internet Connectivity Framework

IIoT Industrial Internet of Things

IoT Internet of Things

MR Mixed Reality

NAT Network Address Translation

OSI Open Systems Interconnection

RE Requirements Engineering

RQ Research Question

SCB Smart Commercial Building

SLR Systematic Literature Review

XR Extended Reality

