Technical University of Munich

Department of Civil, Geo and Environmental Engineering

Chair of Computational Modeling and Simulation

BIM-integration of sustainable building certification criteria in the early design stages

Master's Thesis

for the Master of Science Program Resource Efficient and Sustainable Building

Author:	Lena Drewes
Student Number:	[redacted]
1. Supervisor:	Prof. Dr.-Ing. André Borrmann
2. Supervisor:	Kasimir Forth
Issue Date:	01. June 2020
Submission Date:	30. November 2020

Abstract

Sustainable building certification systems, such as the one developed by the German Sustainable Building Council (DGNB), present a common and holistic baseline for what is considered sustainable in a building context. They provide designers and engineers with a concrete set of measures that can be implemented to optimize a building and make it more environmentally, socially and economically sustainable. However, sustainability is currently still more of an afterthought in the building industry, so it is necessary to reconfigure the conventional design process to include sustainability aspects as a design requirement from the very beginning of the planning process. By focusing on the early design stages, a disjointed and reactionary design process can be replaced by a more integrated and collaborative approach. Building Information Modeling (BIM) is perfectly suited to support such a process. Of the sustainability-BIM integration approaches investigated in this thesis, the methodology developed in the ONIB report (Leibniz University Hanover) presented the greatest potential for adequately documenting and incorporating the sustainability requirements set forth by the DGNB. In this approach attribute matrices are created that contain detailed model information requirements that can be validated with a model checking software. Based on this approach, a sustainability optimization tool was developed for the early design stages, utilizing custom Solibri rulesets that enable an iterative optimization process through straightforward and instant results. Two representative example criteria were implemented for model validation. It was discovered that for qualitative criteria the model spaces and spatial relationships are important for determining if the sustainability requirements have been fulfilled. Quantitative criteria, on the other hand, depended more on the specific material and object-based information stored in the model.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCF	BIM Collaboration Format
BEAM	Building Environmental Assessment Methods
BEP	BIM Execution Plan
BIM	Building Information Modelling
BMC	BIM-based model checking
BNB	Bewertungssystem Nachhaltiges Bauen (Evaluation system for sustainable building)
BPMN	Business Process Modeling Notation
BPS	Building Performance Simulations
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CCTV	Closed-circuit television
CDE	Common Data Environment
COBie	Construction Operations Building Information Exchange
DIN	Deutsche Institut für Normung (German Institute for Standardization)
DGNB	Deutsche Gesellschaft für Nachhalitges Bauen (German Sustainable Building Council)
EIR	Employer’s Information Requirements
ER	Exchange Requirements
FM	Facilities Management
GIS	Geographic Information System

HOAI	Honorarordnung für Architekten und Ingenieure (Ordinance on Architects' and Engineers' Fees)
HTW	Hochschule für Technik und Wissenschaft (University for Technology and Science)
HVAC	Heating, ventilation, and air conditioning
IDM	Information Delivery Manual
IFC	Industry Foundation Class
IREBS	International Real Estate Business School
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
MEP	Mechanical, Electrical, Plumbing
MIDP	Master Information Delivery Plan
MVD	Model View Definition
ONIB	Optimierung der Nachhaltigkeit von Bauwerken durch die Integration von Nachhaltig- keitsanforderungen in die digitale Methode Building Information Modeling (Optimizing the sustainability of buildings by integrating sustainability requirements into the digital method Building Information Modeling)
PA	Public Address
RICS	Royal Institution of Chartered Surveyors
SBC	Sustainable Building Certification
SMC	Solibri Model Checker
USGBC	U.S. Green Building Council
WC	Water Closet/Toilet
XML	Extensible Markup Language

1 Introduction

The idea of sustainability has been around for much of human history, however, the definition that is most commonly used today can be traced back to about 40 years ago. In 1987, sustainability became rebranded as sustainable development by the Brundtland Report and officially defined as: "*… development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." (IISD, 2020) Since then, sustainability has become one of the most common trend topics of our time. Political decision-makers and legislators across all levels of government have become acutely aware of the importance of ensuring environmental protection and social justice while still achieving economic stability and growth (Passer et al., 2014). Despite this increased awareness, integrating the principles of sustainable development into the building industry has proven to be quite a challenge.

The Architecture, Engineering and Construction (AEC) industry currently produces nearly 40% of global carbon dioxide emissions. Of the global final energy consumption, one third is related to the building sector (IEA, 2020). Construction activities are responsible for the consumption of about 30% of the world's resources, including 12% of global water use, and the building industry produces 40% of global waste (UNEP-SBCI, 2012). Furthermore, people in developed countries spend about 90% of their time in buildings, making indoor environments that promote health and productivity essential (UNEP-SBCI, 2012). These numbers are significant and will only increase with global urbanization and if predicted trends turn into reality. The global status report from 2017 states that, "*by 2060, buildings sector floor area will double, adding more than 230 billion* m^2 *to the planet in new buildings construction. Those additions are equivalent to building the current floor area of Japan every single year from now until 2060*" (UN Environment, 2017). Thus, if major depletion and damage are to be avoided, sustainable development must not only be recognized by the building industry but must also actively become integrated and proactively managed.

To understand how this integration could work, it is important to first understand the principles of sustainable development. Since the first definition of the term in 1987, it has been generally recognized that sustainable development is threefold in responsibility, split into the aspects of environmental, economic and social sustainability.

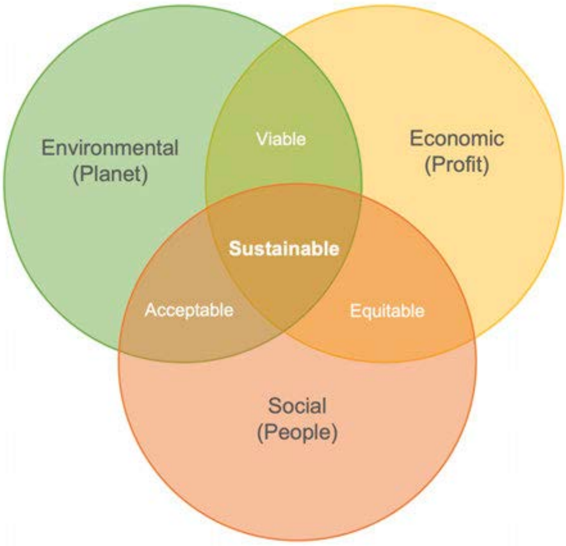


Figure 1.1: Three aspects of sustainability (based on OpenLearn, 2020)

Environmental sustainability is the most widely recognized of the three aspects and the one that typically comes to mind when thinking about sustainability. It is focused on the impact that a building has on resources, the ecosystem and the climate. This aspect works to optimize the use of material, water and energy resources by looking at the entire lifecycle of a building, from the extraction and production of building materials, through the operation of the building, and finally the recycling and disposal of the building components (GXN & Statens Byggeforskningsinstitut, 2018). The environmental aspect of sustainable development aims to reduce the use of toxic substances and the amount of waste produced, mitigate negative impacts on biodiversity and land-use, optimize the use of resources, and improve the quality of water and air. Economic factors are often not associated with sustainability, however, they play a fundamental role in sustainable development. The economic aspect of sustainability controls the balance between the costs and quality of a building (GXN & Statens Byggeforskningsinstitut, 2018). This includes the construction and operating costs and the quality and value of the building over its entire life cycle, including potential building use changes in the future. Durability and reusability factor positively into the economic aspect of sustainability as they correspond with long-term resource productivity and lower operational and maintenance costs (Soltani, 2016). Additionally, the economic aspect includes the value of the property and marketing possibilities. Social sustainability centers around the health and well-being of users and residents. It addresses health and safety implications that result from the areas in and around the building (GXN & Statens Byggeforskningsinstitut, 2018). Social sustainability focuses on spaces that encourage positive social interactions and promote productivity. It includes environmentally friendly transportation and buildings that are accessible to users of all abilities, while preserving social and cultural values (Soltani, 2016). The social aspect deals with functional, cultural and design qualities of a building and how the created spaces affect the health and comfort of users. Essentially, as shown in Figure 1.1, in order for a building to be truly sustainable, it must minimize environmental harm and depletion, be economically viable now and in the future, and be accepted by the people it is design for.

1.1 Motivation

The most common method for integrating sustainability into the building industry has taken the form of sustainable building certifications (SBCs). Since their establishment in the 1990's, SBCs have become known as a way of measuring the sustainability of building projects through a variety of criteria that can be fulfilled to different extents. Each certification system on the market today is slightly different, with the majority focusing on the environmental aspects. However, as the threefold definition of sustainability becomes more widely known and accepted, the building certification systems are being updated to include economic and social criteria as well. The main benefit of SBCs is that despite their slight differences, they create a common and holistic baseline for what is considered sustainable in a building context. They provide designers and engineers with a concrete set of measures that can be implemented to optimize a building and make it more sustainable, by taking seemingly abstract concepts and making them practical and applicable. However, to create a lasting and systemic change in the building industry, the conventional design process must be reconfigured to include sustainability aspects from the very beginning of the planning process.

In the early stages of the planning and design process, important decisions are made about the building appearance, project costs and measures that will influence the performance and acceptance of the building over its entire lifecycle. In these early stages, the ease with which the design can be influenced is high and the costs and effort associated with making design changes is still low. By focusing on the early design stages, a disjointed and reactionary design process can be replaced by a more integrated and collaborative approach. This integrated planning process has become a defining feature of sustainable building and Building Information Modeling (BIM) is perfectly suited to support such a process.

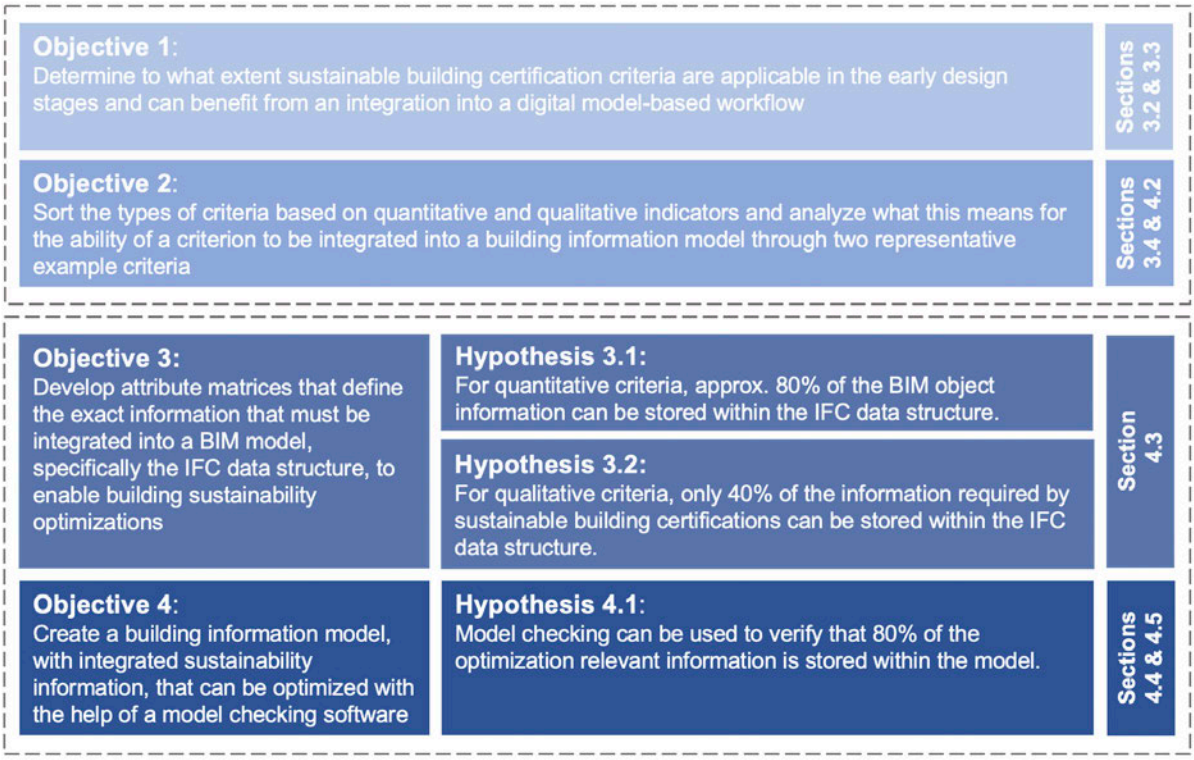
In recent years, BIM has become known as one of the most effective organizational and technological advancements in the building industry. BIM can be broken down into three main dimensions: a digital representation of a planned or built structure, a process of information exchange, and a system of management and collaboration through which the quality and efficiency of a structure are increased (Foliente et al., 2008). BIM technology can facilitate sustainable building by providing an integrated design workflow across all design stages, from project initiation to the demolition stage. Through the use of BIM, all disciplines work together more closely and project goals, especially those related to sustainability, can easily be communicated to the entire team and can be considered and incorporated by all project participants, starting at the very beginning of the project. The multi-disciplinary approach that the BIM methodology fosters can be particularly useful in fulfilling not one but all three aspects of sustainability.

Through the creation of a 3D building model, BIM can intrinsically support many of the environmental aspects measured by SBCs, as these models automatically contain much of the data required for building performance analyses. By using a building information model, designers can compare numerous design variants in the early design stages to home in on the most sustainable option that enhances the overall performance of the building. Most BIM tools provide various features for evaluating material and energy consumption and deliver explicit information about the reduction of energy and material use. Economic decision-making is one of the most common uses of BIM and one of the main contributions that BIM has made to sustainable building. BIM can be used to carry out cost estimates and risk assessments of a project, broken down into the different design stages. To further reduce costs, the time factor can be added to a BIM project to estimate risk more effectively. Implementing BIM in other aspects of a project can also play a role in economic efficiency. Future issues can be detected earlier and collaboration and communication are enhanced among stakeholder, which saves time and improves building management, reducing overall project costs. Social sustainability can be included in a BIM model through lighting and acoustic simulations, analyses of building accessibility and the reduction of health risks associated with material emissions. Overall, it is clear that synergies exist between BIM and sustainable building, especially in the early design stages. Using the criteria set forth by sustainable building certifications as a foundation for the future, the potentials of BIM in sustainable building are immense.

1.2 Research Objectives and Hypotheses

The primary goal of this thesis is to develop an early design stage sustainability optimization tool on the basis of a BIM model that contains consistent and up-to-date, model-based sustainability information. In order to achieve this goal, the information needed for a sustainability evaluation first needs to be analyzed to determined how it relates to the BIM workflow and the model into which it is to be incorporated. Once the information is clearly organized, it can be integrated into a building information model, from which the relevant data can then be exported, checked for proper integration and used to make sustainability optimization suggestions in the early design stages. To support this process, four main research objectives are defined.

The first research objective determines to what extent sustainable building certification criteria are applicable in the early design stages and can benefit from an integration into a digital model-based workflow. This objective helps to create the framework for the thesis by defining which sustainability criteria are relevant for incorporation into an early stage BIM model. Building on the framework established by the first objective, the second research objective focuses on organizing the applicable criteria into quantitative and qualitative indicators and subsequently analyzing what this means for the integration into the BIM model through two representative example criteria. The third research objective aims to structure this integration by preparing the required model information in a way that it can be used not only for this thesis but also for future research efforts and projects. To do this, an approach of creating attribute matrices was selected. These matrices contain all of the required information on a very detailed level, linked, where applicable, directly with the Industry Foundation Class (IFC) data structure. Finally, the fourth research objective tests and verifies the prior preparation and integration work using a prototypical building information model. With the help of model checking software, a successful integration can then be validated and sustainability optimizations can be carried out and assessed. Figure 1.2 summarizes these research objectives, the hypotheses tested, and references the thesis section in which the results can be found.



Objective 1:
Determine to what extent sustainable building certification criteria are applicable in the early design stages and can benefit from an integration into a digital model-based workflow

Sections 3.2 & 3.3

Objective 2:
Sort the types of criteria based on quantitative and qualitative indicators and analyze what this means for the ability of a criterion to be integrated into a building information model through two representative example criteria

Sections 3.4 & 4.2

Objective 3:
Develop attribute matrices that define the exact information that must be integrated into a BIM model, specifically the IFC data structure, to enable building sustainability optimizations

Hypothesis 3.1:
For quantitative criteria, approx. 80% of the BIM object information can be stored within the IFC data structure.

Hypothesis 3.2:
For qualitative criteria, only 40% of the information required by sustainable building certifications can be stored within the IFC data structure.

Section 4.3

Objective 4:
Create a building information model, with integrated sustainability information, that can be optimized with the help of a model checking software

Hypothesis 4.1:
Model checking can be used to verify that 80% of the optimization relevant information is stored within the model.

Sections 4.4 & 4.5

Figure 1.2: Research objectives and hypotheses summary

By focusing on the IFC structure as the basis for the criteria/BIM-object implementation, it is anticipated that the attribute matrices can be used in a variety of openBIM applications. The research conducted in this thesis uses digital methods to achieve an active and conscious integration of sustainability at the early stages of the planning process. A structured and standardized data management on the basis of a BIM model is expected to offer high potentials and efficiency increases in sustainability by enabling quick and low-cost comparisons of different design variants.

1.3 Outline and Structure

This thesis is structured into four main parts. In chapter 2, the necessary background knowledge, in terms of definitions, concepts and methodologies is presented. Sustainable building certifications, the BIM methodology, model-checking and current BIM-sustainability integration approaches are examined. Chapter 3 investigates the criteria of the selected building certification system and evaluates their applicability to this thesis. In chapter 4, two representative criteria are integrated into a BIM model and then verified using a model checking software that also provides feedback for sustainability optimizations. Finally, chapter 5 concludes with a summary and an outlook about potential developments in the field of BIM and sustainability.

2 State of the Art

In order to understand the research carried out within the scope of this thesis, it is essential that certain concepts and methods are explained to create a transparent and common knowledge basis. In the first section several definitions of the early design stages are presented. The second section outlines the general concept of building sustainability certifications and compares three of them based on the different aspects and indicators of sustainability that they represent. Next, the methodology of BIM is introduced, including the most relevant definitions and how sustainability has traditionally been integrated into BIM. Numerous approaches for integrating sustainability certification requirements and criteria into the BIM methodology are then analyzed and used to create the foundation for the integration method developed in this thesis. Finally, different model checking approaches and software packages are presented, which will later be used to check the implementation of sustainability criteria into the BIM model and provide the necessary optimization feedback.

2.1 Early Design Stages

There is no general definition of what exactly the early design stages must entail. Braganca et al. define the early design stage as including only the conceptual phase and ending at the schematic design phase. The conceptual phase encompasses the definition of project goals, objectives and schedules as well as general information regarding materials, the type of architecture and functional aspects of spaces. This phase is presented in the form of early schematic drawings and layouts (Bragança et al., 2014). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the early design stage is broader and includes the schematic design phase as well (ASHRAE, 2006). In this phase the plans, sections and elevations are created, and the design decisions proposed in the conceptual phase are developed to find the preferred design solutions. The American Institute of Architects (AIA) includes not only the conceptual and schematic design phases but goes one step further to include the design development phase where elaborate drawings are created and the design details are confirmed. The German HOAI (Ordinance on Architects’ and Engineers’ Fees) defines the early stages similarly to the AIA, as spanning from service phases 1 to 3, which cover basic project evaluation, preliminary design, and design draft (Schneider-Marin & Abualdenien, 2019). For this thesis, the early design stages can be defined in line with the broader definitions of the AIA and HOAI as including all the design stages before construction documents are prepared and project execution begins.

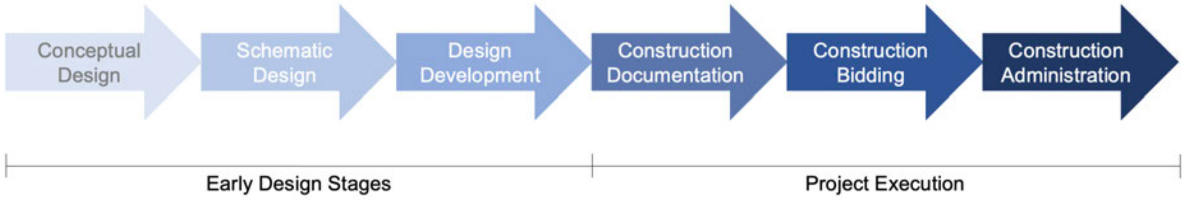


Figure 2.1: Design stages (based on Schneider, 2018)

Increasing complexity and specialization across all areas of planning and construction make it essential for project participants from various disciplines to be brought together at the start of a project. The early stages of the design process have a particularly important influence on the overall appearance of a building, the costs associated with the project, the performance over the total life cycle of the building, and the ability of the building to meet changing needs in the future. In these early stages, the opportunity for influencing the design is still high and the costs associated with these changes are still low. As shown in Figure 2.2, the earlier on a change is suggested, the higher the opportunity for influence and the lower the cost of making the suggested changes. Once the design becomes finalized and the construction phase begins, the cost of making changes increases drastically and the possibilities for making changes become far more restricted.

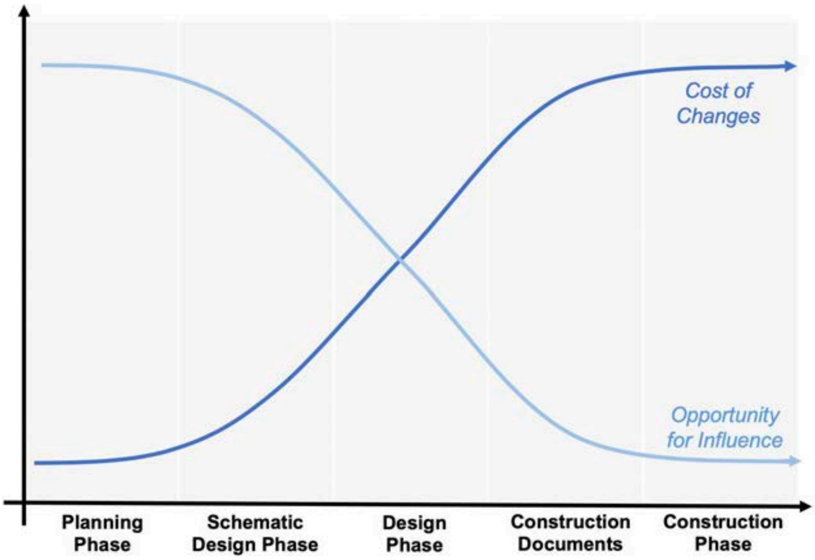


Figure 2.2: Influence and cost of design changes per planning phase (WBDG, 2020)

The greatest opportunity for design optimization, specifically in regard to the implementation of sustainability objectives is in these early design stages. Specifically, the type of construction, the materials selected for the design, as well as energy efficiency measures and building operation concepts can still be influenced the most in these early stages. The early decisions ultimately impact the building across its entire life cycle, so it is important that all relevant objectives are not only discussed thoroughly but are also implemented as early as possible. The criteria catalogs created by established sustainable building certification systems are helpful in supporting these early design decisions. Many of them are set up to help define design objectives by offering concrete recommendations and assessment structures. By placing emphasis on the early design stages, a disjointed and reactionary design process can be replaced by a more integrated and collaborative approach. This integrated planning process has become a defining feature of sustainable building and its application is valued highly in the assessments of many building certification systems (Ebert et al., 2011).

2.2 Sustainable Building Certifications

“Sustainable building certifications help shift the industry and drive innovation by formalizing design and performance criteria so that what was once innovative becomes the norm.” – Tiffany Broyles Yost, Associate Arup

Buildings that are designed and built with the help of sustainability certifications are known to outperform conventional buildings in regard to environmental, economic and social parameters. According to the World Green Building Council, sustainable buildings can achieve energy savings of 30-50%, water savings of 20-50%, and produce up to 62% fewer greenhouse gas emissions (WorldGBC, 2020). Additionally, the construction waste produced by a sustainable building is typically 50-75% less than that produced by a conventional building (Kats et al., 2003). Economically, the value of sustainable buildings can be increased by up to 7.5% and the operating costs can be reduced by up to 9%. Sustainably planned buildings can also have an increased return on investment of up to 6.6% and increase occupancy by 3.5% (Vierra, 2019). Furthermore, due to better natural daylighting, superior indoor air quality, and the overall use of healthier products and materials within sustainable buildings, they can improve occupant health and lead to higher productivity in comparison to conventional buildings (Vierra, 2019). Studies have shown that mental function and memory can be improved by up to 25% and productivity can increase by 18% in sustainable buildings. The prevalence of sick building syndrome, which comes from spending too much time indoors and has symptoms that include headaches, dizziness, fatigue, nausea and difficulty concentrating can be reduced by 70-85% (WorldGBC, 2020). Many sustainability certifications also go beyond the building and help to create more diverse and accessible neighborhoods, that focus on communal participation in the planning process, provide access to alternative modes of transportation and better connections to local amenities, all of which can help improve the quality of life of the building's occupants and the overall livability of a neighborhood.

In addition to the environmental, economic and societal benefits, sustainability certifications can also be used to ensure a high level of quality during the planning, design and construction phases. Building certifications play an essential role in determining which changes to make in the planning process, as they provide a concrete set of recommendations that can be implemented early on to strengthen sustainability agendas and improve a construction project at large. In today's society of rapid development and growth, building planners, designers, consultants and investors are constantly confronted with the challenge of making informed decisions in order to meet the demands of sustainability, which will impact not only the environment but also the economic success of their projects. With the term sustainability becoming more board and the consequences of non-sustainable development becoming more pressing, the pressure on all those involved in the building sector is increasing. As a result, sustainable building certifications now vary greatly in depth and scope and cover a multitude of different applications. However, if these systems are used properly in the early stages of a project, they can help clearly define goals and can provide comprehensive design tools for creators while also acting as valuable verification tools for investors and buyers (GXN & Statens Byggeforskningsinstitut, 2018).

2.2.1 Types of Sustainable Building Certifications

"Sustainable building certifications are tools we can use to measure and document sustainability as well as support integrated design and interdisciplinary collaboration."
- Gitte Gylling, Chief Specialist, Rambøll

Today, there are over 50 different certification systems available on the international market for the sustainability certification of buildings. These certification systems offer a wide variety of evaluation criteria and objectives, however, they ultimately have the following goals in common:

- Creating a mutual understanding of sustainability
- Promoting transparency in a relatively non-transparent market
- Assessing a building over its entire life cycle
- Enhancing performance and value in comparison to non-certified buildings
- Improving marketing potential for sustainable real estate (RICS & IREBS, 2018)

In Germany, three predominant sustainability certification systems are favored. According to a 2017 study by the RICS and IREBS, DGNB, LEED and BREEAM accounted for nearly all certifications carried out within in Germany for new constructions and renovations. Based on this study, the DGNB system was used in nearly 80% of all certifications, followed by LEED with roughly 18%, and BREEAM with approximately 2% of the market share (RICS & IREBS, 2018). The values published by BNP Paribas for new construction certifications in 2017 showed a very similar distribution with approximately 82% DGNB, 16% LEED, and 2% BREEAM (BNP Paribas, 2018). The market share of BREEAM certifications is limited in these reports as the BREEAM system is used more frequently in the certification of existing buildings. A distribution of the market share for existing buildings shows that BREEAM has the clear majority with nearly 57%, while both LEED and DGNB account for only about 20% of the certifications (BNP Paribas, 2018).

The certification within each system is based on a variety of criteria that assess the sustainability performance of buildings using a structured format. The sustainability-related priorities of each certification systems vary based on the weighting and selection of the evaluation criteria. Below is a comparative overview of the three certification systems that are mainly used in Germany.

Table 2-1: Overview of certification systems used in Germany (based on RICS & IREBS, 2018)

Certification System	**BREEAM**	**LEED**	**DGNB**
Established	1990	1998	2009
Organization	Building Research Establishment (BRE) Global	USGBC – U.S. Green Building Council	DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen
Ratings	• Outstanding • Excellent • Very Good • Good	• Platinum • Gold • Silver • Certified	• Platinum • Gold • Silver • Bronze

	- Pass - Acceptable		
Evaluation Criteria	- Energy - Health & Well-Being - Innovation - Land Use - Materials - Management - Pollution - Transport - Waste - Water	- Location and Transportation - Sustainable Sites - Water Efficiency - Energy and Atmosphere - Materials and Resources - Indoor Environmental Quality - Innovation - Regional Priority	- Environmental Quality - Economic Quality - Sociocultural and Functional Quality - Process Quality - Technical Quality - Site Quality
Scope of Application	- New constructions - In-Use - Communities - Infrastructure - Refurbishment and fit-out	- New constructions - Interior Design - Building Operations and Maintenance - Neighborhood Development	- New constructions - Existing buildings - Renovations - Buildings in Use

BREEAM

The Building Research Establishment Environmental Assessment Method (BREEAM) was developed in the United Kingdom in 1990, making it the first sustainable building certification system to enter the market. Originally developed for sole use in the UK, the system has since expanded to certify buildings internationally, and has been used as a template for many of the newer certification systems that have been developed across the globe. As of May 2018, over 564,000 buildings, in 77 countries worldwide, have been certified with BREEAM, using rankings ranging from acceptable, pass, good, very good, excellent to outstanding, which is reflected in a series of stars (1-6) on the BREEAM certificate (BREEAM, 2020; GXN & Statens Byggeforskningsinstitut, 2018).

LEED

Inspired by BREEAM, the Leadership in Energy and Environmental Design (LEED) certification system was developed in 1998 by the U.S. Green Building Council. Today, LEED is geographically the most widespread certification system, being used in 164 countries and having certified over 108,770 buildings as of May 2018. The buildings are certified with a series of levels from certified to silver, gold and platinum (GXN & Statens Byggeforskningsinstitut, 2018). The main aspects included in the LEED certification system are focused around environmental sustainability, which is why LEED certifications are often synonymous with ‘green’ building certifications (GXN & Statens Byggeforskningsinstitut, 2018).

DGNB

The certification system of the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) was created by the German Sustainability Council in 2009. Since then, over 5,900 buildings in 29 countries have been certified using DGNB. It is now considered the most advanced certification system in the world and is “internationally recognized as the Global Benchmark for Sustainability” (DGNB, 2020b). It is the first 2nd generation certification system which means that it goes beyond just the environmental sustainability, by also considering the social, economic and technical aspects over the building’s entire life cycle. This is reflected by the system’s six main focus areas: environmental quality, economic quality, sociocultural and functional quality, process quality, technical quality, and site quality. By meeting the requirements of these six areas, different levels of certification can be achieved. The highest level is platinum, followed by gold, silver and bronze (GXN & Statens Byggeforskningsinstitut, 2018).

These three certification systems (DGNB, LEED and BREEAM) were analyzed further with respect to their guidelines for new construction office buildings to create a comparable starting point. The aim of this analysis was to provide a comprehensive understanding of how the goals and strategies of each building certification system differ and how the level of detail and number of evaluation criteria impacts the quality of the certification.

2.2.2 Comparison of Sustainable Building Certification Systems

To carry out a structured and transparent comparison of the three certification systems, the ‘Open House’ methodology was used. This methodology is based on creating an open platform for building sustainability that can be used to clearly communicate a baseline and find a common ground for all project stakeholders. It was developed with the help of an international consortium of partners and is based on a thorough analysis of assessment methods from over 50 countries (Essig et al., 2011). The Open House methodology is a second-generation building assessment methodology, meaning it takes into account the entire life cycle and all relevant aspects of sustainability. In essence, a comparison with the Open House methodology is based on the six categories summarized in Table 2-2.

Table 2-2: Six categories of the Open House method (based on Markelj et al., 2013)

Environmental Aspects	effects on the environment, energy use, materials, waste and water use
Economic Aspects	costs connected with the building throughout its life cycle, the value of the property and the possibility of marketing
Social Aspects	functional, cultural and design criteria, quality of the interior environment and effects on health
Technical Aspects	protection against fire, the durability of the surfaces and maintenance, resistance to weather
Process and Management	procedures for planning, procurement, construction and the building's operation
Location	the possibility of public transport, proximity of other services and the characteristics of the neighborhood

The comparison was carried out for the latest version of each certification system for assessing newly constructed buildings. To be exact, the following systems were compared: BREEAM 2016 New Construction Offices, LEED v4 Building Design & Construction (updated 2019), and DGNB New Construction Office Building 2018. For each certification system, the individual assessment criteria were sorted into the most fitting of the six Open House categories based on the discretion of the author of this thesis.

By looking at the total number of indicators or credits that are used to represent each aspect of sustainability, the level of detail with which each certification system values the different aspects can be estimated. As shown in Figure 2.3, both BREEAM and LEED focus most on the environmental and social aspects of sustainability, whereas the DGNB has the most indicators for social aspects but overall includes all aspects with a similar distribution of indicators. Especially noteworthy is the emphasis that the DGNB places on economic indicators in comparison to the other two certification systems. This can be partly attributed to the direct Life Cycle Cost (LCC) analysis which the DGNB is one of this first systems in the world to include.

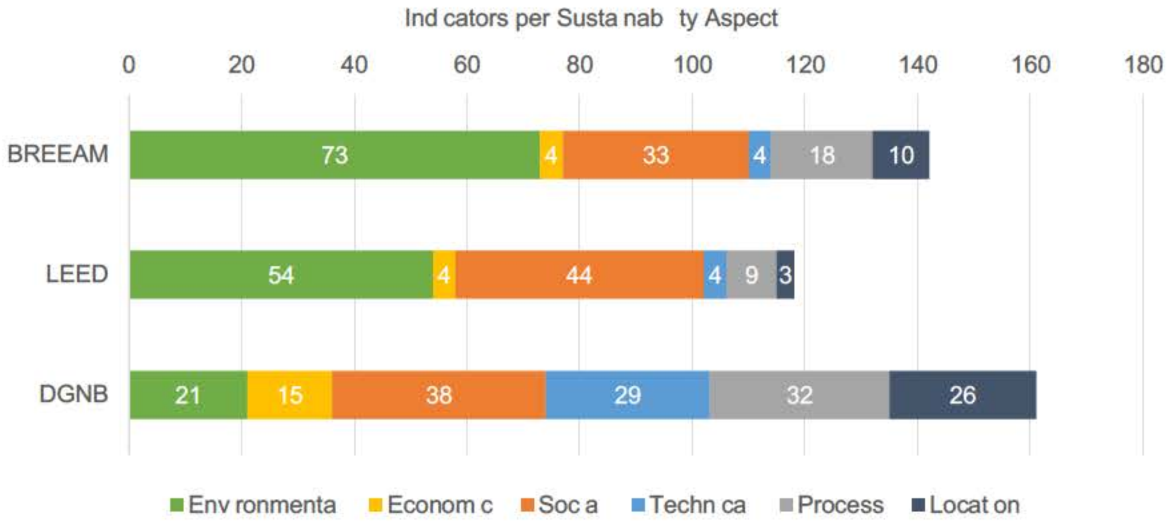


Figure 2.3: Number of indicators per sustainability aspect (based on BRE, 2016; DGNB, 2018a; LEED, 2019)

The weighting of the individual criteria also impacts which aspects of sustainability are valued the most and this weighting is at least partially redefined with each new version of the certification system. In both the BREEAM and LEED systems, this weighting is based on the amount of credits or points than can be achieved for each criterion. The DGNB system weights the criteria based on a percentage that is accounted for in the total score. Figure 2.4 shows this split including the weighting of the criteria.

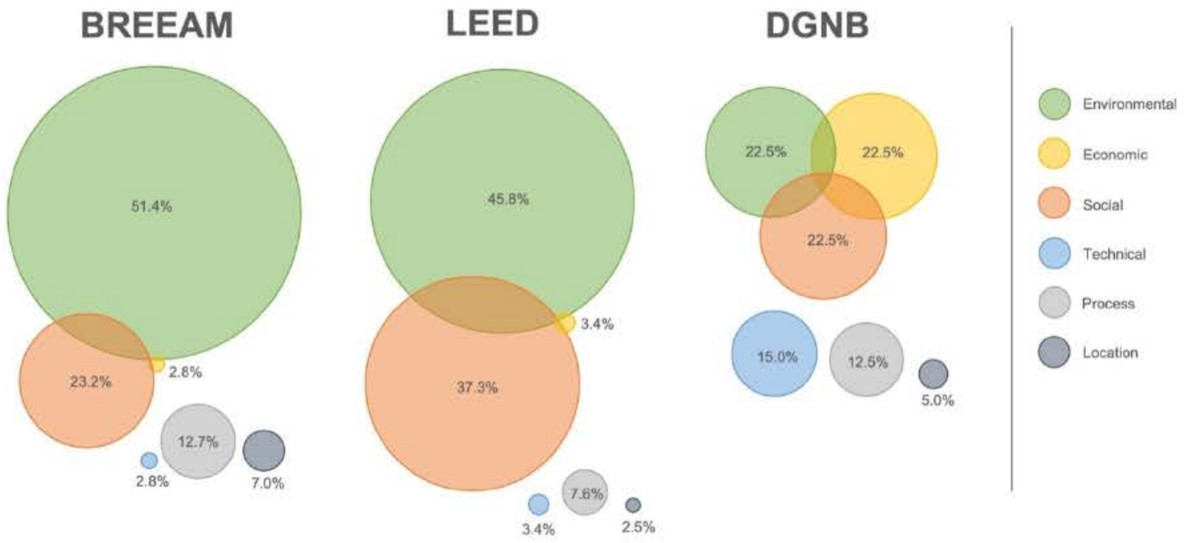


Figure 2.4: Weighting of the sustainability aspects per certification system (based on BRE, 2016; DGNB, 2018a; LEED, 2019)

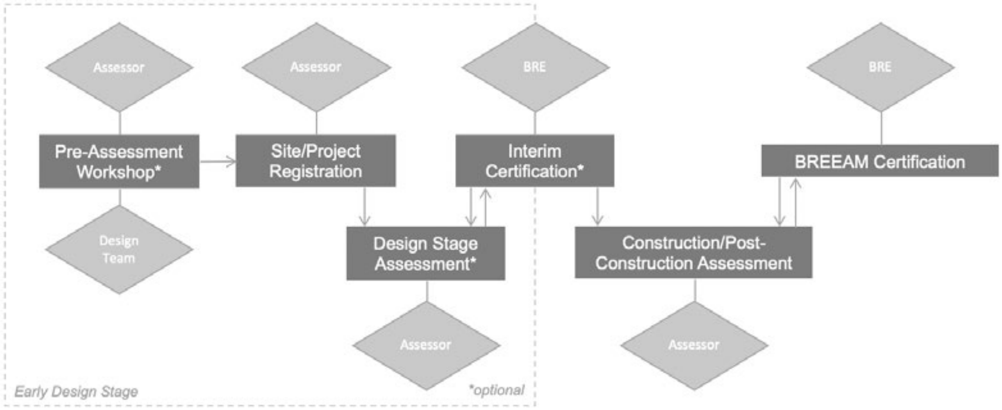
Both BREEAM and LEED are weighted such that about half of their criteria are focused on environmental sustainability, followed by social sustainability at 23% and 37%, respectively (Figure 2.4). The economic focus of both systems is minimal, accounting for about 3% of the total score. The DGNB system on the other hand has an equal split of 22.5% for environmental, economic and social sustainability. Technical quality is given a weight of 15% in the DGNB system, which is significantly higher than the approximately 3% it has been assigned by both BREEAM and LEED. Process quality is similarly weighted by all three systems and the location is weighted negligibly by LEED, while it has some impact in the BREEAM and DGNB systems.

The split of indicators and the weighting of the different aspects shown in Figures 2.3 and 2.4 make it clear that each certification system has its own goals and focuses on different aspects of sustainability based on how the system is set up and the criteria are weighted[1]. In addition to the indicators and criteria that make up each system, it is also important to understand the certification and documentation processes of the different systems and how each system is integrated into the early design stages. Figure 2.5 illustrates the certification processes of the three certification systems.

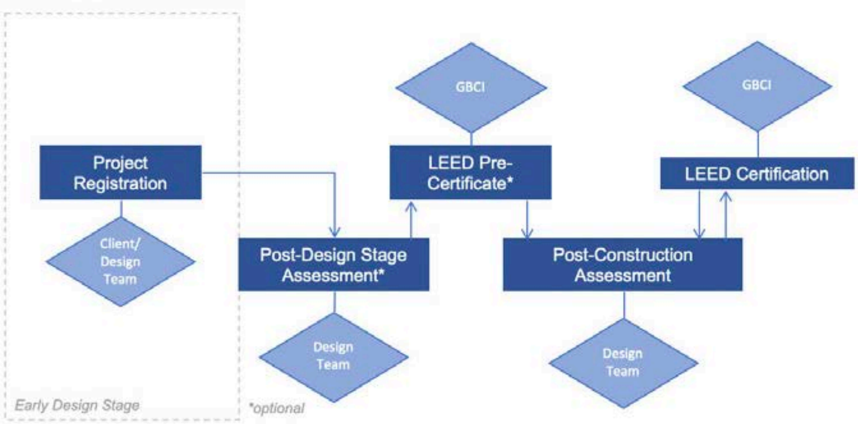
---

[1] For a further, more detailed comparison of the three certification systems using 10 overarching categories with several specific indicators, additional information is given in Appendix A: Comparison of Certification Systems using Specific Indicators.

BREEAM Certification Process



LEED Certification Process



DGNB Certification Process

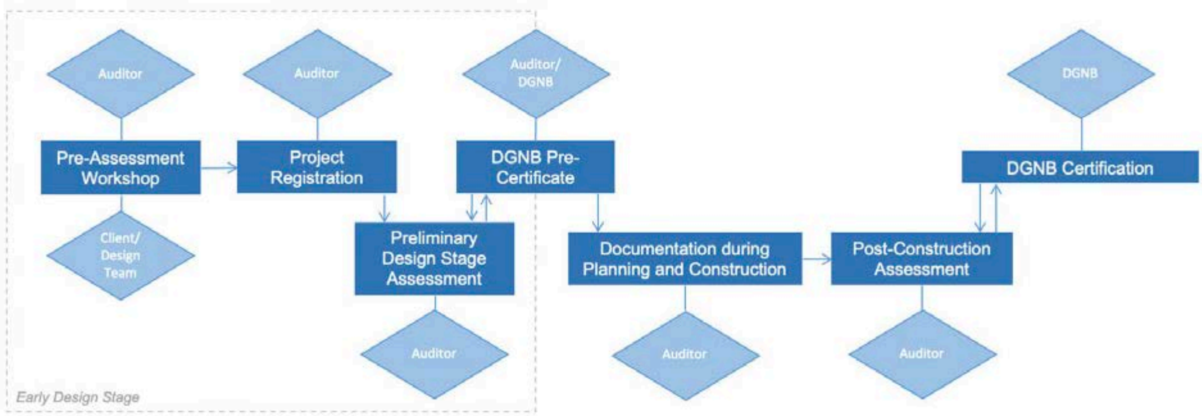


Figure 2.5: Certification process of different certification systems (based on Ebert et al., 2011)

Fundamentally, the certification processes of all three systems process can be split into two phases, the pre-certification during the design phase and the official certification at the end of the construction phase. For both BREEAM and DGNB, the pre-certification is carried out in parallel to the design phase and aims to assist in the early design stages by enabling communication between the certification body and the design team. Through workshops and the definition of project and sustainability goals, the requirements for the final certification are integrated into the design process from the beginning. The LEED certification process on the other hand is not set up for integration into the early design stages. The pre-certification for LEED is carried out once the design process has been completed, only after the criteria are already so well integrated that they can be fully analyzed. LEED also does not require that the certification process is supported by an approved LEED professional, whereas BREEAM and DGNB require that an approved assessor or auditor is involved throughout the entire certification process. In regard to documentation, the LEED system is digitally the most advanced. All documents can be submitted through an internet platform (LEED Online) and hard copies of the plans, calculations and explanations are not required. BREEAM on the other hand, requires documentation in the form of extracts from design and construction documentation, design team and/or client statements, surveys and calculations, as well as the assessor’s site survey and written statement to be submitted to BRE in hard copy format. The DGNB requires documentation to be compiled using a specialized DGNB software package. While the compilation process has been digitalized, the documents that are submitted through the software are largely based on traditional documentation methods such as Excel™ sheets, pdfs and 2D drawing files. The further simplification and digitalization of these documentation processes is necessary in order to keep up with the evolving industry standards (Ebert et al., 2011).

All three certification systems contain inherent differences with regard to content and structure, which can be attributed to when each system was developed and where it’s specific focus lies. This can make it difficult to draw direct comparison between them, however, it can be concluded that specifically first-generation systems like BREEAM and LEED place the main emphasis on environmental aspects and the energy-efficiency of the building (green building approach), while second-generation systems like the DGNB take a more holistic, performance-oriented approach (sustainable building approach), also incorporating technical and process quality. As the idea of sustainability becomes more relevant in the AEC industry, certification systems continue to evolve and even certification systems that started out as first-generation systems are expanding to include a broader range of aspects and ultimately become more comprehensive. When investigating how the essential aspects of sustainability can be integrated into the planning and building process, it is crucial to consider which elements and aspects are the most important for the project as this influences the sustainability certification that that will be used.

2.3 Building Information Modeling

BIM is a methodology for planning, executing and operating buildings using a collaborative approach that is based on a centralized supply of information for common use. BIM is not a software package but rather a method that facilitates both project management and collaboration between disciplines in all phases of a building's life (VDI 2552, 2018). Using BIM, intelligent 3D models are created that act as the primary tools for supporting this methodology and manage all information relevant to the project by linking geometric components with physical and functional characteristics. These models can be used by architects, engineers and contractors to coordinate their work and communicate more effectively, gain insights about the project through multi-disciplinary collaboration and improve overall workflows. Errors and clashes can be caught early on, data loss during information handovers can be avoided, schedules can be improved, and costs can be predicted more accurately, all of which save time and money and result in an overall higher-quality finished project (Eastman et al., 2008).

The data in a BIM model defines the design elements and establishes the behaviors and relationships between model components. When one element is altered it is updated in all views, ensuring consistency and enabling real-time collaboration. The model can also be used to improve and optimize the design before it is constructed by running analyses and simulations, regarding lighting, energy consumptions and structural integrity. Realistic visualizations can be created using the model and design intent can be more effectively communicated to stakeholders and the public. Most importantly a building information model can be used throughout the entire life cycle of a building to ensure that no important information is lost between conceptual design, construction and finally building operation and maintenance (Azhar, 2011).

2.3.1 BIM Motivation

Digitalization is transforming our world and is becoming increasingly more widespread across many industries, increasing productivity, product quality and market variety. However, the use of digital tools is still lacking in the AEC industry compared to other industries, which results in valuable information getting lost at all stages in the building life cycle, especially during data handover between different project phases (Borrmann et al., 2018).

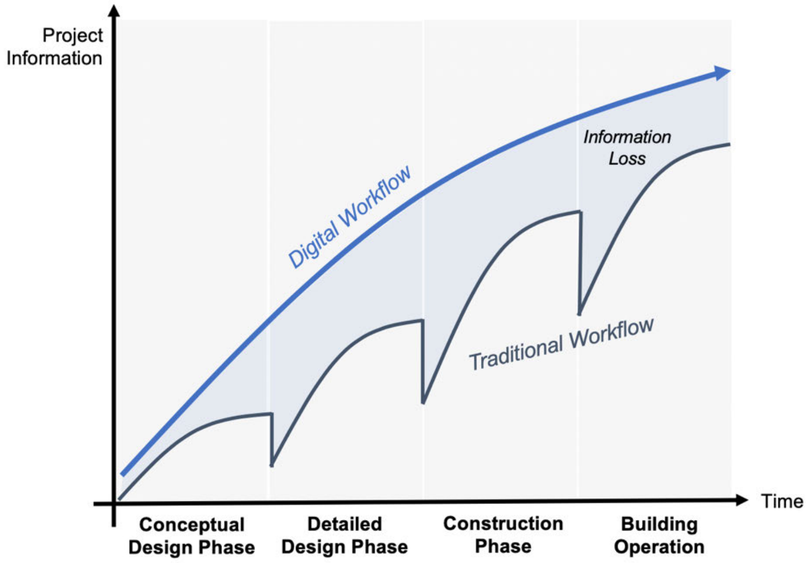


Figure 2.6: Information loss with conventional workflows vs. digital workflows (Borrmann et al., 2018)

Planning and realizing a building are very complex processes that involve a wide range of disciplines. In order for a project to be successful, all of these areas of expertise must constantly work together, exchanging ideas and information, which is difficult when the tools being used do not support this kind of continual communication. Drawing consistency is often still being checked manually and ensuring that all stakeholders have the most recent version of the design can be nearly impossible, leading to inconsistencies often only being discovered after construction has started. Traditional technical drawings are also limited in the depth of information they contain, meaning that information cannot be accessed by downstream applications for calculations, analyses or visualizations. The same applies to building operation and facility management after construction is complete; all information must be gathered manually and reentered into a facility management system (Borrmann et al., 2018). Overall, the way that information is traditionally exchanged in the complex AEC industry is outdated and does not take advantage of the immense potential that information technology provides for supporting project management, construction and building operation.

Building information modeling presents a possible solution for the current shortcomings within the AEC industry. BIM enables a more refined use of digital technologies in the design, engineering, construction and operation of buildings. Using BIM improves productivity and the overall quality of a project by reducing sources of error from manual information transfer and checking. Information is maintained and exchanged using comprehensive and easy to use digital representations or models that can be accesses anywhere and updated in real time (Azhar, 2011). These models allow for better coordination during design, enable the integration of simulations and downstream processing, create better control over the construction process and provide the building operator with all the information they need for proper facility management the moment that construction is complete (Borrmann et al., 2018).

The biggest challenge for proper integration of the BIM methodology into the AEC industry is that such a wide variety of different stakeholder are involved. This creates a large number of digital interfaces, with a diverse range of information being shared, all of which needs to be organized and managed by a single entity. Additionally, a direct translation of traditional workflows is not possible and new, digital means of collaboration can take some getting used to. For this reason, it is ultimately the responsibility of the building owner to mandate the use of BIM and provide support to all stakeholders throughout the entire process.

2.3.2 BIM Methodology

It is crucial to distinguish that BIM is not just a software, rather it’s a process that incorporates specific software products. Implementing the BIM methodology means using intelligent 3D models that contain both geometry and semantics, but also making significant changes to the traditional workflows and project delivery processes (Azhar, 2011).

For the purpose of this thesis, BIM can be defined as a modeling technology and associated set of processes to produce, communicate, exchange and analyze building models throughout the entire lifetime of the building. A building information model is a comprehensive digital representation of a planned or existing building and is characterized by three-dimensional geometry of building components at a certain level of detail. These building components are depicted with intelligent digital representations or objects, meaning that they know what they are, and can be associated with computable graphics, attributes and parametric rules. A defining feature of a building information model is that objects within it have clearly established semantic information associated with them, including the type of object, technical properties, materials, costs, etc. (Borrmann et al., 2018). The objects also include data that describes how they behave and are related to other elements around them. This is necessary for analyses and downstream processing, such as writing specifications, performing quantity take-offs and running performance simulations and structural analyses. All data within the model is consistent and non-redundant so that changes to components are incorporated in real time and in all views (Eastman et al., 2008).

There is no universal definition of exactly what information must be included within a BIM model. Instead, the depth of information is dependent on the use case or the purpose of the specific model. The committee BIM4INFRA2020 was commissioned in 2016 to create a BIM implementation plan for Germany and has defined a list of 20 use cases that can be found in Appendix B: BIM4INFRA2020 Use Cases. Table 2-3 provides an overview of some of the most frequently applied BIM use cases with a brief description of what is required for each use case.

Table 2-3: Frequently implemented BIM use cases (based on Borrmann et al., 2018)

Use Case	**Description**
Existing Conditions Modeling	Incorporating the existing site conditions into the model to create a more realistic basis for the project
3D Coordination	Combing the different discipline models into a coordination model at regular intervals, to detect clashes and reduce errors and costs
Phase Planning (4D Modeling)	Linking model components with their corresponding construction processes to create an accurate construction schedule
BIM-based Simulations and Analyses	Performing structural, energy, daylight, etc. simulations using inputs from the BIM model
Cost Estimation	Using the BIM model for a quantity take-off that can be used as the basis for a cost estimation
Code Validation	Automated checks of the BIM model using digital rule sets of standards
Visualizations	Creating visualizations from the 3D model as a communication tool for project meets, marketing and public relations

Defining the intended use case is one of the most crucial steps at the start of a BIM project execution and is typically defined by the employer or client. The use cases also have a signification impact on the required geometry (level of geometry), the required semantics (level of information), and the different types of exchange scenarios that will be necessary throughout the project. It is common for multiple BIM models to be used across progressing project phases, each adjusted to the requirements and use cases of the specific phase (Borrmann et al., 2018).

2.3.3 BIM Implementation and Relevant Definitions

For a successful implementation of BIM, it is important that several terms are clearly defined to create the foundation for the BIM framework. As already indicated in the previous section, the use cases are the basis for the required geometry and semantics within a building information model. According to Borrmann et al. (2018), the term **Level of Development** (LOD) is used to express the overall required geometric detail (Level of Geometry - LOG) as well as the alphanumeric information (Level of Information – LOI) that must be included in the model. The LOD provides a clear indication of the content, extent and reliability of a building information model and designates the entire amount of information that a BIM element contains (Borrmann et al., 2018). While there are a variety of definitions for what exactly the LOD contains, the BIM-Forum has standardized six LODs of increasing depth and complexity (100, 200, 300, 350, 400, 500).

Table 2-4: LODs with description (based on BIMForum, 2018)

LOD	Description
LOD 100	model elements may be represented graphically with a symbol or generic representation but are not yet geometrically depicted
LOD 200	model elements are graphically depicted as generic placeholders and systems, objects or assemblies only contain approximate sizes, shapes, orientations and locations
LOD 300	model elements are graphically represented as specific systems, objects or assemblies including exact quantities, shapes, sizes, orientations and locations
LOD 350	model elements are graphically represented as specific systems, objects or assemblies including exact quantities, shapes, sizes, orientations and locations as well as the interfaces with other building systems, the parts needed for coordination with other elements, such as supports or connects, are also modeled in this LOD
LOD 400	model elements are graphically represented as specific systems, objects or assemblies including exact quantities, shapes, sizes, orientations and locations including all relevant detailing, fabrication, assembly and installation information, an element from this LOD is modeled with enough detail and accuracy to be properly fabricated
LOD 500	model elements are field-verified representations in terms of quantity, shape, size, orientation and location, this LOD is not typically used as it does not indicate a progression to a higher level of model geometry or information

The LOD requirements are typically included as a part of the **Employer's Information Requirements** (EIR), which are defined at the start of a new project. The EIR is created by the client or the employer and clearly outlines to the bidder which models are required and what the models will be used for. All information regarding the use cases that are to be applied in each phase of the project are definitively stated in the EIR. The goals of the BIM project as well as the technical, managerial and contractual aspects relevant to the project are also defined in this document. Additionally, the EIR contains information regarding the classification (OmniClass, UniClass, DIN276, etc.) and coordinate systems that are to be used during project execution and how information is to be checked and delivered.

In response to the EIR the bidder creates a **BIM Execution Plan** (BEP). This document defines all aspects of how the BIM project is going to be carried out. Typically, a BEP includes detailed information regarding the BIM use case implementation, BIM workflow and data management structures, model contents (i.e., elements, levels of detail, classification, coordinate systems, file formats, etc.) and the major deliveries and milestones with the information that will be provided at each. One of the most crucial parts of the BEP is clearly defining how and what information is going to be exchanged. This is included in the BEP as the **Master Information Delivery Plan** (MIDP). The MIDP contains the primary plan for the preparation of the project information that is required by the EIR. For each stage of the project a list of information deliverables (e.g., models, drawings, specifications, schedules, etc.) is prepared, including when and by whom the information is to be delivered and what protocols and procedures will be followed (Borrmann, 2019).

To make the data exchange in BIM projects more successful, the international nonprofit buildingSMART has created the ‘Information Delivery Manual Part 1: Methodology and Format’. This manual describes the processes and information flows for planning, constructing and operating buildings. It clearly describes the information that needs to be exchanged between parties. In order for the **Information Delivery Manual** (IDM) to be operational it needs to be supported by software, as the main purpose of the IDM is to ensure that data is exchanged in a way that it can be interpreted by the software on the receiving end. The IDM uses the graphical language **Business Process Modeling Notation** (BPMN) to describe the data exchange process in a Process Map, where all exchange requirements are clearly indicated. Today, this methodology is accepted as an ISO standard (ISO 29481) and the resulting document forms the basis for BIM contracts and software implementation (buildingSMART, 2020).

BIM Implementation Levels

Before diving deeper into the implementation of BIM within a project it is important to understand that different levels of BIM implementation exist. The most basic differentiation is between 'BIG BIM' and 'little BIM'. Little BIM means that the BIM methodology is only being used by a single discipline and not by all project participants. With this type of implementation, all external communication is conducted using drawings. BIG BIM is used when all stakeholders are consistently using model-based communication, throughout the entire life cycle of the building. For a BIG BIM implementation, data is exchanged using defined workflows, databases and project platforms. In addition to the extent of BIM use, as defined by BIG and little BIM, the terms 'Closed BIM' and 'Open BIM' (also openBIM) are used to distinguish between the exclusivity of utilized software products. In a Closed BIM implementation, only software products from a single vendor are used and data exchange is based on proprietary formats. Open BIM, on the other hand, allows software products from a wide variety of vendors and data is exchanged freely using neutral data formats. Figure 2.7 provides an overview of the four BIM varieties.

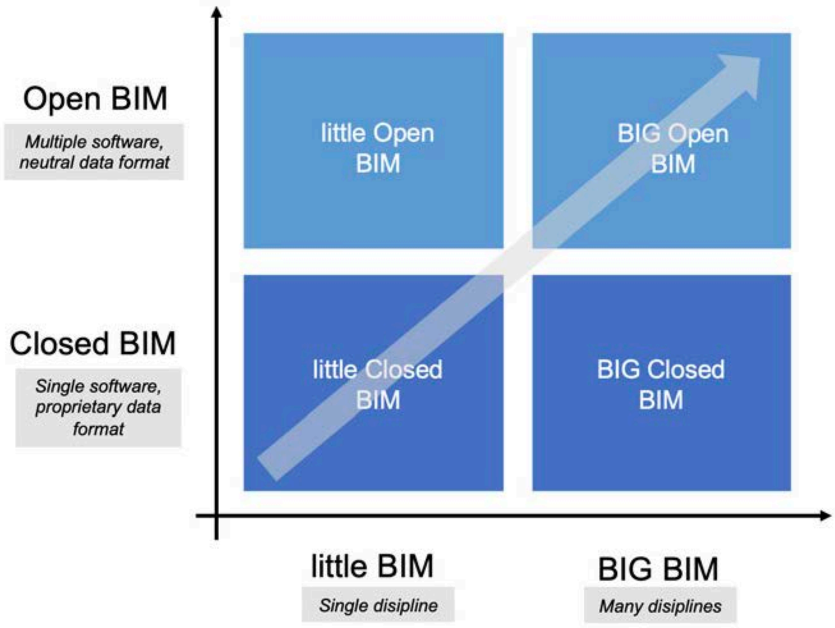


Figure 2.7: Overview of BIG/little/Open/Closed BIM (based on Liebich et al., 2011)

BIM Data Exchange

Due to the complexity of projects within the AEC industry, it is common that data needs to be exchanged between a wide range of different stakeholder, many of which use their own specialized software solutions. To improve the data exchange between these different AEC software programs, buildingSMART defined a vendor-independent, standardized data model for the exchange of building information models, which has become the basis for the Open BIM approach. This data model is known as **Industry Foundation Classes** (IFC) and represents both the geometry and the semantics that are contained within a model. In 2013, the IFC data model was adopted as an ISO standard (ISO 16739) and today all BIM tools provide import and export functionalities for IFC files (Borrmann et al., 2018). Next to the IFC, the **BIM Collaboration Format** (BCF) provides an open exchange format that enables communication within the Open BIM method and is used to track issues within a model. The BCF is based on the XML-Schema, which is a markup language that defines a set of rules for encoding a document in a format than can be read by both machines and humans. Using the BCF, object-specific comments can be created within the model. A BCF-file includes three components, the comment regarding the issue within the model, the viewpoint coordinates on the basis of the digital model and an image file that shows the current view and the issue. Using the BCF-files, errors within the model can be clearly communicated to the responsible parties and the issues can be fixed and a status update can be added right in the original BCF-file (ONIB, 2019).

BIM Roles and Responsibilities

Implementing BIM into the AEC industry not only alters the traditional workflows but also creates new tasks and responsibilities. As a result, new jobs such as the BIM Manager, the BIM Coordinator and the BIM Modeler have been created. The BIM Manager is responsible for setting up project templates and establishing company and model standards surrounding BIM. The BIM Manager is also in charge of handling issues of interoperability and data exchange as well as advising on how best to implement new BIM practices into the workplace. The BIM Coordinator is more specialized and is assigned to specific projects. It is the coordinator’s responsibility to organize the different disciplines, merge sub-models, perform model checking operations and ensure that the client’s needs and demands are being properly met. The BIM Modeler is typically an architect or engineer and is the one responsible for actually creating and developing the building information model and producing the necessary drawings (Borrmann et al., 2018). Table 2.5 provides an overview of the responsibilities associated with each of these three roles.

Table 2-5: Responsibilities of each BIM role (based on AEC (UK), 2012)

	Strategic						**Management**				**Production**	
	Corporate Objectives	Research	Process and Workflow	Standards	Implementation	Training	Execution Plan	Model Audit	Model Coordination	Content Creation	Modeling	Drawing Production
BIM Manager	X	X	X	X	X	X	X					
BIM Coordinator						X	X	X	X	X	X	
BIM Modeler										X	X	X

BIM Dimensions

Finally, there are several different dimensions of BIM that are important to understand in addition to the implementation levels and the typically roles of BIM professionals. 3D BIM is the most familiar dimension and is based on collecting graphical and non-graphical information to create 3D models that are shared in a Common Data Environment (CDE). 4D BIM builds on 3D BIM by also adding time information to the model. This could include information such as installation times, curation of materials or time until operation. 4D BIM can aid planners in creating proposals far earlier than they could using traditional workflows and help collaborators better visualize the progress of the project, thus positively impacting the timeline. 5D BIM is related to costs, such as being able to extract information from the model regarding the costs of specific components and seeing how prices and total costs change over time. This cost data can help with budget tracking and cost analysis of a project, which can result in greater estimate accuracy for the entire project. 6D BIM is focused on the sustainability of a project. The data in this dimension includes information from the manufacturer such as maintenance schedules, component configuration for optimum performance, expected life span, etc. This information can help save energy and money in the operational phase as well as helping to prolong the lifespan of the building and its components by ensuring regular and thorough maintenance (Repo, 2019). With sustainability becoming a more prominent aspect of the AEC industry, BIM will also need to adapt to better represent sustainability criteria and increase the interoperability with sustainability simulations and software.

2.3.4 BIM and Sustainability

The ability of BIM to create a virtual version of a building before construction even begins, can be utilized to create more efficient structures that limit the waste of resources, promote passive design strategies, and optimize energy consumption. By making innovative, sustainable changes in the planning, construction and operation of buildings, more sustainable communities will begin to emerge and over time these trends will not only reduce the impacts on the built environment but also on the ecological environment at large (Bynum et al., 2013).

However, both BIM and sustainability analyses are still relatively new concepts in the AEC industry, so much of their potential is still being discovered. To date, sustainability has been incorporated into BIM by expanding BIM models to include location and weather data that can be used in sustainability simulations, such as daylighting and wind studies. This location data has also been used to optimize building orientation and massing which can increase the efficiency of passive design measures. Additionally, the BIM model can be used to evaluate various building skin options and life cycle analyses can be performed throughout the planning process to optimize the building materials in terms of both environmental impacts and costs. Finally, plug-ins can be utilized to calculate operational energy use and track carbon emissions to create an overall more sustainable building even after construction (Bynum et al., 2013).

There are currently two phases of the BIM tools that can be used to incorporate and analyze sustainability aspects in a BIM model. Phase one includes inherent BIM software features that can be used for sustainability purposes. Phase two includes the export of the BIM model into BIM-based analysis tools that can be used to further investigate and optimize a building's sustainability (Solla et al., 2016). Ultimately the two phases should be combined to create the best results, however, this can often be challenging due to lack of interoperability between different tools. The two phases are described in more detail in Table 2-6.

Table 2-6: Phases of BIM Tools, based on (Wong & Fan, 2013)

	Phase 1	**Phase 2**
	Inherent BIM Features	BIM-based Analysis Tools
Software	Autodesk Revit, Graphisoft ArchiCAD, Nemetschek Allplan, AutoCAD Architecture, Navisworks, Rhinoceros, Vectorworks, MicroStation, etc.	Green Building Studio (GBS), Insight 360, IES-VE, EnergyPlus, HEED, eQUEST, DOE2, FloVent, ODEON Room Acoutics Software, TRNSYS, etc.
Sustainability Aspects	Building orientation and massing, load data, etc.	Building load calculations, energy analysis, solar, lighting and wind studies, ventilation, materials, acoustics, etc.

As the demands for both BIM and sustainability are increasing, it will be necessary to develop even more sophisticated and robust integration procedures to expand the levels of achievement that have been reached so far. Sustainable building certifications provide one way that this integration can continue to evolve. These certifications provide highly structured systems with many different areas of focus that can be used as the basis for expanding the BIM capabilities in the future. By integrating the criteria presented by the certification systems into the basic BIM workflow, sustainability can become engrained in the BIM methodology and both BIM and sustainability can continue to evolve to positively impact the future of the AEC industry.

2.4 Approaches to Check the Integration of Sustainability with BIM

BIM-based model checking (BMC) is one of the major benefits to come out of digitalizing the AEC industry workflows. BMC is software that processes and validates the information contained in BIM-files based on rules from pre-defined procedures. BMC consists of three parts: the software, the rule sets and the BIM-files. It can be used to demonstrate and better understand the power of the information that is contained within a BIM model in a transparent way. This can help improve the overall quality of a building information model, can be used to validate optimizations, and can facilitate communication between different stakeholders (Hjelseth, 2015b).

2.4.1 Types of Model Checking

The term model checking is not clearly defined. It is often used synonymously with clash detection or compliance checking but the term is actually broader. Hjelseth and Nisbet (2015) created a framework for understanding the types of model checking by splitting them into four main categories: validating, guidance, adaptive and content checking.

Validation model checking, often called compliance checking, is based on comparing the model with a set of pre-defined criteria. The model can then either pass or fail in comparison to these criteria. An example of this type of BMC is a rule that states that a doorway is to be at least 800 mm wide. Based on this value the doorways within the model can either pass, if they are 800 mm or greater, or they fail, and the model needs to be adjusted. The intention of guidance checking is to provide the designer with a range of solutions based on best practice rules. This type of checking is based on two elements: rules that identify where an issue occurs and a list of possible solutions that are presented once a problem is identified. Due to the complexity of the AEC industry, and thus the wide range of solutions that would need to be developed, this type of BMC has not been widely implemented in the construction sector. Adaptive model checking is similar to guidance checking, except that problem areas automatically fix themselves, once an issue has been registered. This is done on the basis of embedded behavior rules. For example, if a doorway is less than 800 mm, it automatically adjusts the width of the door to be at least 800 mm. The final type is known as content checking and can be defined as the declaration of specific information. Here information is filtered to be further analyzed either by BMC or another software (Hjelseth, 2015b). Based on the different types of model checking, a variety of different functions can be fulfilled using BMC.

2.4.2 Model Checking Functions

Most commonly, BMC is used for clash-detection. In this case, the model checker finds intersections, overlaps or spatial conflicts between different model elements. Often these issues could also be detected with visual checking, but specifically smaller clashes can often be overlooked, and these are known to cause problems later on, when the model is used in downstream processing software. Using a model checker produces identical results every time and has a far greater reliability than visual inspection. However, when carrying out a clash detection the number of issues found by the software can sometime be overwhelming, as the clash detection rules are rather coarse, and the BIM-files may not be specific enough. To deal with this over-reporting, model checking software has developed a function that allows the issues to be categorized based on severity. This is done with rule-based reasoning, which assigns severity levels based on how to BIM objects are defined. For example, a pipe intersection with an architectural wall is categorized with low severity, while a pipe intersecting with a structural wall could be marked with critical severity. Whereas clash detection focuses mainly on the geometry of the model, BMC can also be used for compliance checking which is primarily information-based checking. Code compliance checking can help determine if the building is designed in accordance with codes, regulations, standards, etc. which can speed up permitting processes. For this type of checking the rule sets are often clustered which allows multiple demands to be checked automatically (Hjelseth, 2015b).

Especially when working with federated BIMs for each discipline, that must be combined at regular intervals, the use of BMC as a coordination and reporting tool is essential. Creating a coordinated model out of discipline-based sub-models can be done directly within the BMC. Reports can be generated and exported in a variety of different formats, including PDF, XLS and BCF format. (Hjelseth, 2015b) This enables communication between the different stakeholders and can also be used to document and track the development of the project.

A model can also be checked for content, meaning that the model is automatically processed for a specific kind of information. This can often be done in a fairly simple manner by just filtering the model for specific information that can then be analyzed in other software programs. Oftentimes this is used during handover of the model or before processing for calculations. It can also be done in preparation for more information intensive model checking processes such as compliance checking (Hjelseth, 2016). In addition to content checking, BMC can also be used for its search functions and to perform quantity and information take-offs, although these are used far less frequently than clash detection, compliance checking, coordination and reporting.

2.4.3 Model Checking Software Solutions

The development of BMC is closely linked with the development of the Open BIM approach and the use of the IFC data format. Overall BIM-based model checking is still fairly new with the oldest software on the market being Navisworks from Autodesk. Navisworks can be used by engineers and architects to open and combine BIM models. It can be used for clash detection and also includes tools that can animate objects for simulations as well as functionalities for creating schedules directly from the project model. Solibri is technically the first true Open BIM-based model checker on the market and is a tool that can be used by all project participants. It is based on rules that are used for analysis and validation and theoretically facilitates unlimited testing of model behavior. Open BIM Model Checker is a tool that can be used to check BIM models, as well as manage the issues that are detected within the model. It is integrated into Open BIM using the IFC standard. Table 2-7 shows the main BCF software solutions on the market today. This table is only meant to provide an overview, the best software cannot be objectively determined, it always depends on the purpose for which it is needed.

Table 2-7: BIM-based model checking software solutions (based on Hjelseth, 2015b)

		Navisworks	**Solibri**	**Open BIM Model Checker**
Functions	Clash Detection	X	X	X
	Compliance Checking		X	X
	Content Checking		X	X
	Search Function	X	X	X
	Reporting	X	X	X
	Quantity Take-off	X	X	X
	Animations	X		
	Scheduling	X		
Exchange Formats	Import of BIM File	Nearly all formats	IFC, dwg	IFC
	Plug-in to Revit	X		
	Export of Reports	pdf, tml, XLS	pdf, XLS	IFC, others
Rule Sets	Separate Rule Sets		X	X
	Modification of Existing Rules Sets	X	X	X
	Combining of Rule Sets		X	X
	Creation of New Rule Sets		X	X
Costs	License Cost	Professional	Professional	Free

In addition to the BMC software shown above, there are a variety of issue management platforms that can be combined with the results from software like Navisworks and Solibri to enhance communication on the basis of the model checking results. These types of software were not included in this analysis as the ability to create rule sets is fundamental to the research in this thesis and only the three software packages listed above provide this capability. Due to its functionalities that allow nearly unlimited model behavior checking, Solibri is the most used BMC software for BIM-files in IFC format, followed by Navisworks (Hjelseth, 2015a).

2.4.4 Limitations of BIM-based Model Checking

There are several limitations of BMC that need to be taken into account to ensure the best possible use of the model checking software. One of the most commonly encountered issues is over reporting, in terms of too many false issues being produced by the software. In addition, the variations in IFC implementation, based on the different backgrounds of modelers, can result in different model styles and depths of information that can either increase or decrease the effectiveness of the model checking software. For successful implementation, knowledge is required about the correlation between the content in the model and the rule sets that will be checking that content. It must be understood how information is properly put in so that it properly comes back out using the model checker. Furthermore, multidisciplinary collaboration requires all the models to be at a similar LOD in order to be able to perform BMC, which can be challenging if these requirements are not communicated well in advance. Ultimately if the BIM-file is not prepared properly during modeling, the BMC does not work effectively. This includes paying close attention to the naming conventions for different elements, the proper modeling of connections between elements and the correct allocation of element attributes within the IFC data structure (Hjelseth, 2015b). However, if the modeling standards and requirements are clearly defined in the BEP and are made available for all model creators, BIM-based model checking can be one of the best ways to illustrate and verify the information contained within a BIM-file. It enables collaboration between disciplines, results in higher quality BIM models and if understood and used appropriately can save immense amounts of time.

2.5 Current Integration Approaches of Sustainability Certifications with BIM

Integrating the sustainability certification process into the BIM methodology can lead to many benefits. Above all, a proper integration with BIM improves the communication and information consistency between all project participants (ONIB, 2019). Specifically in the early design stages, different design variations can easily be compared with respect to both environmental and economic factors (Ernst & Essig, 2016). By having one centralized building model that is always up to date, the repetition of recollecting data every time the model is updated can be reduced. Sharing the required data, plans and information about the building can also be done more easily and directly using the building information model and does not depend on drawings that are generated by each stakeholder, which can vary greatly in depth and quality. Certain values that are required for the certification can be generated directly within the model and checking of these values can even be automated. Furthermore, simulations can be carried out more easily and it is no longer an issue to run new simulations each time the design is changed (Petrova et al., 2017). By combining the BIM methodology with the conformity-based workflows of the certification systems, more consistent models and results can be generated and the certification processes can become more standardized. Overall, the entire certification process can become more efficient and transparent if it is properly integrated into the BIM methodology.

2.5.1 Conventional vs. BIM Integrated Certification Process

To understand how the certification process can actually be improved using BIM, it is important to first understand how conventional certification processes work and where potential data loss occurs. (For an overview of the conventional processes used by BREEAM, LEED and DGNB, see Chapter 2.2.2.) As an example, the DGNB system will be investigated further in this chapter to illustrate how BIM can be integrated into the process.

There are three main stakeholders involved in the DGNB certification: the client or building owner, the DGNB auditor, a highly specialized expert on the DGNB system, and the DGNB GmbH itself. The client ultimately signs contracts with both the DGNB GmbH and the auditor as well as with the designing engineers and architects who in turn work together with the DGNB auditor (Figure 2.9).

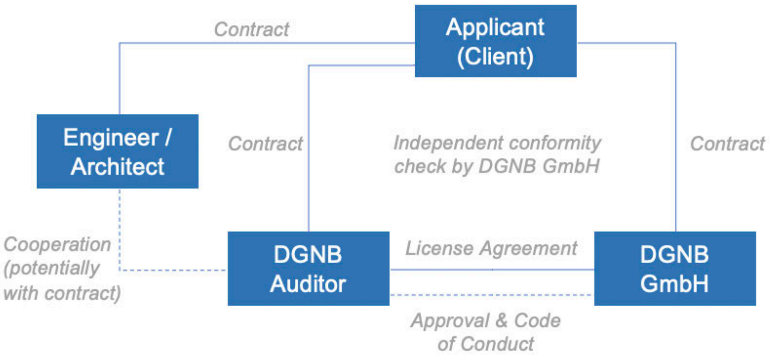


Figure 2.8: DGNB certification stakeholders (based on DGNB, 2020a)

The coordination of all disciplines and the collection of all relevant information is the sole responsibility of the DGNB auditor. Information is collected for all six categories of the DGNB from the respective designers and engineers, in a wide variety of data formats. The traditionally decentralized information results in potential loss of relevant information and requires the auditor to regularly double check the information to make sure it is still up to date. Rigorous and continuous communication is required between all stakeholders to make sure all changes are clearly communicated to the auditor. The left half of Figure 2.10 shows the conventional DGNB certification process with potential data loss points indicated in red and the right half shows what the process could look like using BIM.

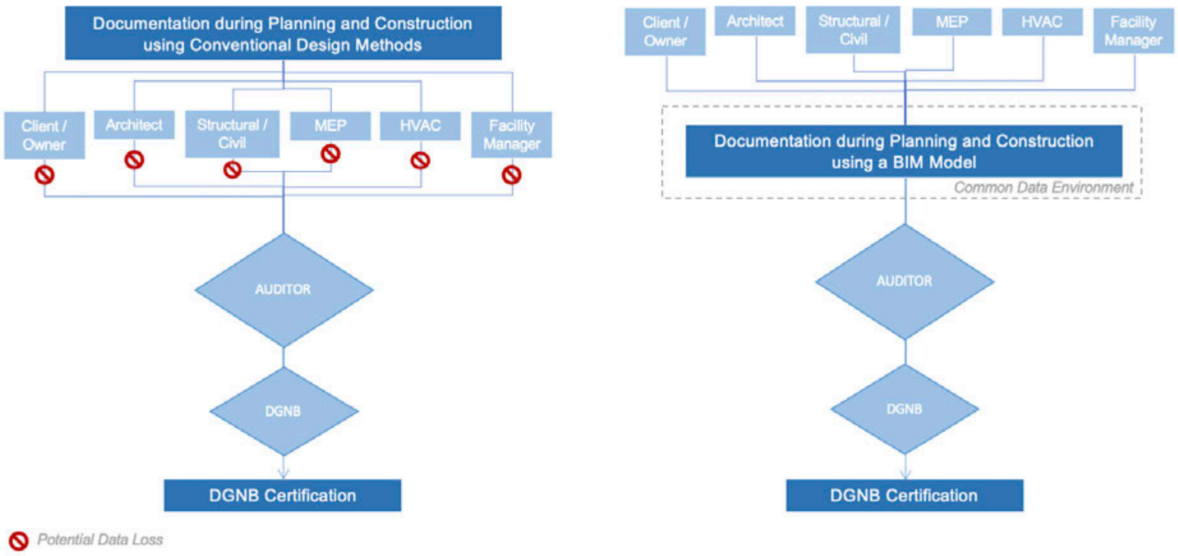


Figure 2.9: Conventional (left) vs. BIM-based DGNB certification process (right) (based on DGNB, 2020a)

The auditor checks the certification using a target/actual comparison, where the current design is compared to the requirements needed to achieve the desired certification level. This target/actual performance is done iteratively throughout the buildings planning and construction process as well as during the post-construction assessment. Throughout this iterative process, information can get lost during every data handover between the design team and the DGNB auditor. To reduce the time and effort involved in collecting the required data from each designer and engineer every time the design is updated, a BIM model can be used to represent the single source of truth for the project and can be used as the communication platform between the auditor and the members of the design team. The reduction in data loss points as a result of interposing the BIM model can be seen on the right side of Figure 2.10.

As illustrated in Figure 2.11, the BIM model that is developed in the early design stages can be used as the basis for the DGNB Pre-Certificate as well as for the final certification. All changes to the design during the planning process are automatically updated in the model and even the construction process and the post-construction, as-built verification can be incorporated into the model. By having a single model, the auditor can access the required information in just one place and the variety of data formats that must be collected is significantly reduced. Plans, specifications, quantity take-offs, life cycle assessment and simulation results can all be gathered directly from the BIM model and downstream processing software in real time.

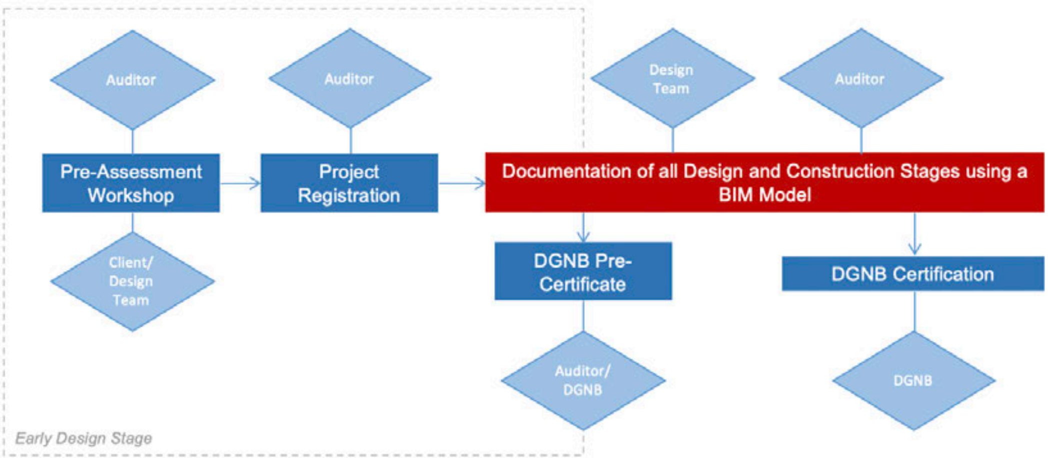


Figure 2.10: DGNB certification process with BIM integration

In order to improve the conventional certification process, it is important that the factors and criteria that will end up defining the certification level are determined in the early design stages. The communication between all participants must be direct and transparent throughout the entire process. All appointments and data exchange deadlines must be strictly adhered to, data must be managed centrally, and verification processes must be standardized. As far as possible, automatization of specific criteria should be realized. The following approaches have been developed in an attempt to optimize the conventional process by integrating the certification process into the BIM methodology.

2.5.2 Attribute Matrix Approach

The Attribute Matrix Approach was developed in 2019 at the Leibniz University Hannover as a part of the ONIB research project. It is based on Open BIM, meaning the sustainability criteria and requirements are defined in a generally applicable manner, independently of the used software products. The approach uses a common data environment on the basis of IFC as the single source of truth for all information and data exchange as well as for transparent communication. The BCF is used to support task-management and communication between stakeholders. The BIM Coordinator is responsible for the mapping of sustainability criteria in the building information model, ensuring the quality and completeness of all information necessary for model-based criteria checking, as well as being the main point of contact for the officials from the certification system.

This approach began by creating a process model for the workflows using BPMN. Next a workshop was carried out within the scope of the ONIB project, to determine the most relevant certification factors as well as data and communication standards. The results of the workshop were then turned into an EIR and BAP, defining the overarching BIM goals. BIM-Specialists were asked to review the information in the EIR and BAP for consistency and practicality. Through the creation of clear workflows, the information requirements for the individual model objects and sub-models for each discipline could be gathered and then organized in attribute matrices. These define all objects that are to be modeled, as well as naming conventions, data types and the relevant attributes of all objects. The attributes defined in the matrices were then incorporated into the model for two different sustainability criteria and checked using the software Solibri.

By using a standardized naming convention and proper placement within the IFC data-structure it was possible to model the information required to depict the relevant sustainability criteria. Checking the model with predefined rulesets proved successful and efficient, however, it was not yet possible to depict the results of these checks in such a way that they could automatically be used to perform the certification. Overall, it was found that the currently available software products can only be used to depict partial aspects of the total certification process. For both of the criteria that were analyzed as a proof-of-concept in this study only about 30% of the required information could be depicted geometrically within the model. In order to further improve the implementation of sustainability criteria into the BIM methodology, this approach suggests that uniform attribute matrices must be developed for all criteria and the process of creating rule sets for model checking must also become more standardized (ONIB, 2019).

2.5.3 Rule Set Approach

This approach, developed by Druhmann and Ashworth (2016) at the Zurich University of Applied Sciences, is based on developing a workflow that can efficiently verify compliance with specific sustainability levels during the planning phase of a building project. Using the specific information requirements for the BIM model, based on the sustainability criteria, the creation effort, the estimated programming effort, and the success of validation with model-checking tools can be determined.

First, sets of rules were created for all assessment criteria, based on the which information should and could be contained in the BIM model attributes. A building model was then created on the basis of these rulesets. Using IFC exports to model-checking software (Solibri), the building models could then be analyzed and evaluated with respect to the sustainability criteria. These intermediate results could then be used to optimize the model and the overall design of the building. The final evaluation of the sustainability of the building was done in a separate rating/certification platform, where the results of the model checker were imported and rated based on the underlying standards of the certification system.

The results of the implementation of this approach showed that not all sustainability criteria can be combined with the BIM workflow as it is known today. In order to evaluate these other criteria, additional tools such as a rating-/certification platform need to be developed. To realize efficient BIM-based sustainable assessments in the future, this approach suggests that a requirement profile for the building model needs to be standardized, so the necessary tools can be specifically designed to carry out the assessments (Druhmann & Ashworth, 2016).

2.5.4 Phase Approach

This approach was developed by Romano and Riediger (2019) at the HTW in Berlin and is based on 13 phases that can be used to implement sustainable building certifications in BIM. The 13 phases were developed based on a literature review, semi-structured interviews with sustainable building certifications experts, a case study analysis, and work meetings with a BIM expert. The approach is split into three different levels. The first involves the selection of the phases that are to be applied, the second examines the criteria of the certification that are to be considered and the third deals with the selection of requirements and documentation.

<u>Phases</u>:

1. Develop an external data base with all the information required
2. Define the type of project, the scope and the requirements of the different phases

3. Collect all the data for the BIM model (information and guidelines)
4. Transform the data according to the BIM language
5. Creation of the model in a BIM platform (considering all the parameters required)
6. Develop the simulation (different software involved)
7. Develop a building certification module (plug-in developed for some of the certification systems)
8. Develop a map of the relationship between BIM analysis methods and the certification system requirements
9. Design the neighborhood modulation (BIM/GIS)
10. Establish the method to aggregate the results from different software
11. Evaluate the certification system requirements achieved
12. Calculation of the certification costs
13. Report the results according to the certification requirements

This approach was tested by focusing solely on the energy requirements of different certification systems. The study found that using just 5 of the 13 phases (phase 2, 4, 5, 6 and 11), it was possible to use the BIM tool Revit to support all of the DGNB energy requirements. It was also found that it is vital to transform the data collected into a type of information that can be read by BIM so that it is easier to communicate with other project participants using the same language. This study also concluded that using the traditional certification method may require less implementation time at the beginning, however, this time needs to be reinvested every time a change is made. Using the BIM method on the other hand requires a slightly larger time investment at the start of the project but after that the process is automatized and doesn’t require any additional time input (Romano & Riediger, 2019).

2.5.5 IDM/MVD Approach

This approach was presented by Petrova et al. (2017) as a part of the 15th International Building Performance Simulation Association Conference and is based on understanding the roles and responsibilities of all parties involved in creating a BIM model and carrying out a sustainability certification. To gain this in-depth understanding, buildingSMART’s methodology for creating an Information Delivery Manual (IDM)/Model View Definition (MVD) was followed. The goal of this approach is to create a well-defined process that can be used to understand the information management requirements and can serve as the basis for developing technical solutions for process automation.

The method used in this approach began with an assessment of all actors, including their specific roles and areas of involvement. Next, all exchange requirements (ER) related to the sustainability criteria that were to be analyzed were defined. In this study the main focus was on LCA and building energy demand. After the ERs were clearly defined, they were mapped to the IFC data model. Finally, a Model View Definition was developed as the foundation for software implementation and to verify whether or not the provided information complied with the exchange requirements.

This approach showed that the IFC schema has a rich structure that largely supports the implementation of sustainability certification information requirements. However, there are still many use case specific attributes that are not yet defined using IFC and it needs to be verified if the missing entities, attributes and properties exist within the buildingSMART data dictionary for future implementation. Additionally, this approach found that ultimately an entirely new sustainable design process needs to be developed that goes past just using advanced tools and focuses more on the how all actors can use these tools from the beginning to create a more collaborative design process (Petrova et al., 2017).

2.5.6 Systemic Approach

This approach, developed by Kreiner et al. (2015) at the Graz University of Technology, is based on the systemic optimization of a building's sustainability. The method used in this approach allows the relative influence of each assessment criterion to be quantified and the individual optimization potential of each criterion to be identified. A focus is also placed on how the current building certification systems can be improved by considering potential interdependencies between the individual criteria. In order to estimate early trade-offs, the building certification system is combined with Vester's sensitivity model.

In this approach, a general identification of suitable optimization criteria was carried out using parts of Vester's sensitivity model. The influence of single measures on the overall and specific targets were then analyzed using a semi-quantitative calculation algorithm. Optimization measures were then defined and a matrix was created with the results. System influence was identified using a project specific network analysis. The software tool Consideo Modeler was used to qualitatively determine system interdependencies caused by measure variation during the sustainability optimization process. A systemic improvement was carried out based on the results from the Consideo Modeler. Finally, the sustainability of each measure was assessed and the influence range of the measure was identified.

The use of a systems approach made it possible to highlight trade-offs between different optimization measures, which is essential when implementing sustainable planning processes in early design phases. However, the integration of the methods developed in this approach still need to be more concretely connected with the BIM methodology to further improve the operationalization of the approach (Kreiner et al., 2015).

2.5.7 BEAM/BPS Approach

The final approach investigated was developed by Calquin (2017) and was also presented at the 15th International Building Performance Simulation Association Conference. It is based on creating a link between BIM, Building Performance Simulations (BPS), and Building Environmental Assessment Methods (BEAM) such as the DGNB or LEED. This approach can be split into five steps. First, the requirements of the certification system (BEAM) are analyzed. A BIM model for architectural design is then created based on BPS protocols. Next, the model is evaluated in a BPS environment such as DesignBuilder, Ecodesigner, or Green Building Studio. Based on BPS results, changes are made to the BIM model until the BEAM requirements are fulfilled. The case study analyzed using this approach, automatically relayed the information from the BIM model into a BEAM spreadsheet where the fulfillment level could be evaluated.

BEAM → BIM → BPS → BIM → BEAM

The workflow used in this approach created an automated link between BIM information and BEAM documents, a step which usually needs to be completed manually. The approach also showed that much of the information that is already added to a BIM model can be re-used for building certifications. While this approach focused on creating a link between the actual certification documentation and the BIM model, it did not analyze how much of the actual information required for the certification can be depicted digitally and with that is missing vital information about the actual applicability and practicability of this approach (Calquin, 2017).

2.5.8 Comparison of Integration Approaches

The following table provides an overview of the most important characteristics of the six approaches discussed above.

Table 2-8: Comparison of certification/BIM integration approaches

Approach	Degree of BIM Integration	Open BIM	Discussion of Applicability to all Criteria	Integration Check	Link to Documentation
Attribute Matrix	High	X	X	X	
Rule Set	High	X	X	X	
Phase	High	X			
IDM/MVD	Medium	X			
Systemic	Low		X		
BEAM/BPS	Medium				X

Based on the analyzed approaches that were developed within the last five years, the Attribute Matrix and Rule Set Approaches were found to be the most coherent and practical for the use case of performing sustainability optimizations and certifications. These two approaches shared a similar methodology that ultimately focused on the specific requirements of the sustainability criteria and validated the implementation of these requirements using a model checking software. The last two approaches analyzed (Systemic and BEAM/BPS) both lack depth and clarity. For the Systemic Approach the concrete integration with BIM was not adequately developed and the BEAM/BPS Approach was missing information regarding how the criterial requirements were added to the BIM model and to which extent all of the criteria could even be included. The Phase Approach presented important information about the different steps that are needed for a successful BIM and DGNB integration but remained more surface level and general, ultimately not providing enough proof-of-concept for a holistic sustainability certification integration. The IDM/MVD Approach also provided a detailed implementation methodology, however, the validation of the final MVD to be used in the actual certification of the building has not yet been developed so the final step of model validation is lacking. A general consensus of all investigated approaches was that the lack of standardization and the limitations of the current BIM software make it difficult to depict sustainable building certifications in a comprehensive and holistic way. Nevertheless, the Attribute Matrix Approach in combination with the Rule Set Approach provides an excellent starting point for creating a more concrete and standardized solution for implementing sustainability certifications into the BIM methodology.

3 Sustainability Criteria Analysis

To concretely define sustainability for the research within this thesis, it was crucial to first select a certification system that best represented the holistic definition of sustainability. Following the selection of a certification system, the individual criteria and indicators within the system were analyzed on their applicability in the early design stages as well as their potential to be integrated into a digital model-based workflow. In addition to this applicability analysis, the indicators were also split into quantitative and qualitative categories. This in-depth analysis and categorical differentiation were necessary for creating a comprehensive overview of the applicable certification system criteria which could be used later on as the basis for developing a representative model integration process. Focusing the analysis on all criteria instead of just a few illustrative ones was important for maintaining the holistic view of sustainability and getting a better understanding for how the selected certification system can increase the sustainability of a project as a whole.

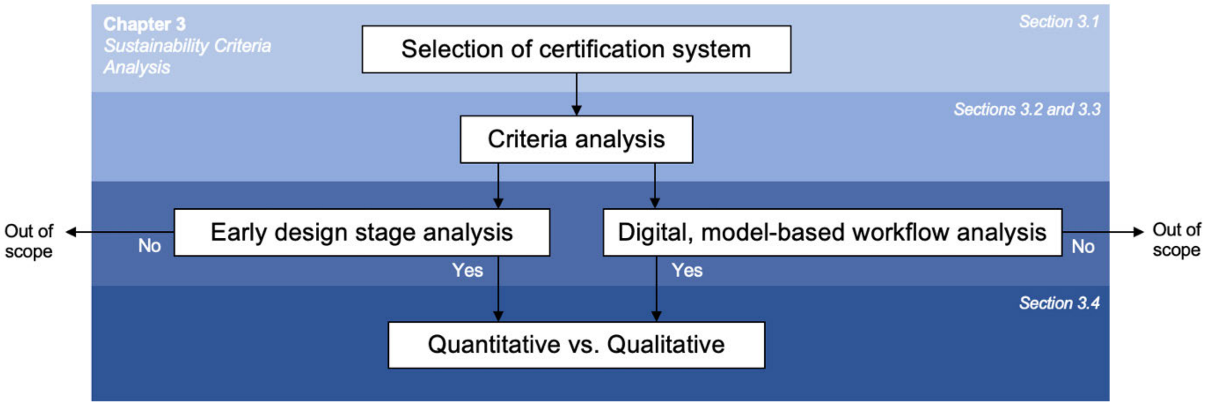


Figure 3.1: Sustainability criteria analysis flow chart

3.1 Sustainable Building Certification System Selection

This thesis uses the threefold definition of sustainability that includes not only the environmental aspects, but equally values the economic and social aspects as well. Therefore, the certification system selected for this thesis needed to be a 2nd generation system that is based on the idea that a sustainable building should ensure the following:

- Environmental protection, by conserving resources (materials, energy and water) at all stages of the building life cycle

- Economic viability, by keeping investment risk as low as possible and saving money in the long term
- Emphasis should be on the user, ensuring that the building is used for as long as possible by focusing on health, well-being and user comfort and creating high-quality, flexible indoor and outdoor spaces
- Climate and culture are essential in creating a building that fits the local needs and reflects the values of the society

As the Open House analysis in Section 2.2.2 revealed, the DGNB certification system meets all of these requirements more diligently than LEED or BREEAM. The complete life cycle of the building is considered throughout the entire DGNB system. In this way, environmental and economic impacts are considered during construction, use and even final demolition. By making it an intrinsic part of the DGNB, considering the entire life cycle of the building and its components becomes second nature to all those involved in the project, which results in lasting mind-set changes for users, designers, contractors, and manufacturers alike. Compared to other certification systems the DGNB criteria can also easily be adapted to meet regional conditions and circumstances, including regulatory requirements, local market conditions and regional climate variations. Different strategies for achieving targets are allowed, based on different base conditions, which results in positive contributions to the built environment on a more holistic level (DGNB, 2018b).

Furthermore, the DGNB is a performance-oriented system, so it values the buildings overall performance and impact over just the ticking off of implemented measures. Taking into account the actual effects of the measures emphasizes the overall goal of sustainability and encourages the different actors to work together to find the most appropriate solutions. As a result, innovation is promoted and people’s willingness to try something new is not only acknowledged but encouraged. In comparison to other systems, the DGNB criteria are evaluated in a more detailed manner, not just whether indicators are fulfilled or not. This is done by allowing for a greater differentiation of achievable levels based on limits, targets and references values. As a result, the DGNB system makes sure that the criteria are applied in a meaningful way and not just to maximize scores, which also ensures that individual factors that drive sustainability are not overlooked (DGNB, 2018b). This performance-oriented evaluation, that focuses on measurability, can be supported by using a digital building model, which also makes the DGNB system a clear front-runner for integration with the BIM methodology (ONIB, 2019).

There are several disadvantages of the DGNB system that should be noted. For example, getting a DGNB certification can be rather costly, ranging in price from €2,500 to €73,500 depending on the building typology, gross area and DGNB membership status (GXN & Statens Byggeforskningsinstitut, 2018). The certification process also requires timely and meticulous record keeping, accompanied by hours' worth of labor to collect and submit the necessary paperwork, that then needs to be reviewed and often revised. The complexity and interconnectivity of the system also requires in-depth training or professional assistance to fully understand (Brooks-Church, 2012). Specifically, this complexity and time-intensive documentation process are part of the DGNB that could benefit the most from a building information model integration. Automating and simplifying some of the complexities with a building information model integration would allow for quick and easy, iterative optimizations to be carried out in the early design stages. This would in turn reduce the effort required for collecting and submitting the documentation, as much of the needed information is available in a "single source of truth" model. Finally, optimizing the design in the early stages reduces the likelihood of required revisions later in the design process after the documentation can be reviewed.

Overall, the DGNB system was selected because it represents the most holistic certification system. It includes the environmental and economic aspects through the intrinsic integration of life cycle assessments and life cycle costing throughout all parts of the building and the certification process. The social objectives are weighted equally with the environmental and economic objectives and are anchored within the system in that the quality of the indoor space must be ensured in order for a building to receive a DGNB certification at all. As Figures 2.3 and 2.4 illustrated, the technical aspects only carried a significant weight within the DGNB system and were nearly neglected in the other two systems. The process and management categories are well represented in the most recent versions of all three systems, however, the performance-oriented system of the DGNB compared to the measure-oriented BREEAM and LEED systems is clearly superior in creating an innovative design process and an overall more meaningful score. Finally, the location aspects are incorporated more thoroughly by the DGNB with its adaptability to local conditions and its emphasis on creating buildings that promote local building culture and ensure the acceptance and longevity of the project.

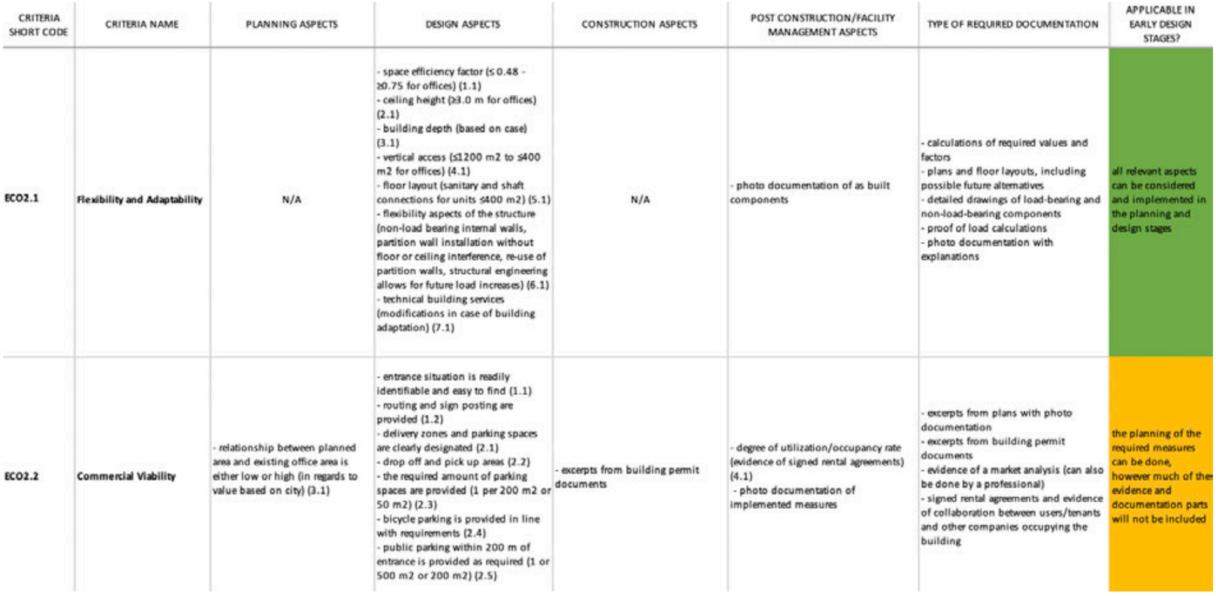
The DGNB system can be applied in both new and existing buildings, however, for this thesis the category of new buildings was selected as it provides more opportunities for BIM integration into the design process than an already existing building does. The current DGNB system (version 2018) offers certifications in 16 different use schemes, all of which are built on the same framework but have minor differences on the criterion level. The focus of this thesis has been placed on the use scheme for new construction office buildings as this was the first scheme to be implemented by the DGNB in 2009 and therefore has had the most time to be developed and improved (DGNB, 2009). Additionally, the DGNB certifies more office buildings than any other use scheme, giving research related to the office scheme the greatest impact on the largest scale.

3.2 Sustainability Criteria in the Early Design Stages

The DGNB criteria included in this thesis have been limited to those relevant in the early design stages. As described in Section 2.1, the early design stages include the project planning and design development phases and end with the production of construction documents and the beginning of the physical project execution phase. This cut off was selected because in the early stages the opportunities for changing the design are the greatest and the cost of making potential changes is still low (see Figure 2.2). Integrating sustainability at this point, therefore, poses the highest potential for innovation and experimentation, while also fundamentally incorporating sustainable thinking into the traditional design process (Ebert et al., 2011). Ultimately, early integration enables sustainability to become a design requirement, rather than an afterthought.

In order to determine which criteria could be considered relevant in the early design stages an in-depth analysis of the detailed DGNB criteria descriptions was carried out. The descriptions were divided into planning, design, construction and post construction/FM aspects, with the aspects planning and design encompassing the early design stages. Each criterion was broken down into its individual indicators to determine exactly what parts of the criterion were applicable in which stage of the design and construction process. It was also noted which type of documentation was required for each criterion. This was important to help determine at which point in the design process specific plans, calculations, simulations, photos, etc. would be required.

Once all indicators had been placed in their respective categories, the overall applicability of the criteria was decided based on how many indicators it had in each aspect. The overall applicability was denoted using a color scheme with green indicating that the criteria could be fully considered in the early design stages, yellow indicating that some indicators fell into the planning and design aspects, however, a substantial number of indicators could not be fulfilled until the construction or post-construction stages and red indicating that a criterion could only be considered after building construction had been completed. For each criterion, the colored ranking was also supplemented with a brief text to further explain the reasoning for the selected color. Figure 3.2 shows a cut out from the early design stage analysis table that can be found in Appendix C. In this figure, it can be seen how each indicator, with its indicator number denoted at the end, has been placed in the applicable category. The required documentation, color scheme and brief reasoning are also shown.



CRITERIA SHORT CODE	CRITERIA NAME	PLANNING ASPECTS	DESIGN ASPECTS	CONSTRUCTION ASPECTS	POST CONSTRUCTION/FACILITY MANAGEMENT ASPECTS	TYPE OF REQUIRED DOCUMENTATION	APPLICABLE IN EARLY DESIGN STAGES?
ECO2.1	**Flexibility and Adaptability**	N/A	- space efficiency factor (≤ 0.48 - ≥0.75 for offices) (1.1) - ceiling height (≥3.0 m for offices) (2.1) - building depth (based on case) (3.1) - vertical access (≤1200 m2 to ≤400 m2 for offices) (4.1) - floor layout (sanitary and shaft connections for units ≤400 m2) (5.1) - flexibility aspects of the structure (non-load bearing internal walls, partition wall installation without floor or ceiling interference, re-use of partition walls, structural engineering allows for future load increases) (6.1) - technical building services (modifications in case of building adaptation) (7.1)	N/A	- photo documentation of as built components	- calculations of required values and factors - plans and floor layouts, including possible future alternatives - detailed drawings of load-bearing and non-load-bearing components - proof of load calculations - photo documentation with explanations	all relevant aspects can be considered and implemented in the planning and design stages
ECO2.2	**Commercial Viability**	- relationship between planned area and existing office area is either low or high (in regards to value based on city) (3.1)	- entrance situation is readily identifiable and easy to find (1.1) - routing and sign posting are provided (1.2) - delivery zones and parking spaces are clearly designated (2.1) - drop off and pick up areas (2.2) - the required amount of parking spaces are provided (1 per 200 m2 or 50 m2) (2.3) - bicycle parking is provided in line with requirements (2.4) - public parking within 200 m of entrance is provided as required (1 or 500 m2 or 200 m2) (2.5)	- excerpts from building permit documents	- degree of utilization/occupancy rate (evidence of signed rental agreements) (4.1) - photo documentation of implemented measures	- excerpts from plans with photo documentation - excerpts from building permit documents - evidence of a market analysis (can also be done by a professional) - signed rental agreements and evidence of collaboration between users/tenants and other companies occupying the building	the planning of the required measures can be done, however much of the evidence and documentation parts will not be included

Figure 3.2: Early design stage analysis cut out

In carrying out the early design stage analysis, it was important to consider which indicators actually mattered at which stage. For example, certain indicators may only require that a material or element be verified after the building is completed, however, the decisions regarding the material selection or object placement must of course already be considered in the design stage. In order to achieve more accurate analysis results, the type of documentation required for indicator fulfillment and the detailed DGNB descriptions regarding the fulfillment method (DGNB System, Appendix A, III. Method) of the indicator were also considered. This helped determine the essence of what the indicator was trying to achieve and provided better insights into when the indicator requirements needed to be added and measured.

In creating an overview of the criteria that were relevant in the early design stages, both green and yellow criteria were considered to be applicable. Yellow criteria were also included because even if not all of the indicators were fulfilled in the early design stages, they often included elements that needed to be considered or at least communicated in the early design stages. While the documentation and verification of fulfillment is of course a very important aspect of achieving the points for a criterion, in this analysis the deciding factor was the point in the design process at which the information needed to be included.

3.2.1 Early Design Stage Analysis Results

The early design stage analysis of the DGNB criteria was necessary in narrowing down the scope of the thesis and determining which criteria were relevant for integration into an early BIM model. By looking at both the overall criteria and the individual indicators, the potentials and challenges for an early design stage integration of the DGNB could be identified. As the main goal of this thesis was creating a tool that could be used to help optimize the sustainability of a building in the early design stages, the results of this analysis were the foundation for all further work.

The majority of criteria that were deemed not applicable in the final analysis fall under the DGNB topic ‘Process Quality’. This topic is mainly focused on increasing the construction quality assurance and incorporating facility management aspects, making the criteria relevant in the construction and building use stages instead of the early design stages. The criterion for sustainable resource extraction from the ‘Environmental Quality’ topic was also excluded because the DGNB requirements for this criterion are exclusively aimed at post-construction documentation. Nearly all yellow indicators required verification, in most cases by an expert in the later design stages. However, the elements required for verification still need to be communicated and included in the design at the early stages which is why these criteria were nevertheless deemed applicable in this analysis. Table 3-1 provides an overview of the criteria applicability as discussed above. The full early design stage analysis table with all justifications can be found in Appendix C.

Table 3-1: Early design stage analysis overview

TOPIC	**CRITERIA SHORT CODE**	**CRITERIA NAME**	**APPLICABLE IN EARLY DESIGN STAGES?**		
			🟩	🟨	🟥
Environmental Quality	ENV1.1	Building Life Cycle Assessment	x		
	ENV1.2	Local Environmental Impact		x	
	ENV1.3	Sustainable Resource Extraction			x
	ENV2.2	Potable Water Demand and Waste Water Volume	x		
	ENV2.3	Land Use	x		
	ENV2.4	Biodiversity at the Site	x		
Economic Quality	ECO1.1	Life Cycle Cost	x		
	ECO2.1	Flexibility and Adaptability	x		
	ECO2.2	Commercial Viability		x	
Sociocultural and Functional Quality	SOC1.1	Thermal Comfort	x		
	SOC1.2	Indoor Air Quality	x		
	SOC1.3	Acoustic Comfort	x		
	SOC1.4	Visual Comfort	x		
	SOC1.5	User Control	x		
	SOC1.6	Quality of Indoor and Outdoor Spaces	x		
	SOC1.7	Safety and Security	x		
	SOC2.1	Design for All	x		
Technical Quality	TEC1.2	Sound Insulation	x		
	TEC1.3	Quality of the Building Envelope	x		
	TEC1.4	Use and Integration of Building Technology	x		
	TEC1.5	Ease of Cleaning Building Components	x		
	TEC1.6	Ease of Recovery and Recycling		x	
	TEC1.7	Immissions Control		x	
	TEC3.1	Mobility Infrastructure		x	
Process Quality	PRO1.1	Comprehensive Project Brief	x		
	PRO1.4	Sustainability Aspects in Tender Phase			x
	PRO1.5	Documentation for Sustainable Management			x
	PRO1.6	Procedure for Urban and Design Planning	x		
	PRO2.1	Construction Site/Construction Process			x
	PRO2.2	Quality Assurance of the Construction			x
	PRO2.3	Systematic Commissioning			x
	PRO2.4	User Communication			x
	PRO2.5	FM-compliant Planning	x		
Site Quality	SITE1.1	Local Environment	x		
	SITE1.2	Influence on the District	x		
	SITE1.3	Transport Access	x		
	SITE1.4	Access to Amenities	x		

Overall, the final analysis including both green and yellow criteria, revealed that 81%, or 30 of the 37 criteria, could be considered applicable in the early design stages.

3.2.2 Early Design Stage Analysis Discussion and Validation

This analysis revealed that nearly all criteria can and need to be considered early on in the design process. Even if the verification and documentation needed to attain the actual points don’t come into play until later, these points can only be achieved if the proper details have been incorporated starting in the early design stages. As the DGNB is built on the principles of being a holistic and life cycle assessment-based approach, it comes as no surprise that achieving the criteria is also a process that begins with the earliest planning and project discussion stages and extends to facility management and even possible deconstruction scenarios.

Other research in this field has been limited to investigating just individual criteria, such as those regarding LCA, LCC and energy performance criteria (Brunsgaard & Larsen, 2019). Additionally, the ONIB report, mentioned in section 2.5.2, determined that criteria SOC2.1 and ECO2.1 could be fully depicted in the early design stages (ONIB, 2019). Beyond these examples of distinct criteria, a similar early design stage analysis, that includes all DGNB criteria, was not found in the current literature.

3.3 Sustainability Criteria in a Digital Model-based Context

Following the early design stage analysis, all DGNB criteria were analyzed for their ability to be represented and verified using a semantic building information model. The purpose of this analysis was to carry out a comprehensive analysis that included all criteria, to maintain a holistic view of the DGNB, but ultimately filtered out those that would benefit from an integration into a digital workflow. The added value that could be gained from a digital workflow integration was integral to this analysis as the building information model was to be used as the “single source of truth” for storing and accessing all sustainability relevant information.

For this analysis each criterion was again split into all of its respective indicators to get the most accurate results. Each indicator was then determined to be either quantitative or qualitative and the form (i.e., plan, simulation, photo, etc.) and type of output was also recorded for each indicator. Including the output information was key in determining if the indicator had the potential of being depicted in a building information model, as the output is ultimately what needs to be created or achieved in order to attain points for the indicator. Clearly outlining the different outputs was also useful in determining if an indicator was qualitative or quantitative. If, for example, the output of an indicator was a “unique feature that attracts users and/or employees”, this indicated an emphasis on the quality of the features and not just an evaluation of whether or not certain features had been included, making it a qualitative indicator.

Several indicators required the creation of concepts and/or manuals in order to achieve the points available. For this thesis all indicators that include concepts and manuals were defined as qualitative, because in order to meet the requirements, as intended by the DGNB, the quality of the actual concept needed to be evaluated and not just whether or not one was provided. Generally speaking, concepts (i.e., site, building usage, cleaning, etc.), manuals, trainings, evaluations of specific measures, system integrations, and impact evaluations were classified as qualitative outputs, while quantitative outputs included calculations, simulations, target values (defined by the DGNB or DIN standards), measurements, data sheets, building component catalogs, reports and certificates, and numbers of implemented measures. Where floor plans were required, the output was defined as quantitative if it was used to determine specific values and distances or to run a simulation and as qualitative if it was used to assess room quality and user comfort.

The analysis also included a specific section for the added value that could result from digitalization. This was included as a type of feasibility check and preliminary filter. It was meant as a chance to think critically about the effects of integrating everything into a digital model in terms of time expenditures and realistic levels of detail that would be necessary. The added value section was also used to help determine the overall ranking of the indicator in regard to the digital model-based workflow.

Similar to the early design stage analysis, the same three-color system was used. Green denoted indicators that could be fully represented in a building information model and provided a definite added value from being integrated into the digital workflow. Yellow was used for indicators that could only be partially included in the model but where the added value was still clear. This included indicators that potentially required GIS modelling in addition to building modelling, external simulation, storing of measurements, as-built documentation and concepts for later FM use, scheduling for construction-based indicators, and the use of a digital model for the generation of Excel™ data. The color red was used for indicators that could not be incorporated into the digital model-based workflow, such as indicators that required external verifications of data sheets, specific values used in calculations, external reports and records, post-construction measurements and written statements. Figure 3.3 shows a sample digital model-based workflow analysis for the criterion ‘SOC1.4 Visual Comfort’. The full digital model-based workflow analysis, with all color-coded results, can be found in Appendix D.

CRITERIA SHORT CODE	CRITERIA NAME	QUANTITATIVE/ QUALITATIVE?	PLAN (DWG)/EXCEL/SIMULATION/ DOCUMENT/PHOTO/OTHER?	ATTRIBUTES AND OUTPUTS	ADDED VALUE FROM DIGITALIZATION	DIGITAL REPRESENTATION?
SOC1.4	**Visual Comfort**					
	1.1 Daylight Factor (DF)	quantitative	calculation, simulation	daylight factor (%) for 50% of the useable area in accordance with DIN V 18599-4 or simulation	a digital model can be used to perform the daylight simulation	🟩 a digital model can be used as the basis for the simulation
	2.1 Annual relative motive exposure	quantitative	calculation, simulation	annual relative motive exposure (%) in accordance with DIN V 18599-4 or simulation	a digital model can be used to perform the daylight simulation	🟩 a digital model can be used as the basis for the simulation
	3.1 Available lines of sight to the outside	qualitative	floor plans, calculations	analysis of visual links to the outdoors	all changes to the floor plan and layout can be see immediately	🟩 the analysis can be carried out using floor plans generated within the digital model
	4.1 Absence of glare due to sun/glare protection system	quantitative	manufacturer data sheets	classification of sun glare protection system	N/A	🟥 the data sheets need to be checked manually as they differ for each project/product used
	5.1 Minimum requirements for artificial light	quantitative	calculation, product data sheets	requirements of DIN EN 12464-1 (Maintained illuminance level, glare limitation, uniformity of illuminance, color rendering, illuminance of the walls, luminance limits for lights at workstations with monitors)	a digital model can be used to perform the daylight simulation	🟩 a digital model can be used as the basis for the simulation
	5.2 Artificial light overfulfilment	quantitative	calculation, product data sheets	requirements of DIN EN 12464-1 (Maintained illuminance level, glare limitation, uniformity of illuminance, color rendering, illuminance of the walls, luminance limits for lights at workstations with monitors)	a digital model can be used to perform the daylight simulation	🟩 a digital model can be used as the basis for the simulation
	6.1 Color rendering index R(a)	quantitative	spectral calculation, manufacturer data sheets	color rendering index Ra	N/A	🟥 this indicator is based on data sheets and a calculation that do not require a digital model
	7.1 Duration of exposure to daylight	quantitative	floor and site plans, calculations, sun progression chart	duration of exposure to daylight on 17.01 and 21.03/21.09 in accordance with DIN 5034	N/A	🟨 the sun path can be overlayed in the digital model

Figure 3.3: Digital model-based workflow analysis cut out

For the overall assessment, criteria with the majority of both green and yellow indicators were included, as they provided a certain added value with integration into the digital model-based workflow.

3.3.1 Digital Model-based Workflow Analysis Results

The overarching goal of this analysis was to determine which criteria, and more specifically which indicators, had the potential of benefiting from an integration into a digital building model. The results of the analysis were used to further narrow down the scope of this thesis and to determine which criteria were realistic to be selected as representative example criteria.

The analysis found that several criteria in the ‘Environmental Quality’ topic would likely not benefit much from an integration into the digital workflow. This included criteria like ENV2.3, 2.3 and 2.4, that were based on numerical calculations, external records, and written expert evaluations. Furthermore, the ‘Process Quality’ topic contained numerous criteria that were omitted as they relied on the completion of organizational tasks before a digital model would typically have been created and on the submission of separate user manuals. Fulfilling the ‘Site Quality’ criterion SITE1.2 was also determined to rely more on participative actions and marketing within the community and less on the integration of information into a digital building model. Finally, SOC1.5 was omitted as the DGNB required the criterion to be verified with manufacturer data sheets and it is common for most BIM elements to not get updated past design intent. This means that generic objects are rarely replaced by manufacturers objects that are linked to real product data (Grani, 2016). The majority of yellow criteria had indicators that were better represented in a facility management model or a GIS model than a traditional building information model. However, including these in their respective types of digital models provided clear added value, which is why they were nevertheless included as applicable in this analysis. Table 3-2 provides an overview of the criteria applicability as discussed above. The full digital model-based workflow analysis table can be found in Appendix D.

Table 3-2: Digital model-based workflow analysis overview

TOPIC	CRITERIA SHORT CODE	CRITERIA NAME	DIGITAL MODEL-BASED WORKFLOW?		
			🟩	🟨	🟥
Environmental Quality	ENV1.1	Building Life Cycle Assessment	x		
	ENV1.2	Local Environmental Impact		x	
	ENV1.3	Sustainable Resource Extraction		x	
	ENV2.2	Potable Water Demand and Waste Water Volume			x
	ENV2.3	Land Use			x
	ENV2.4	Biodiversity at the Site			x
Economic Quality	ECO1.1	Life Cycle Cost	x		
	ECO2.1	Flexibility and Adaptability	x		
	ECO2.2	Commercial Viability	x		
Sociocultural and Functional Quality	SOC1.1	Thermal Comfort	x		
	SOC1.2	Indoor Air Quality	x		
	SOC1.3	Acoustic Comfort	x		
	SOC1.4	Visual Comfort	x		
	SOC1.5	User Control			x
	SOC1.6	Quality of Indoor and Outdoor Spaces	x		
	SOC1.7	Safety and Security	x		
	SOC2.1	Design for All	x		
Technical Quality	TEC1.2	Sound Insulation	x		
	TEC1.3	Quality of the Building Envelope	x		
	TEC1.4	Use and Integration of Building Technology	x		
	TEC1.5	Ease of Cleaning Building Components	x		
	TEC1.6	Ease of Recovery and Recycling	x		
	TEC1.7	Immissions Control		x	
	TEC3.1	Mobility Infrastructure	x		
Process Quality	PRO1.1	Comprehensive Project Brief			x
	PRO1.4	Sustainability Aspects in Tender Phase			x
	PRO1.5	Documentation for Sustainable Management		x	
	PRO1.6	Procedure for Urban and Design Planning			x
	PRO2.1	Construction Site/Construction Process		x	
	PRO2.2	Quality Assurance of the Construction		x	
	PRO2.3	Systematic Commissioning		x	
	PRO2.4	User Communication			x
	PRO2.5	FM-compliant Planning		x	
Site Quality	SITE1.1	Local Environment		x	
	SITE1.2	Influence on the District			x
	SITE1.3	Transport Access		x	
	SITE1.4	Access to Amenities	x		

The analysis found that of the approximately 28 criteria (overall 76%) that would benefit from an integration into a digital workflow, about 11% required a facility management model, and another 11% were based on data that would typically be contained in a GIS model. A further 22% of the applicable criteria would use the model as the basis for some type of simulation. Overall, about 35% of the criteria required either a partial or full manual evaluation, the majority of these manual criteria falling into the red category. Only one green criteria, ECO2.2, was concluded to required partial manual evaluation for certain indicators in the form of market-based calculations.

3.3.2 Digital Model-based Workflow Analysis Discussion and Validation

On the basis of this analysis, it can be said that the clear majority of DGNB criteria would benefit from an integration into the digital model-based workflow that defines the BIM methodology. This finding is not surprising, as the aim of using a building information model is to have all building-relevant data stored in one place and this all-encompassing data is exactly what the DGNB needs to access to carry out a building certification. For many of the criteria, and more specifically the individual indicators, using a building information model reduces inconsistencies and repetitive, time consuming tasks. In a traditional certification workflow, creating models on which to run daylight, acoustic, flow and thermal simulations requires a substantial amount of time and effort. However, this can be drastically reduced if the existing digital model can simply be used as the basis for these simulations, which need to be carried out to fulfill a significant portion (22%) of the criteria. In addition to being used as the basis for simulations and other downstream software applications, the digital model can also be used to create up-to-date material catalogs and schedules, find values required for calculations, create visuals/renderings, carry out quick variant comparisons, or produce always up-to-date floor plans, elevations, 3D views etc. Overall, a properly created building information model can be used as the “single source of truth” for gathering and storing data for a vast range of topics and functions associated with the DGNB certification process.

Similar research in the field of DGNB and building information model integration found that approximately 50% of the criteria could be depicted and analyzed using BIM (Lanisa, 2018). This is considerably less than what was found in this thesis, however, in the results of the Lanisa study, over 25% of the criteria had not been evaluated, so the results cannot be directly compared. As was found with the early design stage analysis, directly comparable results were difficult to find in the current literature, but some studies did investigate the applicability of specific types of criteria for a BIM integration. For example, Romano & Riediger (2019) found that BIM can support 100% of DGNB energy criteria. These energy criteria include ENV1.1 Building Life Cycle Assessment, ECO1.1 Life Cycle Cost and TEC1.4 Use and Integration of Building Technology. Overall, many studies have focused on the integration of LCA and LCC criteria with a model-based workflow and confirmed Romano and Riediger's findings, that the integration is overwhelming successful (further references provided in Section 3.4). However, an overarching analysis of all current DGNB criteria, with the same depth as was carried out in this thesis, could not be found in the current literature.

3.4 Overall Determination of Applicable Criteria and Important Trends

To conclude the sustainability criteria analysis, it was necessary to compile the results from both the early design stage and model-based workflow analyses to determine exactly which DGNB criteria fell into the scope of this thesis. Despite the analyses being conducted on the indicator level to gain more detailed insights, in defining the scope of this thesis, only full criteria were considered. This was done to provide a better overview at the criterion level and to simplify the decision about which of the 37 criteria could be deemed applicable to the scope of this thesis.

In addition to the results of the early design stage and model-based workflow analyses, several other exclusions conditions were defined. First, the criteria for Life Cycle Assessment (ENV1.1) was excluded from the scope as it presents a complex and extensive subject matter and LCA and BIM integration has already been extensively covered in other research papers. For example, Tsikos et al. used the visual programming language Dynamo to connect a Revit model with an external material life cycle inventory database. A permanent link with unique material IDs was created and the environmental and material take-off information were collected in one script and then exported to Excel™ to create the charts and graphs necessary for analysis (Tsikos et al., 2017). Bueno and Fabricio carried out a theoretical review of the integration of LCA information with the BIM model in the form of LCA data embedded directly within the BIM elements (Bueno & Fabricio, 2017). Basbagill et al. (2012) proposed material quantity formulas and embodied GHG emission factors that could be embedded in the BIM authoring tool as a method for applying LCA in the early design stages to inform designers about the environmental impact of their material and dimensioning choices. Dupuis et al. (2017) developed a method that used a novel data layer and format that automatically performed LCA calculations in the LOD100 level. The data layer closed the information gap between the extracted BIM data and the existing LCA data that can be found in common LCA databases such as 'ecoinvent'. Stella (2018) developed guidelines regarding material selection, quantity take-offs and workflows for conducting LCAs at each level of development (LOD 100 to LOD 500) using One Click LCA and Revit. These papers only represent a fraction of the past and ongoing research in the field of LCA-BIM integration and are simply intended to show the range of topics already covered in this area. For additional sources on this topic see ‘ENV1.1 Building Life Cycle Assessment’ in Appendix E.

In close connection with the LCA topic, the criterion dealing with ‘Life Cycle Costing (ECO1.1)’ was also excluded from the scope of this thesis. Similarly to LCA-BIM integration, the LCC-BIM topic is already very well represented in current research and it is not realistic to perform an LCC without also performing and LCA, as many of the fundamental steps are interrelated. For more information on papers that have recently been published regarding this topic see ‘ECO1.1 Life Cycle Costing’ in Appendix E. Furthermore, all criteria that require a geographic information systems (GIS) model also fell outside of the scope, as this thesis focused exclusively on the early design stages of the building itself. Finally, the criteria ‘ECO2.1 Flexibility and Adaptability’ and ‘SOC2.1 Design for All’ were also omitted, as they had been extensively investigated in the ONIB report using a similar methodology (ONIB, 2019).

Based on the exclusion conditions defined above and the analyses conducted in Sections 3.2 and 3.3, it was determined that overall 17 criteria, or 46%, were appliable for the further research carried out in this thesis. These 17 criteria accounted for approximately 44% of the overall weighting of the DGNB system. Table 3-3 provides an overview of the results of both analyses, the criteria that do not fall under the exclusion conditions and ultimately which criteria are applicable. As indicated in this table, a criterion was only applicable if it received an “x” in all three analyses. The full overview of the criteria analysis, including information on the indicator level, can be found in Appendix E.

Table 3-3: Sustainability criteria analysis overview

TOPIC	CRITERIA SHORT CODE	CRITERIA NAME	APPLICABLE? (only if three x's)				QUANTITATIVE VS. QUALITATIVE
			Early Design Stage	Digital Model-based Workflow	No Other Exclusion Condition	YES	
Environmental Quality	ENV1.1	Building Life Cycle Assessment	x	x			quantitative
	ENV1.2	Local Environmental Impact	x	x	x	x	**quantitative**
	ENV1.3	Sustainable Resource Extraction		x			quantitative
	ENV2.2	Potable Water Demand and Waste Water Volume	x				qualitative
	ENV2.3	Land Use	x				qualitative
	ENV2.4	Biodiversity at the Site	x				quantitative
Economic Quality	ECO1.1	Life Cycle Cost	x	x			quantitative
	ECO2.1	Flexibility and Adaptability	x	x			qualitative
	ECO2.2	Commercial Viability	x	x	x	x	**quantitative**
Sociocultural and Functional Quality	SOC1.1	Thermal Comfort	x	x	x	x	**quantitative**
	SOC1.2	Indoor Air Quality	x	x	x	x	**quantitative**
	SOC1.3	Acoustic Comfort	x	x	x	x	**quantitative**
	SOC1.4	Visual Comfort	x	x	x	x	**quantitative**
	SOC1.5	User Control	x				quantitative
	SOC1.6	Quality of Indoor and Outdoor Spaces	x	x	x	x	**qualitative**
	SOC1.7	Safety and Security	x	x	x	x	**qualitative**
	SOC2.1	Design for All	x	x			quantitative
Technical Quality	TEC1.2	Sound Insulation	x	x	x	x	**quantitative**
	TEC1.3	Quality of the Building Envelope	x	x	x	x	**quantitative**
	TEC1.4	Use and Integration of Building Technology	x	x	x	x	**qualitative**
	TEC1.5	Ease of Cleaning Building Components	x	x	x	x	**quantitative**
	TEC1.6	Ease of Recovery and Recycling	x	x	x	x	**quantitative**
	TEC1.7	Immissions Control	x	x	x	x	**quantitative**
	TEC3.1	Mobility Infrastructure	x	x	x	x	**quantitative**
Process Quality	PRO1.1	Comprehensive Project Brief	x				qualitative
	PRO1.4	Sustainability Aspects in Tender Phase					qualitative
	PRO1.5	Documentation for Sustainable Management		x			qualitative
	PRO1.6	Procedure for Urban and Design Planning	x				qualitative
	PRO2.1	Construction Site/Construction Process		x			qualitative
	PRO2.2	Quality Assurance of the Construction		x			quantitative
	PRO2.3	Systematic Commissioning		x			quantitative
	PRO2.4	User Communication					qualitative
	PRO2.5	FM-compliant Planning	x	x	x	x	**qualitative**
Site Quality	SITE1.1	Local Environment	x	x			quantitative
	SITE1.2	Influence on the District	x				qualitative
	SITE1.3	Transport Access	x	x			qualitative
	SITE1.4	Access to Amenities	x	x	x	x	**qualitative**

The major trend establish in the primary analysis process was that the criterion can clearly be split into quantitative and qualitative indicators. In preparation for the integration of these indicators into the digital building model, it is important to distinguish that quantitative indicators can be expressed by predefined parameters, for example a maximum window height in meters or the total number of safety equipment items installed in a building. Qualitative indicators, on other hand, are dependent on subjectively defined parameters. This means that the parameters and the values integrated into the model must first be decided on by the designer and can vary based on the opinions and experiences of the creator of the model.

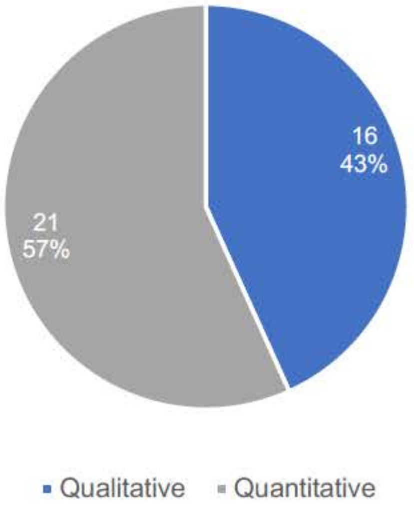


Figure 3.4: DGNB 2018 distribution of qualitative vs. quantitative criteria

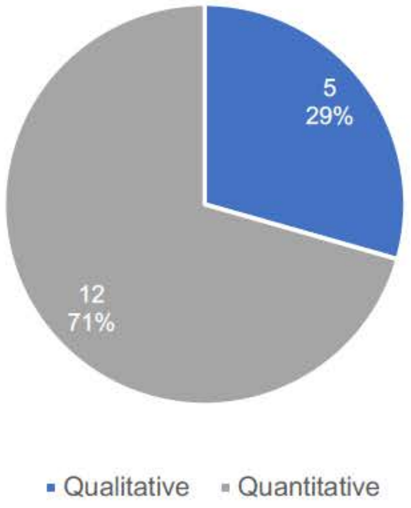


Figure 3.5: Thesis applicable distribution of qualitative vs. quantitative criteria

Overall, the analysis revealed that 43% of the DGNB 2018 criteria can be considered qualitative and 57% can be classified as quantitative (Figure 3.4). Of the 17 criteria deemed applicable to this thesis, 29% were qualitative and 71% were quantitative (Figure 3.5). This skewing to the quantitative side was to be expected, as quantitative criteria are generally more likely to benefit from an integration into a digital model-based workflow and are therefore more likely to have been considered applicable to this thesis. This distinction between qualitative and quantitative criteria was the basis for the research carried out in Chapter 4, where one representative example from each was selected for model integration.

4 Sustainability Criteria Integration

Based on the current state-of-the-art approaches compared in Section 2.5, the ONIB approach was selected as the basis approach to be further developed in this thesis. This approach was selected due to its high degree of BIM integration and its emphasis on openBIM workflows. It also discussed how the approach could be applied to other criteria, not just the two investigated in the ONIB report, and it developed a clear methodology for validating its results using a model checking software. Specifically, these last two points were fundamental to the overarching goal of this thesis, to establish trends that can be applied to all DGNB criteria and to develop a simple model validation procedure that can be used for quick sustainability optimizations in the early design stages. The ONIB approach presented a straightforward and precise integration and validation approach, the overall structure of which was used in this thesis. However, the essence and final applicability of the methodology developed in this thesis were very different from the goals of the ONIB approach.

The ONIB approach was focused on applying their methodology to two DGNB criteria that could be fully depicted using a building information model with the end goal of verifying that all aspects of the DGNB criterion had been fulfilled. In this thesis the selected DGNB criteria were instead meant to be representative of the overall trends found during the sustainability criteria analysis. The results were intended to be applicable to all other criteria that followed the same trend, to include all criteria more readily and not just those that are weighted the heaviest or are the easiest to document. Furthermore, the focus was on using model verification software not to evaluate the overall DGNB criterion fulfillment but rather to provide instant feedback that could be used to iteratively optimize the design in its early stages. This meant that the rulesets created in this thesis were simplified to provide overall feedback on the design and its sustainability, instead of producing a highly detailed output that could be used to determine the overall DGNB score of the building.

4.1 Integration Method Overview

On the basis of the two distinct types of indicators found in the sustainability criteria analysis, two representative example criteria were selected and for each criterion, an in-depth attribute matrix was developed. A building information model was then created, into which the parameters outlined in the attribute matrices could be integrated.

The development of the attribute matrices and the creation of the model were heavily interconnected as an understanding of the building information model was essential for properly defining and integrating the parameters within the attribute matrices. Once the model had been created, a suitable model checking software was used to validate the attribute integration and provide optimization feedback on the design.

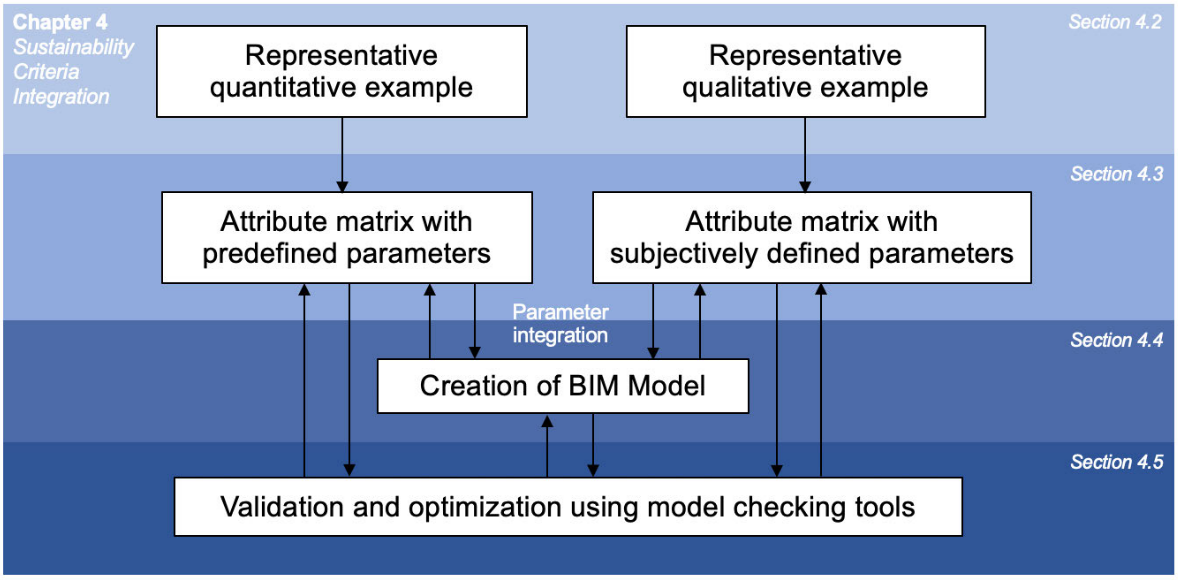


Figure 4.1: Sustainability criteria integration flow chart

4.2 Selection of Representative Example DGNB Criteria

The selection of two, representative example DGNB criteria was based on several boundary conditions. The criteria needed to be applicable in the early design stages and the digital model-based workflow analysis needed to have shown that the criteria would sufficiently benefit from being integrated into a digital model. One needed to represent a quantitative criterion and the other a qualitative criterion. Furthermore, the criteria needed to be from separate DGNB topics to underline the holistic approach of this thesis. It was decided that one criterion should be from the technical quality topic of the DGNB as this area is one of the features that separates the DGNB from other certification systems. Additionally, a conversation with a DGNB auditor (Frau Laub, Drees & Sommer Advanced Building Technologies) revealed that in order to receive a DGNB certification it is necessary to consider all criteria, regardless of weight or number of indicators, even if this consideration is just to explain why no points are achieved in it (DGNB, 2018a). This is required by the DGNB to maintain their well-rounded and holistic approach to sustainability. As a result of this information, it was decided to select the representative example criteria based not on which criteria are weighted the most heavily, as these commonly get the majority of attention, but rather to focus on smaller criteria, such as those weighted with less than 5%. This was done to specifically find criteria that would benefit the most from a digital workflow integration as it would make them easy to include in a holistic design optimization. The idea was that this would then make them less likely be passed over with just a brief explanation as to why no points were achieved and rather be considered quickly but still as an important part of the design. In addition to this furthering the goal of the DGNB to consider all criteria, it also supported the fundamental aim of this thesis to promote the holistic definition of sustainability, also including the smaller often neglected aspects. On the basis of the previously explained conditions, two criteria were selected, 'TEC1.5 Ease of Cleaning Building Components' as the quantitative, technical quality criteria and 'SOC1.7 Safety and Security' to represent the qualitative criteria.

TEC1.5 Ease of Cleaning Building Components

The objective of this criterion is the implementation of structural and technical measures to decrease the effort and cost associated with cleaning both the interior and exterior components of the building. Cleaning of the building can have a significant influence on the costs and environmental impacts of the building' facility management during its use. Ensuring that surfaces and components can be cleaned easily and require fewer cleaning agents result in lower cleaning costs and minimized environmental damages. For the office use scheme this criterion accounts for 1.5% of the total score and has a weighting factor of 2. It uses a total of seven indicators to evaluate the type and scope of the technical and structural measures implemented to improve the ease of cleaning.

Table 4-1: TEC1.5 indicator requirements and possible points (DGNB, 2018a)

Indicator	Requirements	Points
1. Accessibility of the exterior glass surfaces	The façade can be cleaned either with or without any aids, with aids: 0.1 point per % of glass, without aids: 0.15 point per % of glass	Max. 15
2. Exterior and interior components	Measures have been implemented to reduce the cost and effort required for cleaning the exterior and interior components, this includes measures that make cleaning unnecessary	10
3. Floor covering	Flooring is either partially or completely patterned, mottled or structured)	Max. 20

4. Dirt Trap	There are dirt traps at every main entrance and all dirt traps comply with either the three or five-step-principle	Max. 15
5. Unobstructed floor plan	Radiators, railings, sinks, toilets, freestanding supports, lighting and closets are integrated in such a way that they do not create obstacles within the floor plan	Max. 20
6. Surfaces	Measures have been implements to make surfaces that are frequently used and those that are difficult to access easier to clean	10
7. Concept for ensuring ease of cleaning	Measures to support cleaning have been taken into account in the planning process and a detailed cleaning concept has been developed.	10

In total, 100 points can be awarded for this criterion and the majority of aspects are to be documented using floor plans with some written documentation (DGNB, 2018a).

SOC1.7 Safety and Security

This criterion has the objective of preventing dangerous situations in and around the building. Ensuring a high sense of safety and security is essential for user comfort and well-being. If a person does not feel safe in their environment it can cause anxiety and uncertainty which can restrict freedom of movement. This criterion accounts from 1.0% of the total score for office buildings with a weighting factor of 1. It is evaluated using just one indicator that is split into three subpoints.

Table 4-2: SOC1.7 indicator requirements and possible points (DGNB, 2018a)

Indicator	Requirements	Points
1. Subjective perception of safety and protection against assault	An appropriate level of visibility is provided in general and parking areas, thoroughfares, paths and parking areas are well-lit and a number of technical safety installations have been included in the building and surroundings	Max. 100

A maximum of 100 points can be achieved in this criterion. The documentation consists of detailed design plans, written explanations and photo documentation.

4.3 Creation of Attribute Matrices

The purpose of the attribute matrices was to define all of the sustainability parameters outlined by the respective DGNB criteria in such a way that they could more easily be integrated into a building information model. This meant determining exactly what the DGNB criterion required as well as understanding the capabilities of the digital building model. In order to create the attribute matrices, it was therefore necessary to simultaneously also create the building model. However, this section will deal exclusively with the detailed structure and content of the attribute matrices and the specifics of creating the digital prototype building will not be discussed until the following section 4.4.

4.3.1 Analysis of Sustainability Criteria Requirements

In order to determine what aspects are necessary to include in the attribute matrices, it was first necessary to understand the actual requirements of the criteria themselves. For both criteria, TEC1.5 and SOC1.7, a process analysis of the criteria requirements was carried out as the basis for determining the necessary model content. By using process diagrams, the verification requirements and the resulting necessary model information could be derived.

TEC1.5 Ease of Cleaning Building Components

As already mentioned in section 4.2, the criterion ‘TEC1.5 Ease of Cleaning Building Components’ is made up of seven indicators that define how easy it is to clean certain elements of the building. In order to achieve the maximum 100 points, it is necessary to fulfill all seven indicators. This means assessing the accessibility of exterior glass surfaces, analyzing the proposed measures for cleaning both interior and exterior components, determining the dirt resistance of different floor coverings, checking the plans for dirt traps at the entrance and making sure these dirt traps meet the length requirements. In addition, it must be investigated if unnecessary obstructions in the floor plan, that would make cleaning more difficult, have been avoided and if regularly used surfaces are design in such a way that they minimize cleaning efforts. It must also be proven that ease of cleaning was considered as a part of the design process and an overall cleaning concept for the building must be provided. Figure 4.2 shows the process diagram for achieving the maximum number of points available in this criterion.

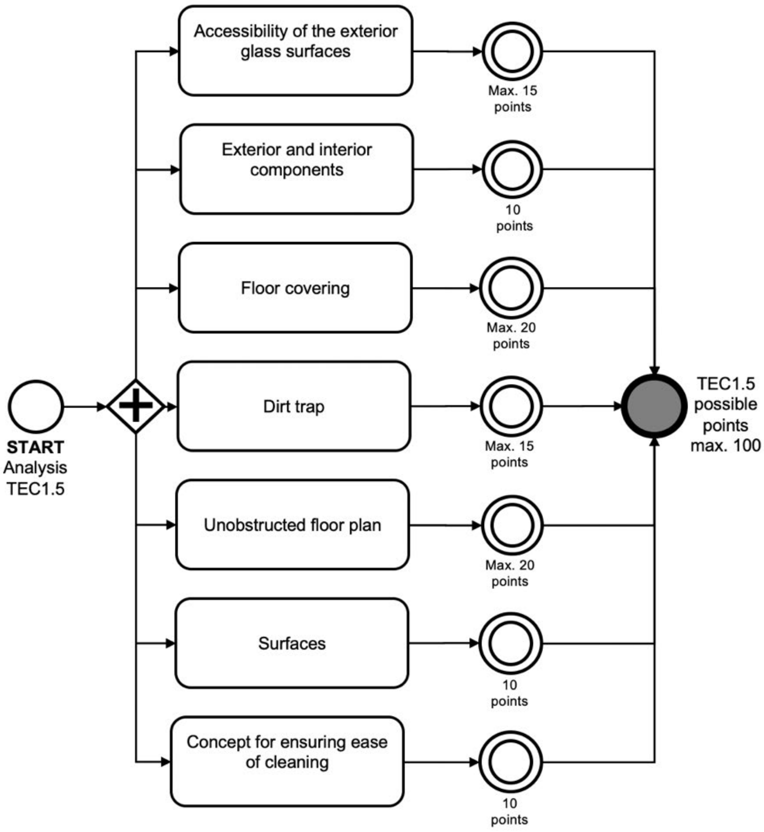


Figure 4.2: Process diagram for criterion TEC1.5

The specific requirements that must be fulfilled in order to achieve the full points in each indicator are defined by individual sub-processes. The sub-processes required for Indicator 2 'Exterior and Interior Components' has been shown in Figure 4.3 to provide an example of how these sub-processes can be understood.

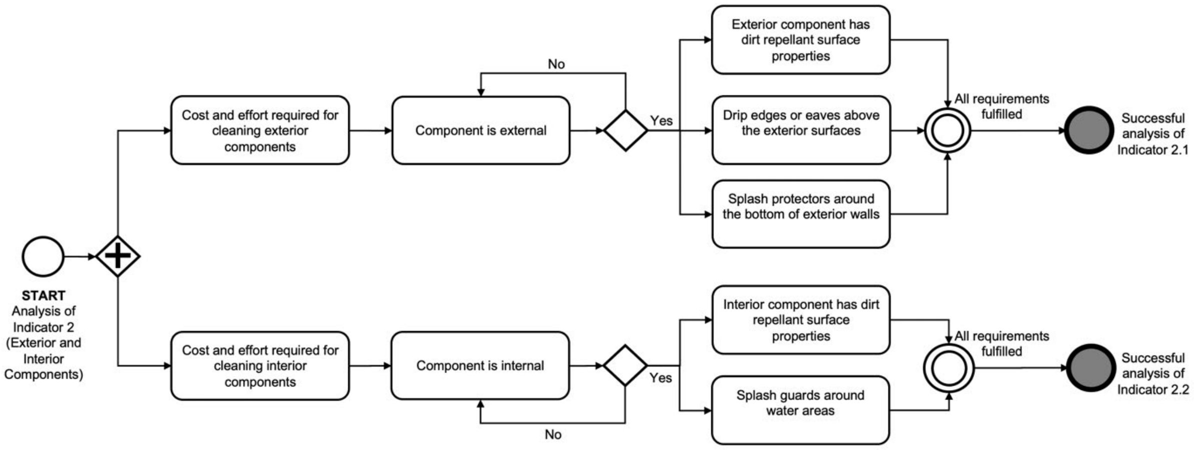


Figure 4.3: Sub-process diagram for TEC1.5 Indicator 2 'Exterior and Interior Components'

The indicator 'Exterior and Interior Components' is only achieved if the necessary sub-indicators are fulfilled. For sub-indicator 2.1, this means checking that the components are external and then verifying if they have dirt-repellant surface properties, drip edges or eaves above them and if the bottoms of the external walls have splash guards. Only if all of these requirements have been met, is an ease of cleaning exterior components ensured. A similar process applies for sub-indicator 2.2, which presents two requirements that must be fulfilled to ensure that the interior components can also be cleaned more easily.

SOC1.7 Safety and Security

Criterion SOC1.7 is made up of just one indicator that accounts for the total 100 points that can be achieved. However, this indicator can be split into three very distinct subcategories. To achieve all of the points in the first category, clear visibility must be ensured in entrance areas, main thoroughfares, courtyards, all parking structures and parking lots. In the second category, main thoroughfares, paths to car parks and bicycle parking areas must be well lit and all paths must be as direct as possible in order to help increase the user's sense of safety. For the third category, a specific number of technical safety equipment must be provided, this includes things like emergency telephones, CCTV, PA systems, and voice alarm systems. Only if all of these categories have been considered, can the total 100 points be achieved, as shown in Figure 4.4.

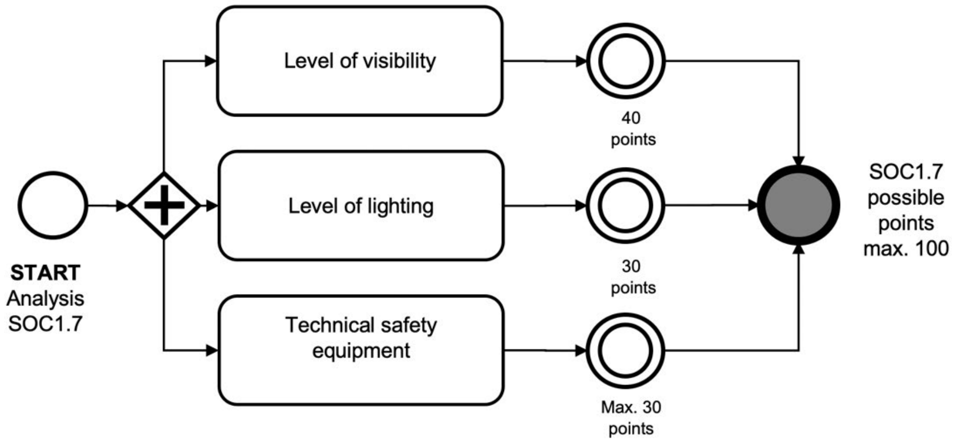


Figure 4.4: Process diagram for criterion SOC1.7

The specific requirements that must be fulfilled in order to achieve the full points in each sub-category of SOC1.7 are defined by further sub-processes. The sub-processes required for Indicator 1.2 'Level of Lighting' are illustrated in Figure 4.5.

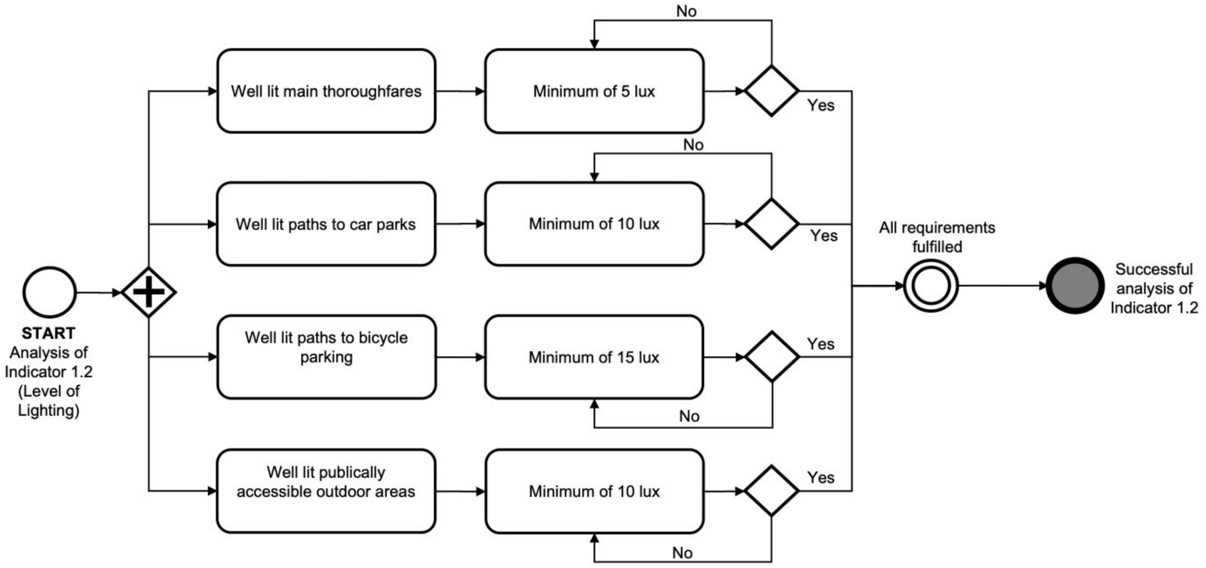


Figure 4.5: Sub-process diagram for SOC1.7 indicator 1.2 'Level of Lighting'

The indicator 'Level of Lighting' is only achieved if the necessary sub-indicators are fulfilled. For 1.2, this means ensuring minimum lux levels in a variety of different locations around the building, main thoroughfares, car parks, bicycle parking and public areas. Only if the minimum lux value is achieved in all of these areas, does the level of lighting ensure that user safety and security is improved.

On the basis of the process diagrams developed for all sub-processes, the information requirements for the model-based evaluation of TEC1.5 and SOC1.7 were transferred to the attribute matrix of the respective criterion. The procedural mapping of the verification requirements also served as the basis for the later development of rules in the model checking software.

4.3.2 Structure and Content of the Attribute Matrix

The attribute matrices are the basis for the sustainability requirements that are to be integrated into the BIM model. They define the requirements for the logical verification of the individual sustainability requirements and the parameterization of the model. The content of each requirement in the criteria catalog was therefore analyzed and translated either into specific model attributes or a geometric verification requirement for the model. Normative requirements could be represented purely parametrically by assigning semantic information to specific components or they could be described by geometric specifications. Combinations of these information requirements or dependencies between several components were also possible.

In order to ensure understandable and consistent attribute matrices for all criteria, the specific structure and basic information content of the matrices needed to be clearly defined. Table 4-3 provides an overview of the structure and content of the attribute matrices.

Table 4-3: Information content requirements for the attribute matrices (based on ONIB, 2019)

Information Requirement	**Range of Values**	**Example**
Indicator explanation	Text that briefly describes the intent of the indicator	*Feasibility of façade cleaning with or without aids*
Type of documentation	Describes in what form the attribute is documented [component attribute, component geometry, etc.]	*Component attribute*
Type of check	Describes how the attribute can be checked in the model [logical check of attribute, model geometry, visual model check, logical check of several attributes, etc.]	*Logical check of component attribute*
Logical check	Questions that formulate the criterion requirements in such a way that they can be answered using the model parameters	*Check 1: does the window open inwards?*
Requirement of additional parameters	Are additional parameters necessary to depict the information requirement that are not part of the IFC data structure? [yes or no]	*yes*
Type of parameter	Defines if the attribute can be depicted using an IFC parameter or if a custom parameter must be created [IFC Parameter, Custom – Shared Parameter]	*Custom – Shared Parameter*
Model object type	Type of model object to which the attribute applies [Window, Wall, Door, Roof, Floor, etc.]	*Window*
IFC entity	The specific IFC entity to which the attribute applies [IfcWall, IfcSlab, IfcRoof, IfcCovering, IfcFlowTerminal, etc.]	*IfcWindow*
IFC type	Further defined where in the IFC data structure the attribute is to be stored [IfcDoorStyle, IfcWindowType, IfcLightingFixtureType, etc.]	*IfcWindowStyle*

IFC parameter	Name of the IFC parameter that can be used to depict the attribute [top elevation, bottom elevation, IsExternal, Name, etc.]	*[-]*
Attribute name	Name of the custom parameter that has been created to depict the attribute [TEC1.5_RoofEaves, TEC1.5_WindowOpeningInwards, etc.]	*TEC1.5_WindowOpeningInwards*
Attribute explanation	Only applies to custom parameters, brief definition of what exactly the new parameter defines	*this attribute defines if it is true that the window opens inwards*
Attribute data type	Data type used to represent the attribute expressed by the parameter [Boolean, double, List<string>, etc.]	*boolean*
Units	Unit of the attribute [(yes/no), m, “name”, etc.]	*[yes/no]*
Default value	Used for model checking as the target value that can be used to determine if the parameter fulfills the requirement or not	*yes*
Discipline	Defines the discipline for which the parameter is relevant [Architecture, MEP, Structural, etc.]	*Architectural*
LOD	Level of development at which the specific parameter become relevant [LOD 100 - LOD 500]	*LOD 200*

The LOD category of the attribute matrix functioned as a secondary analysis of the applicability of the indicator in the early design stages. For this thesis the early design stage cut off what drawn at LOD 300, before the interface information needed for construction documentation is added in LOD 350.

Attribute Nomenclature

When defining custom sustainability parameters, it was essential that a common nomenclature scheme was used. This was necessary to differentiate between IFC parameters and those created as custom shared parameters and to ensure clarity and consistency within the model. Specifically, for manual model checking of individual requirements during the design process, a clear nomenclature makes the element data easier to identify and update.

By using the DGNB topic abbreviation and criterion number, it was possible to quickly identify which parameters in the model were associated with which criterion. Including a parameter name that was human readable and clearly defined the objective of the parameter made it easy to see which additional information had been added in both the attribute matrix and the model itself. Explicitly naming the parameters with the requirements they aimed to fulfill also enabled external parties to quickly understand and, if necessary, easily use and update the parameters as needed.

4.3.3 Attribute Matrix Results

The full attribute matrices for both TEC1.5 and SOC1.7 can be found in Appendix F.

TEC1.5 Ease of Cleaning Building Components

TEC1.5 could be separated into 31 different attributes that were necessary to evaluate the 10 sustainability indicators relevant to this criterion. If applicable to be added to the building information model, these attributes could be categorized as either IFC Parameters or Custom-Shared Parameters. Of the 31 total attributes, just over 61% could be represented using existing IFC parameters, 23% required custom parameters and the final 16% were not applicable to be integrated into the model. An attribute was determined to be “not applicable” if it either required subjectively answering a question, such as “was a detailed cleaning concept created?”, or if it required details that would only be included at a LOD over 300.

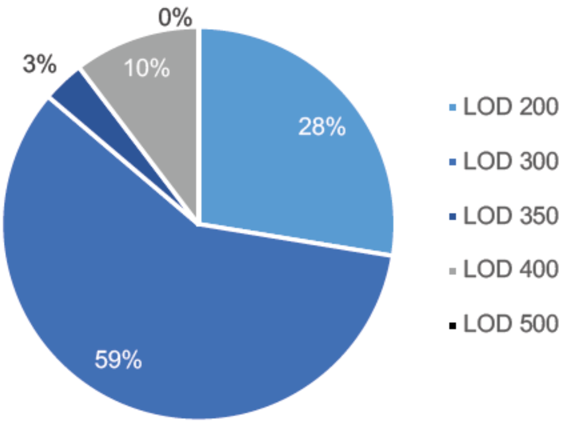


Figure 4.6: LOD distribution for criterion TEC1.5

The majority of attributes, approximately 59%, required details that would typically be depicted in the model starting at LOD 300. The second largest percentage went to LOD 200, with approximately 28%. The attributes that required details typical for LOD 350 and LOD 400 came out to less than a quarter of the total number of attributes. For this criterion, all attributes could be considered before construction was completed and none required information from LOD 500 (Figure 4.6.).

SOC1.7 Safety and Security

The criterion SOC1.7 only has one indicator that could be split into 16 attributes. Of these attributes, 81% could be depicted as IFC parameters, 13% as custom shared parameters, and just one attribute was deemed not applicable as it required information typically included at LOD 500.

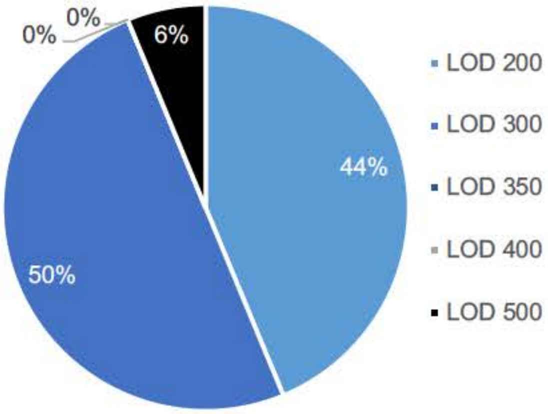


Figure 4.7: LOD distribution for criterion SOC1.7

Besides the one attribute from LOD 500, the majority of attributes could be distributed fairly evenly between LOD 200 and LOD 300, with LOD 200 accounting for 44% and LOD 300 accounting for 50% (Figure 4.7.).

4.3.4 Attribute Matrix Discussion

For the quantitative criterion TEC1.5, the high percentage of attributes in LOD 300 was to be expected, as many of the indicators for this criterion require fairly detailed component information to determine the ease of cleaning. For SOC1.7, the greater focus on LOD 200 was also expected as the safety and security aspects are mainly influenced by spatial connections and the basic layout of the building and are not as dependent on specific component details.

Similar trends can also be predicted for the other quantitative and qualitative criteria applicable to this thesis. For example, of the 12 applicable quantitative criteria, twothirds (predominantly the TEC and ENV criteria) are evaluated based on building component and material properties similarly to criterion TEC1.5. The rest are based on achieving target values or carrying out building simulations, both of which are also dependent on detailed, specific component information that is typical of LOD 300. The five qualitative criteria, on the other hand, are all based more on the spatial relationships within the model and the overall layout of the building. As was seen with criterion SOC1.7, much of this more general design and layout information is included in the model starting at LOD 200, when generic component information is sufficient.

On the attribute matrix level, this means that for quantitative criteria it can be expected that there will typically be more attributes required than for qualitative criteria, as more specific components need to be included in the analyses. In addition, the attribute matrix detail required for quantitative criteria will likely be higher to account for all of the specified target values and percentages that have been defined by the DGNB and need to be verified for the individual model components. As previously mentioned, the evaluations of the qualitative criteria are based more on subjective opinions as to the level and success of specific criterion implementation and fulfillment, which can be difficult to include at the attribute matrix level. This will be discussed further in the model checking section 4.5, as it was found that the qualitative criteria are actually easier to check with rulesets that evaluate the design as a whole instead of attempting to attach subjective design evaluations as individual component attributes.

Overall, the results of this section can be used to assess the two hypotheses 3.1 and 3.2. The first hypothesis stated that for quantitative criteria, approximately 80% of the object-information could be stored in the IFC data structure. This hypothesis can be confirmed as the representative quantitative criterion TEC1.5 found that with a combination of pre-existing IFC parameters and several additional custom parameters, 84% of the required criterion information could be stored in the building information model. The second hypothesis was actually rejected as it turned out that far more qualitative information could be stored in the model than initially predicted. Criterion SOC1.7 found that with just IFC parameters, a surprising 81% of attributes could be included. With both existing IFC and custom parameters, nearly 95% of the required information could be added to the building information model. This can be partially attributed to the way that qualitative criteria are more dependent on the overall design than on specific component attributes. This means that IFC and other model parameters that describe the overall structure and layout of the building can actually be used to evaluate a qualitative criterion. This can happen without the need of any object specific information to be added with custom parameters, which was initially predicted to be rather complex and even impossible for certain qualitative information.

As indicated at the beginning of the section, the creation of the attribute matrices was very closely linked with the development of a BIM model for a prototypical small office building. The BIM model was used to determine which IFC parameters already existed, the IFC entity and type of the different model objects, to what extent the model objects could actually be modified, and how custom parameters could be added. The following section will take a closer look at how the BIM prototype was developed and how this influenced the attribute matrix content.

4.4 Integration of Sustainability Attributes into a BIM Model

In order to complete the attribute matrices with all the necessary information defined by the selected DGNB criteria, a building information model was established. This model was created entirely within the course of this thesis and was intended to function only as a prototypical office building on which to test the use case of sustainability optimization through attribute integration. The following sections will outline how the modeling software was selected, all of the necessary model boundary conditions and assumptions, and ultimately the process of attribute integration and model development.

4.4.1 Selection of Modeling Software

Revit 2019 was selected as the BIM modeling software because it is very closely integrated with the BIM methodology, meaning it can be used to create the smart building information model that is used by architecture, engineering and construction professionals to efficiently plan, design, construct and manage a building project (Autodesk, 2018). Revit automatically produces high-quality construction documentation, can be used for quantity and cost take offs, 3D visualizations, effective coordination between disciplines, and for straightforward interoperability with commonly used data formats such as IFC (Panagiotidou, 2018). It allows for 3D parametric modeling which means that each element created in Revit has parametric qualities that can be edited in both 2D and 3D drawings. The key for this is that all of the information used to create the model is stored in a single database so whenever a change is made, the database is updated, and the change is applied everywhere. This dynamic ability can save an immense amount of time by eliminating tedious, repetitive work in the design process, leading to far more consistent drawings overall. Revit also has access to a huge library of parametric components and elements that can be loaded into the model and updated as needed. In addition to the predefined parametric elements, custom parameters can be added to the Revit model as well through global, shared and project parameters. This was especially useful for the work in this thesis as it was determined early on that many of the DGNB requirements may not intrinsically be part of the IFC data structure and would need to be represented with custom parameters.

4.4.2 Boundary Conditions and Assumptions

The created example model was an office building of approximately 872 m^2 surface area across two stories (Figure 4.8). The building contained several office rooms, conference rooms, toilets, kitchens and storage rooms, as well as an open office space and a foyer/reception area.

Figure 4.8: East elevation view of Revit model

The model was only furnished in areas required to fulfill the DGNB criteria described by the attribute matrices. A parking area, access road and vegetation were also only added insofar as they were required by the attribute matrices (Figure 4.9). The building was meant only as a basic architecture model, thus, the structural integrity of the building and fire safety aspects were not considered. As the scope of this thesis covers only the early design stages and with that up to LOD 300, certain design details and intricacies were disregarded. The Revit model can be found in the digital Appendix G.

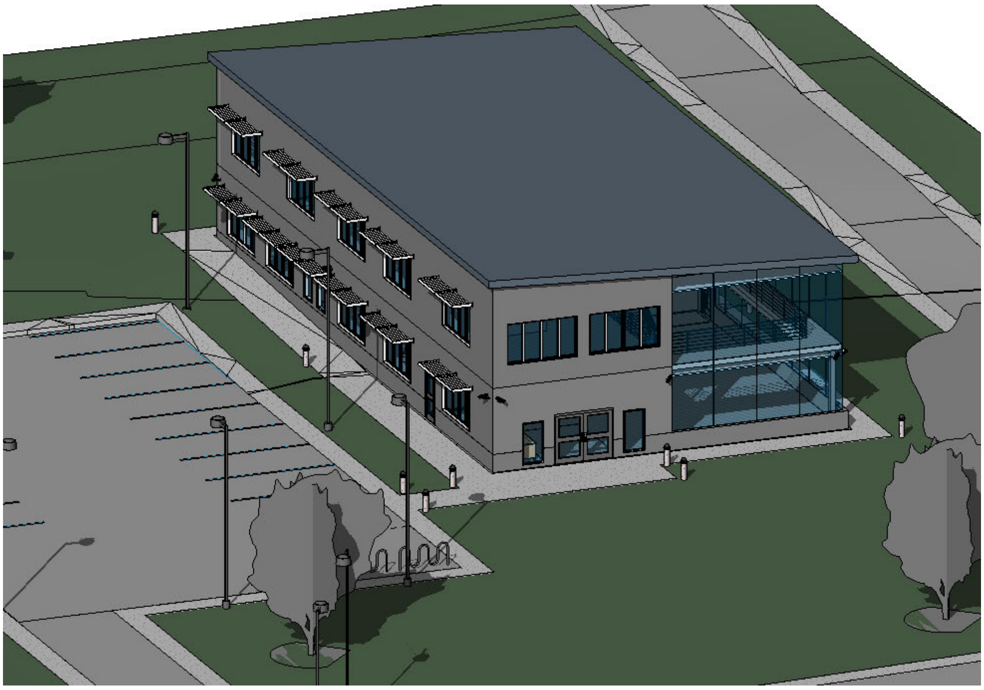


Figure 4.9: Aerial view of Revit model

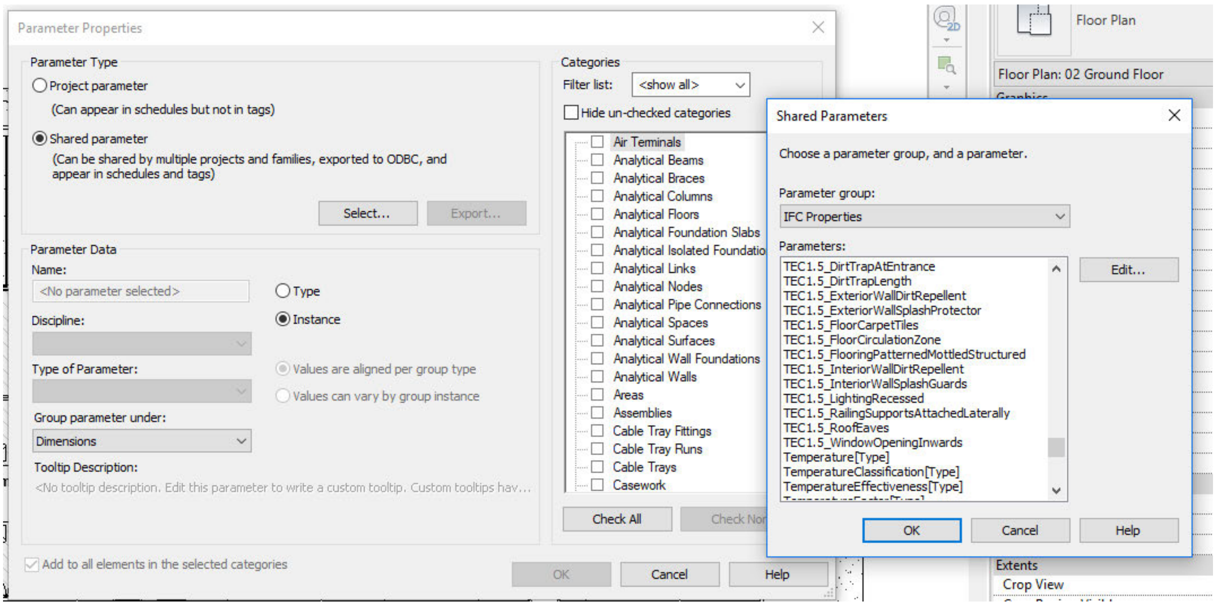
For exporting the model, IFC2x3 Coordination View was used as opposed to the newer and more advanced IFC4. This choice was made after the IFC4 export from Revit 2019 resulted in distorted lighting fixtures and did not transfer certain model elements. Overall, IFC2x3 is also still the most popular and widely used of the IFC versions. In order to include as much information in the IFC export as possible, that could be relevant to model checking later on, both Revit and IFC common property sets were selected to be exported. All other export settings were left unchanged.

4.4.3 Process of Attribute Integration

In order to integrate the attributes into the BIM model, it was first necessary to add some of the needed elements and investigate which semantic and geometric information was already present in the model objects. For example, several windows were placed in the model to see which dimensional, material, and relational information they inherently contained. It was then explored to what extent the required information was already associated with the element. To continue with the window example, the attribute matrix required that the window contain the information that it was external, had a head height of less than 4 meters and opened inwards to allow for easier cleaning. By exporting the Revit model as an IFC file and opening it in Solibri, it was determined that the IFC parameter IsExternal was automatically a part of the window information. The 4 meters of required head height were also stored in the object as “top elevation”.

Information regarding the opening direction of the window could not be determined based on the IFC file so a custom parameter was created for this attribute. This process was repeated again for all model objects included in the attribute matrices.

Creating custom parameters was vital to ensuring that all of the sustainability requirements could actually be integrated into the BIM model. In order to create a custom parameter, it is first necessary to create a text file in which the new parameter data can be stored. For this thesis, a new text file was created called 'Custom Shared Parameters DGNB 2018' (digital Appendix H). Once this text file had been saved, a new parameter group could be added, and new shared parameters could be created. Once the shared parameter had been created based on the name and data type specified in the attribute matrix for that indicator, it could be added to the specific Revit project under 'Project Parameters'. Before adding the parameter to the project, it was important to decide if the parameter was to apply on the type or instance level and for which categories the parameter was applicable. Once all selections had been made, the new parameter could be added to the project and then populated with data in its respective location.



Parameter Properties

Parameter Type
○ Project parameter
(Can appear in schedules but not in tags)
● Shared parameter
(Can be shared by multiple projects and families, exported to ODBC, and appear in schedules and tags)

Parameter Data
Name: <No parameter selected>
○ Type
● Instance
Group parameter under: Dimensions
Tooltip Description: <No tooltip description. Edit this parameter to write a custom tooltip. Custom tooltips hav…
☑ Add to all elements in the selected categories

Categories
Filter list: <show all>
☐ Hide un-checked categories

Shared Parameters

Choose a parameter group, and a parameter.

Parameter group: IFC Properties

Parameters:
TEC1.5_DirtTrapAtEntrance
TEC1.5_DirtTrapLength
TEC1.5_ExteriorWallDirtRepellent
TEC1.5_ExteriorWallSplashProtector
TEC1.5_FloorCarpetTiles
TEC1.5_FloorCirculationZone
TEC1.5_FlooringPatternedMottledStructured
TEC1.5_InteriorWallDirtRepellent
TEC1.5_InteriorWallSplashGuards
TEC1.5_LightingRecessed
TEC1.5_RailingSupportsAttachedLaterally
TEC1.5_RoofEaves
TEC1.5_WindowOpeningInwards
Temperature[Type]
TemperatureClassification[Type]
TemperatureEffectiveness[Type]

Figure 4.10: Adding shared parameters to the Revit project

The goal of the attribute integration method was to make the process as simple, straight-forward and logical as possible. This was meant to make it understandable to the widest range of potential users, while leaving enough flexibility that any possible new parameter could be added using the same process in the future. However, the particular parameter creation method described here only applies within Revit and during the IFC export process, the Revit property sets also needed to be selected in order for the newly created shared parameters to show up in the IFC model. Therefore, it is important to note that for a practical application supporting the openBIM approach, the individual parameters need to be created in the model authoring software in such a way these are exported properly. That being said, user created parameters can be defined similarly in Allplan Architecture and it is assumed that other BIM modeling software provide similar capabilities as well.

4.4.4 EIR and BEP Requirements for Successful Attribute Integration

In order for the attribute integration to be successful, the sustainability optimization use case and the resulting model requirements must be clearly defined in the EIR before the project begins. For the consideration of sustainability criteria, the information requirements are of fundamental importance, as a high degree of standardization is necessary in the model content for the digital verification of sustainability information. In response to the requirements included in the EIR, the BIM Coordinator will typically create a BEP in which the realization of the requirements is clearly explained. The following Table 4-4 contains a condensed version of the information typically included in the EIR and the BEP for the use case of building sustainability optimization and certification.

Table 4-4: EIR and BEP requirements (based on ONIB, 2019)

REQUIREMENTS	**EIR**	**BEP**
Project Information	- project definition of sustainability - selected certification system - important certification deadlines - overall certification level to be achieved	- use of EIR defined certification system - adherence to certification system deadlines - documentation of certification level as a part of the contract
BIM Goals	- criteria that are to be integrated into the digital model - criteria that are to be verified using the digital model	- integration of overall BIM project goals with sustainability goals
BIM Use Cases	- use cases related to the BIM goals	- defining to do's and responsibilities based on the use cases
Roles and Responsibilities	- BIM Manager = checking model quality in regard to attribute requirements, verification of the certification requirements	- Confirmation of roles and responsibilities by accordingly assigning the relevant tasks to concrete project participants

	- BIM Coordinator = integration assurance of attribute matrix requirements, quality control of component models - BIM Modeler = integration of attributes into BIM model-content - Auditor = support during design and integration, execution of building certification	
Collaboration	- CDE requirements - data formats for models and certification documentation - model-checking procedure - sustainability-focused meetings and appointments	- Selection of an EIR-conforming CDE software solution Description of selected model-checking software in terms of both basic model-checking and criterion verification
Modeling Guidelines and Data Requirements	- Depth of information in the coordination models, LOD of specific sustainability attributes, list of criteria to be included in the model, nomenclature	- Selection of software that allows for the integration of the attribute matrix requirements and IFC exports - Integration of specific criteria into the model according to all EIR requirements (*creation of a shared parameters file)
Software	- Software functionality requirements, certification system specific software	- Selection of modeling and model checking software with regard to building certification capabilities

The BIM Coordinator is ultimately responsible for how the sustainability criteria are depicted in the building information model, for ensuring the quality and completeness of all necessary information and for the model-based verification of the sustainability criteria. It is the BIM Coordinator that must work together with the DGNB auditor or consultant, who has the necessary sustainability understanding that a BIM Coordinator is typically lacking, to create the attribute matrices for all relevant DGNB criteria. Based on the matrices created with the help of the auditor, it is then the BIM Coordinator's job to develop the rulesets that will be used to verify if the information in the matrices has been incorporated correctly and to make optimization suggestions. This step also benefits from collaboration with a DGNB auditor or consultant as they can later use these rulesets in the overall certification process for the building. Once the attribute matrices have been fully developed, they are passed on to the BIM Modeler, most commonly the project architect or engineer, who is then responsible for integrating all of the attribute requirements into the building information model. When the attributes have been integrated, the BIM Coordinator imports the model into the checking software to verify the attribute implementation and ultimately provide the BIM Modeler with any feedback necessary to make sustainability optimizations to the design.

Essential in communicating the relevant information to all parties is the BCF. This can be used to add object-specific comments within the model, based on the issues or lack of information discovered in the model viewer and/or model checker by the BIM Coordinator. Using the components of the BCF, the issue or missing information can be noted and the location described. The BIM Modeler can then use this information to add the relevant parameter or adjust the parameter to better fulfill the criterion requirements.

Overall, the success of the attribute matrix creation, integration and final validation as an optimization tool is based on the proper execution of the requirements contained in the EIR and BEP and constructive collaboration between the BIM Coordinator, DGNB auditor and the BIM Modeler. The following section describes how the model integration validation and design optimization could work based on a selected model checking software.

4.5 Validation and Optimization with Model Checking Tools

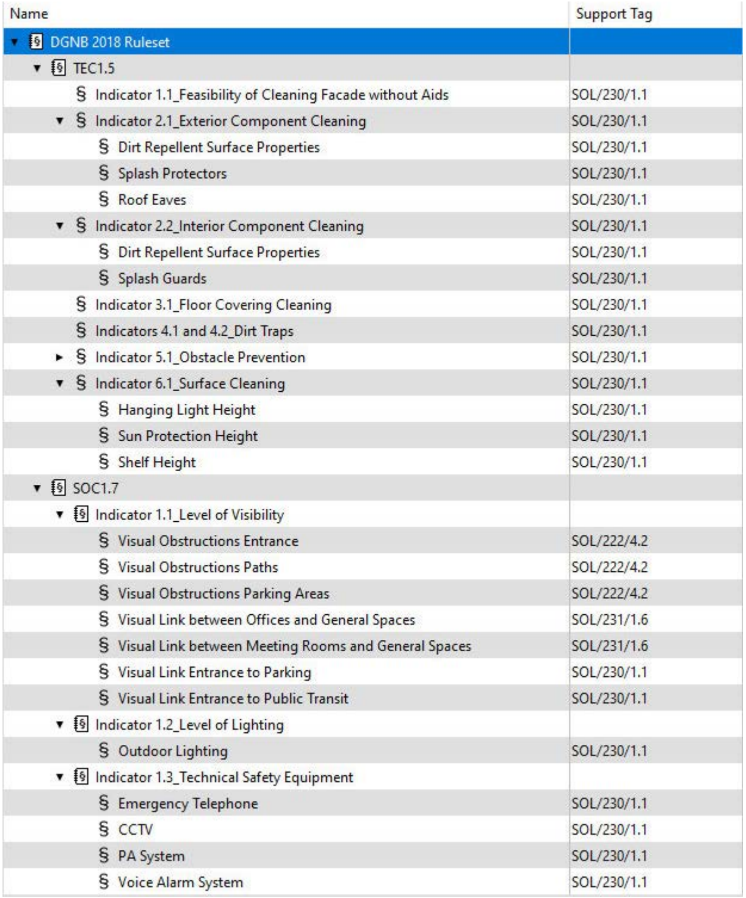
In order to validate the integrated sustainability attributes and provide feedback about possible design optimizations a model checking tool was used. Solibri Model Checker (SMC) (version 9.10.8) was selected as the model checking software for this thesis based on the analysis conducted in Table 2-7. The software offers both content and compliance checking abilities, both of which were necessary to check if the model content required for DGNB fulfillment had been successfully integrated. Solibri also provides a variety of previously created rulesets to choose from as well as allowing the user to create new, customizable rulesets within the software. The pre-existing rulesets were important for checking the overall quality of the architectural model and the customizable rulesets were essential in checking the more specific sustainability indicators. Solibri can also be used as a model viewer and has an overall easy-to-use, intuitive interface.

As the model was being developed within Revit, it was exported as an IFC file at regularly intervals and opened in Solibri to check the overall model quality and ensure that a fully functioning model was being created. These checks were done on the basis of the three rulesets that Solibri automatically selects when a model is opened within the software, ‘BIM Validation – Architectural’, ‘General Space Check’, and ‘Intersection between Architectural Components’. These rulesets checked, among other things, that all model objects and spaces were correctly defined, that distances between objects were reasonable and met specified minimums, and that there were no intersections of any components.

Once the model was determined to meet all of the basic requirements of these general checks, Solibri was used as an IFC viewer in the attribute matrix creation process. In Solibri, individual elements could be selected and semantic and geometric information that had been assigned within Revit could be verified. Using Solibri as an IFC viewer made it possible to see where specific information that had been added within Revit was being stored. It also provided the first insights as to how this information could be accessed later on in the development of the custom rulesets.

4.5.1 Creation of Rulesets for Model Checking

The Solibri Ruleset Manager was used to produce a custom ruleset named “DGNB 2018 Ruleset” under which two individual rulesets were created, one for each representative DGNB criterion, TEC1.5 and SOC1.7. Within each criterion ruleset, independent rules were created to check each indicator, with sub-rules created for the indicators that required numerous different parameters as defined in the attribute matrices. Figure 4.11 provides an overview of the ruleset structure created in Solibri.



Name	Support Tag
▾ DGNB 2018 Ruleset	
▾ TEC1.5	
§ Indicator 1.1_Feasibility of Cleaning Facade without Aids	SOL/230/1.1
▾ § Indicator 2.1_Exterior Component Cleaning	SOL/230/1.1
§ Dirt Repellent Surface Properties	SOL/230/1.1
§ Splash Protectors	SOL/230/1.1
§ Roof Eaves	SOL/230/1.1
▾ § Indicator 2.2_Interior Component Cleaning	SOL/230/1.1
§ Dirt Repellent Surface Properties	SOL/230/1.1
§ Splash Guards	SOL/230/1.1
§ Indicator 3.1_Floor Covering Cleaning	SOL/230/1.1
§ Indicators 4.1 and 4.2_Dirt Traps	SOL/230/1.1
▸ § Indicator 5.1_Obstacle Prevention	SOL/230/1.1
▾ § Indicator 6.1_Surface Cleaning	SOL/230/1.1
§ Hanging Light Height	SOL/230/1.1
§ Sun Protection Height	SOL/230/1.1
§ Shelf Height	SOL/230/1.1
▾ SOC1.7	
▾ Indicator 1.1_Level of Visibility	
§ Visual Obstructions Entrance	SOL/222/4.2
§ Visual Obstructions Paths	SOL/222/4.2
§ Visual Obstructions Parking Areas	SOL/222/4.2
§ Visual Link between Offices and General Spaces	SOL/231/1.6
§ Visual Link between Meeting Rooms and General Spaces	SOL/231/1.6
§ Visual Link Entrance to Parking	SOL/230/1.1
§ Visual Link Entrance to Public Transit	SOL/230/1.1
▾ Indicator 1.2_Level of Lighting	
§ Outdoor Lighting	SOL/230/1.1
▾ Indicator 1.3_Technical Safety Equipment	
§ Emergency Telephone	SOL/230/1.1
§ CCTV	SOL/230/1.1
§ PA System	SOL/230/1.1
§ Voice Alarm System	SOL/230/1.1

Figure 4.11: Custom DGNB ruleset in Solibri

Solibri provides access to a library with a multitude of pre-defined rules that can be altered and combined as required. The majority of the rules were created using the property rule template with component filters. For TEC1.5, nearly 95% of all parameters could be checked using this rule as a basis. Only the rule for checking free standing support distances under Indicator 5.1 used the distance between components template. For SOC1.7, approximately 60% of the rules used the property rule template, with 25% using the distance between components template and approximately 16% using the spaces must have doors rule as a foundation.

In creating custom rulesets on the basis of these templates, it was discovered that several qualitative indicators could be more reasonably included on the model checking level than within the Revit model itself. For example, visual obstructions in front of doors could be much more intelligently checked using Solibri than manually measuring distances within the model and saving these values as a door parameter. The same was true for determining if surfaces had dirt-repellent properties. Creating rules that evaluated the materials included in a wall construction instead of whether or not a box had been selected that made the dirt repellent surface properties of the wall ‘true’, led to a far more accurate results that were also far more likely to remain up-to-date as design changes were made. Ultimately, many previously defined parameters were removed as it became clear that it made more sense to check certain things objectively and automatically with the model checker than basing the verification of specific elements on the statements or manual confirmations of the designer. Specifically, parameters that had initially been added to the model as boolean parameters were replaced by rules in Solibri as it became clear that updating these parameters could likely be forgotten if the design was changed. In total, the seven initially created custom SOC1.7 parameters were reduced to just two in this process.

Using Solibri also has the benefit of more easily and comprehensively adding target values and changing these based on the subjectivity of the designer or DGNB auditor. Additionally, acceptable ranges could be defined in the Solibri rules, which allowed for a greater variety of possible values and therefore provided more room for creativity and innovation without needing to worry about updating numerous parameters in the process.

As the custom rules were being developed in Solibri, it was important to verify that the rules were actually finding the targeted components and the correct semantic and geometric information associated with them. Since the model was built using the DGNB criteria as a guide for what elements should to be included, several rules were automatically passed, which in Solibri meant that it was not possible to see what components had actually been analyzed. In order to verify that the rules indeed functioned as intended, incorrect values and/or objects were substituted in and certain elements were temporarily deleted from the Revit model. For example, maximum shelf and light fixture heights were changed from the required 4 m to 1 m to confirm that all shelves and lights were being correctly identified. Once the rule was no longer passed, the actual functionality of the rule could be explored. This proved especially useful in checking the consistency of the Revit/IFC models and in understanding the relationships between different model components.

In addition to understanding how the rules themselves worked, it was also pertinent to understand the goals of the DGNB criteria that the rules were meant to evaluate. To create meaningful rulesets that ensured that the overarching goals of the indicators and furthermore the criteria were actually achieved, it was necessary to make several assumptions.

4.5.2 Assumptions for Model Checking Rulesets

Overall, the qualitative criterion TEC1.5 did not require many assumptions in the rule creation process, as the majority of requirements were clearly outlined by the DGNB. However, it was necessary to decide in advance, how many of the suggested elements needed to be added in order for an improvement in cleaning cost and effort to be achieved. In general, it was decided that including all clearly stated suggestions from the DGNB within the model would be considered adequate. For future applications, additional elements defined within a specifically developed cleaning concept can easily be added on the model checking level, using similar rules to those already created in the scope of this thesis. The following assumptions applied to the rules created to check TEC1.5:

- To assess the dirt-repellent properties of both internal and external surfaces, it was checked that the outer material layer contained the word “dirt-repellent”, as specific coating materials with this name had been created in Revit. However, for future applications the rule can be altered to contain the names of a variety of materials that all count as having “dirt-repellent” properties, to allow for a greater variation in the types of materials that can be used to fulfill this indicator.

- Elements that needed to be attached to the wall instead of the floor, such as toilets, sinks and radiators were evaluated by checking that the bottom elevation of the object was at least 15 cm high. This value was defined by the DGNB as the minimum value for cleaning under the radiators, so it was assumed that this value would be adequate for cleaning under toilets and sinks as well.
- The evaluation of the work surface and the types of handles, doorknobs, light switches and lift buttons used was not included in the model checking evaluation, as this type of information is not typically stored within the BIM model, as it makes the model unnecessarily complex and it is better checked using data sheets at a later stage in the design process.

The qualitative criterion on the other hand required that a variety of subjective values be defined in order for the indicators to be properly evaluated using the model checker. It is important to note that as these values are subjective in nature, they are prone to change, depending on the background and opinions of the designer and/or auditor. However, the rules have been structured in such a way that that they will work regardless of the final values that the designer or auditor selects. The subjective assumptions that were made in creating the basis ruleset to check SOC1.7 are listed below:

- A 10 m clear distance surrounding main and side entrances was selected on the basis that this distance provides a reasonable view of the surrounding area and approximately 10 steps should give users enough time to react should an unsafe situation arise. For paths and parking areas, 5 m were selected as users in these areas are likely already moving and creating areas away from the building that feel too open can have the opposite effect on a sense of security by making people feel unnecessarily exposed and vulnerable.
- Comprehensive sign posting was left out as this can only be evaluated after building construction is complete (LOD 500), which is outside of the scope of this thesis.
- Visual links from entrances to parking areas were created as boolean parameters assigned to entrance doors that needed to be manually evaluated by the designer/auditor within the Revit model. This was done as it was not possible to create a rule in Solibri that could evaluate visual connection between two spaces/objects that did not face each other, this means that doors that did not have a visual link to

the required space were simply not analyzed, however, creating the boolean parameters made it so that the doors that did not have visual links were flagged and could be filtered out as not fulfilling the rule.

- In order to evaluate the level of lighting, a further model analysis in the form of a lighting simulation was necessary. As the results of such a simulation were not able to be checked in Solibri, it was instead just checked that lighting fixtures had been provided in all necessary external areas. Within the attribute matrix, minimum lux requirements were defined using DIN EN 12464-1 for all external spaces. These values could be used in future applications, if an external lighting simulation were to be carried out with a program such as DIALux or the Revit Plug-in ElumTools. It should be noted that simulation results are required to be submitted as external documentation by the DGNB for specific criteria so the results of these simulations don’t necessarily need to be incorporated into the BIM model, unless the results are unsatisfactory, in which case the model used for the simulation needs to be updated and the simulation needs to be run again.
- Technical safety equipment needed to be labeled properly in order to be recognized by Solibri. To fulfill the indicator, it was just necessary for the objects to be included in the design and it was not important how many or where exactly the items were installed, so the rules could be written to simply recognize the name of the respective object. For the CCTV sub-indicator, the DGNB required that the entire exterior of the building be visible with the installed cameras, however, this requirement needed to be evaluated manually as it was not possible to get camera angle and coverage information from the CCTV camera objects used. In a real-world application, the full CCTV system would need to be modelled in a separate electrical component model as not to overcomplicate the architecture model. In this specialized model, a more advanced camera object could be created that includes coverage information to evaluate if a certain area around the building is indeed under CCTV surveillance as required by the criterion.

Specifically, for qualitative criteria it is essential to openly document and justify all ruleset assumptions so the decision-making process can be followed and later communicated to the DGNB auditor. Ideally, the rulesets and the assumptions they include, would be developed with the support of an auditor from the very beginning of a project so that the DGNB requirements are clearly understood and any uncertainties can be resolved before the iterative criterion implementation process even begins.

4.5.3 Iterative Checking Approach

As already mentioned, creating the attribute matrices, the Revit model and the Solibri rulesets was a heavily interconnected and iterative process. Both the Revit model and the IFC export of the model were necessary in determining which parameters were intrinsically a part of the IFC structure and which needed to be added as custom parameters. In this regard, Solibri was used primarily in its capacity as a model/IFC viewer to help determine and classify the information needed for the attribute matrices. Once the matrices had been filled with the relevant parameter data, the Revit model was updated to include all of the necessary information from the matrices before Solibri was used in its model checking function to verify that all parameters had indeed been added correctly, using the most reasonable checking approach and that the criterion had successfully been fulfilled. Parallel to filling the attribute matrices with information from the Revit and IFC models, the Solibri rulesets also needed to be developed. These were based on the logical checking questions included in the attribute matrices so any change in the matrix data, also required an update of the rulesets. Figure 4.12 provides an overview of the iterative process required for successfully implementing a DGNB criterion.

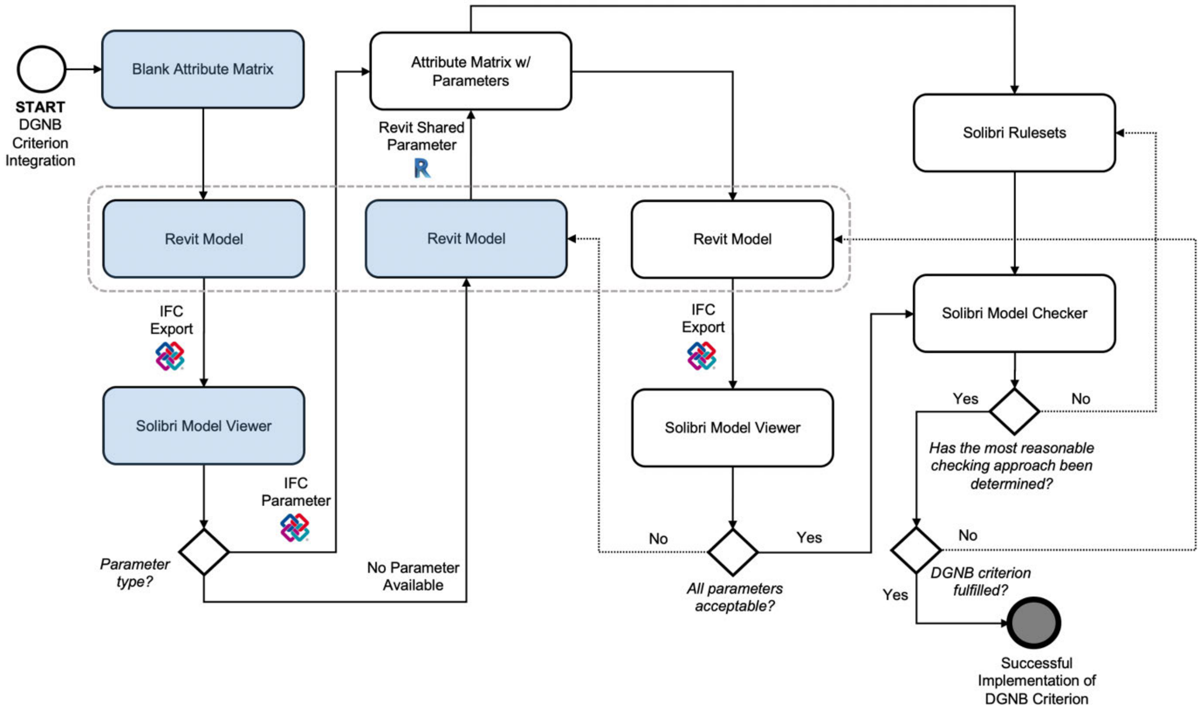


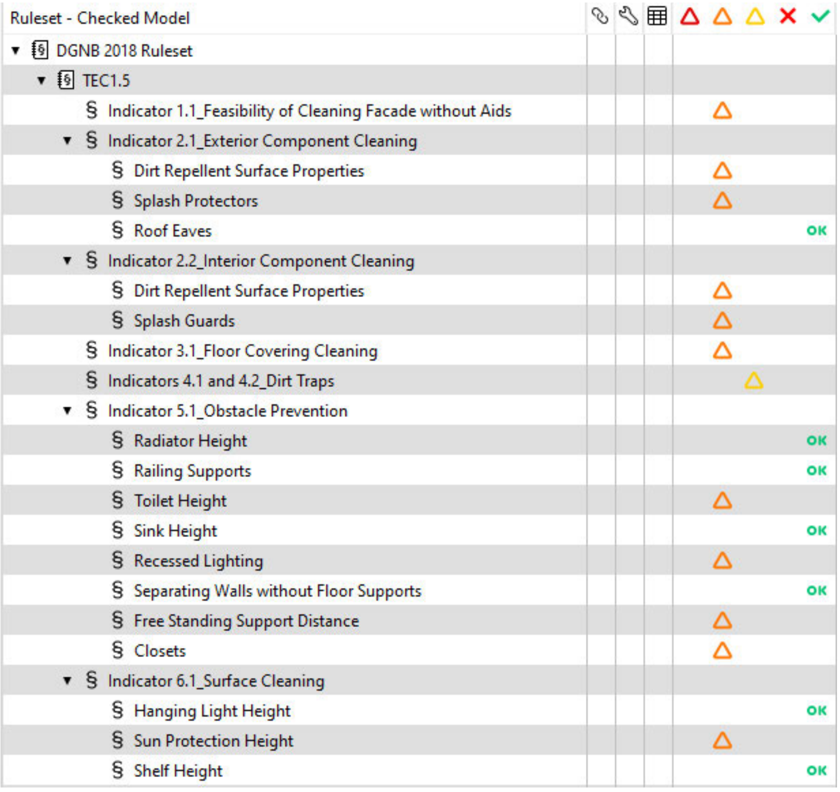
Figure 4.12: DGNB criterion integration process diagram

The items highlighted in blue are steps that only need to be completed once in the creation of the attribute matrices. This means that once an attribute matrix and the associated ruleset have been fully developed for a criterion, they can automatically be applied to any other project designed in Revit. The Solibri ruleset file that contains the rules for checking both TEC1.5 and SOC1.7 can be found in the digital Appendix I.

4.5.4 Model Validation and Optimization Results

The Solibri rulesets were created to both validate the integration of the parameters from the attribute matrices but more importantly to provide feedback about where and how a design can be optimized to meet more of the sustainability requirements set forth by the DGNB. As the intention of the model checking feedback was to improve the sustainability of the design in the early design stages and not carry out a final certification of the building, only the attributes applicable in these early stages, specifically attributes that are typically relevant at an LOD of 300 or under, were included.

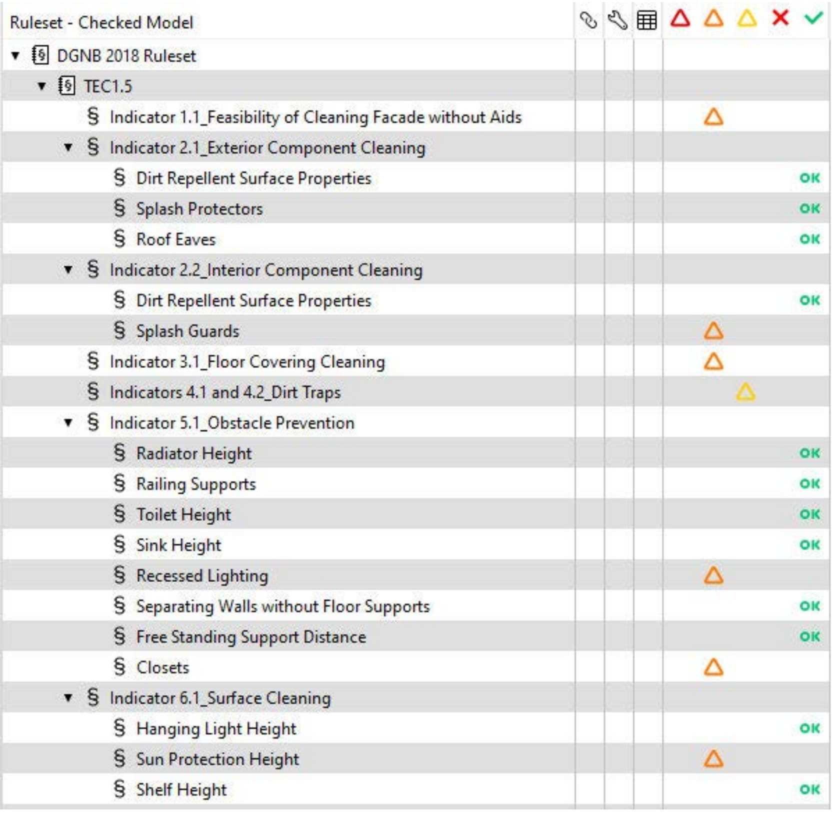
In the first check of criteria TEC1.5, there were still many areas that could be improved in terms of sustainability. For example, there were still several windows identified as not opening inwards or being more than the required 4 m off the ground, numerous surfaces without dirt-repellent properties, missing splash guards in wet areas, and building components that did not meet the required minimum or maximum heights for cleaning. There was a total of 12 issues that could be optimized in this first check (two separate elements under Indicator 1.1). In Figure 4.13, these optimization potentials are indicated by orange triangles.



Ruleset - Checked Model				△	△	△	✕	✓
▾ DGNB 2018 Ruleset								
▾ TEC1.5								
§ Indicator 1.1_Feasibility of Cleaning Facade without Aids					△			
▾ § Indicator 2.1_Exterior Component Cleaning								
§ Dirt Repellent Surface Properties					△			
§ Splash Protectors					△			
§ Roof Eaves								OK
▾ § Indicator 2.2_Interior Component Cleaning								
§ Dirt Repellent Surface Properties					△			
§ Splash Guards					△			
§ Indicator 3.1_Floor Covering Cleaning					△			
§ Indicators 4.1 and 4.2_Dirt Traps						△		
▾ § Indicator 5.1_Obstacle Prevention								
§ Radiator Height								OK
§ Railing Supports								OK
§ Toilet Height					△			
§ Sink Height								OK
§ Recessed Lighting					△			
§ Separating Walls without Floor Supports								OK
§ Free Standing Support Distance					△			
§ Closets					△			
▾ § Indicator 6.1_Surface Cleaning								
§ Hanging Light Height								OK
§ Sun Protection Height					△			
§ Shelf Height								OK

Figure 4.13: Initial Solibri results for criterion TEC1.5

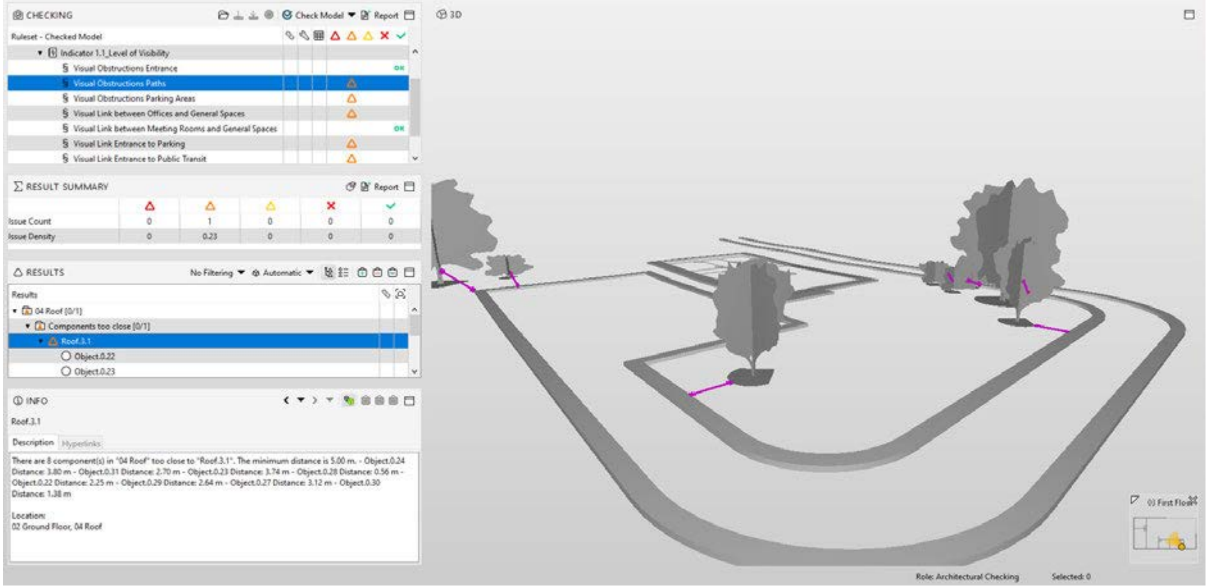
Based on the results of the first check, the window opening direction was added to the windows that were previously fixed, splash protectors and a dirt-repellent surface finish were added to all external walls that touched the ground, the toilet height was increased, dirt-repellent properties were added to bathroom separating walls, and columns were moved further away from surrounding components. Making these changes took approximately 20 minutes and fixed six of the previously discovered issues, for a percent improvement of 50% (Figure 4.14.).



Ruleset - Checked Model			▦	△	△	△	✕	✓
▼ DGNB 2018 Ruleset								
▼ TEC1.5								
§ Indicator 1.1_Feasibility of Cleaning Facade without Aids					△			
▼ § Indicator 2.1_Exterior Component Cleaning								
§ Dirt Repellent Surface Properties								OK
§ Splash Protectors								OK
§ Roof Eaves								OK
▼ § Indicator 2.2_Interior Component Cleaning								
§ Dirt Repellent Surface Properties								OK
§ Splash Guards					△			
§ Indicator 3.1_Floor Covering Cleaning					△			
§ Indicators 4.1 and 4.2_Dirt Traps						△		
▼ § Indicator 5.1_Obstacle Prevention								
§ Radiator Height								OK
§ Railing Supports								OK
§ Toilet Height								OK
§ Sink Height								OK
§ Recessed Lighting					△			
§ Separating Walls without Floor Supports								OK
§ Free Standing Support Distance								OK
§ Closets					△			
▼ § Indicator 6.1_Surface Cleaning								
§ Hanging Light Height								OK
§ Sun Protection Height					△			
§ Shelf Height								OK

Figure 4.14: Solibri results for criterion TEC1.5 after optimization

A similar, basic optimization of SOC1.7 based on the initial results of the model checker determined that within eight minutes, three of the five issues found in Solibri could be updated within the model. The optimizations included creating more space around the paths and parking areas to reduce visual obstructions (Figure 4.15), as well as adding an internal window to the office that did not yet have a visual connection to the general spaces within the building.



Ruleset - Checked Model
- Indicator 1.1_Level of Visibility
  - § Visual Obstructions Entrance OK
  - § Visual Obstructions Paths △
  - § Visual Obstructions Parking Areas △
  - § Visual Link between Offices and General Spaces △
  - § Visual Link between Meeting Rooms and General Spaces OK
  - § Visual Link Entrance to Parking △
  - § Visual Link Entrance to Public Transit △

	△	△	△	✕	✓
Issue Count	0	1	0	0	0
Issue Density	0	0.23	0	0	0

Results
- 04 Roof [0/1]
  - Components too close [0/1]
    - Roof.3.1
      - ○ Object.0.22
      - ○ Object.0.23

Roof.3.1

There are 8 component(s) in "04 Roof" too close to "Roof.3.1". The minimum distance is 5.00 m. - Object.0.24 Distance: 3.80 m - Object.0.31 Distance: 2.70 m - Object.0.23 Distance: 3.74 m - Object.0.28 Distance: 0.56 m - Object.0.22 Distance: 2.25 m - Object.0.29 Distance: 2.64 m - Object.0.27 Distance: 3.12 m - Object.0.30 Distance: 1.38 m

Location:
02 Ground Floor, 04 Roof

Figure 4.15: Solibri result for criterion SOC1.7 path obstructions

Overall, it was found that for TEC1.5 all 26 attributes from the matrices, that were applicable to be added to the model, were able to be checked using the Solibri rulesets. For SOC1.7, all attributes were also able to be checked with the developed rulesets. However, it did not seem reasonable to claim that the four attributes that were actually based on simulation results could be adequately checked just by using Solibri to verify that the components necessary for the simulation had been provided. Therefore, it was more sensible to conclude that for SOC1.7, only 73%, or 11 of the total 15 attributes integrated into the model, could be properly checked using the Solibri rulesets.

4.5.5 Model Validation and Optimization Discussion

Although TEC1.5 exceed and SOC1.7 came close to the prediction set forth in hypothesis 4.1, that at least 80% of the optimization relevant information could be verified using the model checking rulesets, these results do not actually prove that the rulesets are as successful as it might seem. Table 4-5 was created to provide an overview of the limitations of the developed Solibri rulesets, as these limitations are crucial in discussing the overall success and relevance of using Solibri as a DGNB sustainability optimization tool.

Table 4-5: Solibri ruleset limitations

TEC1.5 Ease of Cleaning Building Components		
Indicator	**Intended Check**	**Actual Check Possible in Solibri**
1.1 Feasibility of Cleaning Façade without Aids	Are the tops of external windows less than 4 m from the floor and do external windows open inwards?	All external windows and curtain walls could be checked as intended.
2.1 Exterior Component Cleaning	Do all ground level or below surfaces have dirt-repellent properties? Do the exterior walls dirt and water splash protectors around the bottom? Does the roof have eaves?	It was possible to check the material properties and splash protectors as intended, however the roof eaves could only be checked with a boolean variable as the eaves themselves could not be separately defined in Revit nor could the overhang itself be checked using Solibri.
2.2 Interior Component Cleaning	Do interior walls have dirt-repellent surface properties and are there splash guards in wet areas such as WCs and kitchens?	All walls were analyzed for splash guards, not just those in wet areas, so the fulfillment of the criteria could not be determined based on the results provided by Solibri.
3.1 Floor Covering Cleaning	Are floors located in circulation areas covered in patterned, mottled or structured carpet and have carpet tiles been used? Does the same apply for floorings in other parts of the building?	Solibri was only able to check all floorings and could not separate the covering based on location/space in the building.
4.1 and 4.2 Dirt Traps	Have dirt traps been provided by all entrances and are these at least 2.4 if not 4.0 m long?	The dirt traps were able to be checked as intended, however the checking could have been improved if the program could have identified the location of the mats itself, without the addition of the boolean variable assigned to the doors that specified if a mat had been placed in front of it or not.
5.1 Obstacle Prevention	Are radiators at least 15 cm off the floor? Have railing supports been installed laterally? Are the toilets and sinks at least 15 cm off the floor? Are the light fixtures recessed? Have separating walls been designed without floor supports? Are free standing structures at least 20 cm from other elements? Have built-in closets been included in the design?	All of these elements besides the lateral railing supports could be checked as intended. It was not possible to determine any information about the railing supports within Solibri, so this information was included as a boolean variable.

6.1 Surface Cleaning	Are hanging lights, fixed sun protection measures and shelves/ledges at most 4 m off the ground?	All elements could be checked as intended.
SOC1.7 Safety and Security		
Indicator	**Intended Check**	**Actual Check Possible in Solibri**
1.1 Level of Visibility	Are the entrances visual obstruction free for at least 10 m? Are path and parking areas visual obstruction free for at least 5 m? Are there visual links between offices, conference rooms and general areas? Is there a visual link between the entrances and the parking area and/or public transit stops?	All visual obstructions and most visual links could be checked as intended, however the visual links between entrances and outdoor spaces could not be verified directly in Solibri as spaces/objects that did not face each other could not be analyzed, therefore a boolean parameter needed to be added in Revit that the model checker could access instead.
1.2 Level of Lighting	Do all thoroughfares have a minimum lux level of 5 lux? Do carparks have a minimum level of 10 lux? Do paths to bike parking have at least 15 lux? Do all publicly accessible outdoor areas have at least 10 lux?	It was only possible to check that lighting fixtures were provided in the outdoor areas, but the actual lux levels theses fixtures would provide could not be checked in Solibri.
1.3 Technical Safety Equipment	Have an emergency telephone, a CCTV system, a PA system and a voice alarm system been installed in the building?	These elements could be checked as intended.

In addition to the checking limitations mentioned in Table 4-5, there were also certain difficulties in creating the rulesets to function as they did. Developing rulesets that are prepared to handle all possibilities for how an element may be included can be a very time-consuming and, in some cases, a nearly impossible task. For example, including all materials that could be considered dirt-repellent or all types of floor coverings that could fall under patterned, structured or mottled would be an unrealistic task. Here the focus of the rulesets should rather be on reminding the designer that the materials selected are important and can actually make a difference in regard to the sustainability of the overall design. For the BIM Coordinator and modeler, it is important to remember that just because a specific material selected for the design might not be included in the pre-determined ruleset list, this doesn’t mean that material cannot be used. The rulesets are designed to function as a tool that brings attention to certain areas and not as the final determination of what is and isn’t sustainable.

Furthermore, creating the initial rulesets for all applicable DGNB criteria would require a significant time investment. For the two criteria rulesets developed in this thesis, it took about 3-4 days to create the basic structure with all indicators and parameters in Solibri. The majority of this time was dedicated to the ruleset for TEC1.5, which was used to gain an understanding of how the ruleset manager worked and what rule templates had which functionalities. Once the first full ruleset had been created, the second one took a fraction of the time, as Solibri is very user-friendly in terms of copying existing rules and editing and updating components with a minimal number of clicks. The library of pre-existing rules in Solibri also took some time to understand but once the relevant rules had been filtered out, this also helped speed up the new ruleset creation process significantly and create more effective rules overall. After the initial ruleset structure and components had been added, it took several more days of trial and error, iterative adjustments and checking of the model before the rules were working as intended for as many indicators as possible.

Aside from the limitations and the initial time investment required to create and adjust the rulesets, they bring many benefits in the early design stages. Using the rulesets as a tool for sustainability optimization allows a designer to quickly see in which areas there is still room for improvement and small updates can be checked iteratively and quickly until the desired outcome is achieved. By defining acceptable ranges in Solibri, the degree of fulfillment can be better assessed and there is greater potential for optimization and letting the designer chose in which areas they wish to invest the most time and energy. Using the rulesets as a preliminary check in the early design stages will decrease the number of updates and changes required later on, in the actual certification process, and can be used as a documentation tool for the DGNB auditor in the Pre-Certification process.

In general, it can be expected that as seen with TEC1.5, checking other quantitative criteria will also prove to be successful. As discussed in Section 4.3.4, the quantitative criteria are predominantly evaluated based on material/component properties and compliance of these properties with specified values. Solibri is very good at accessing information stored in the model components and comparing it to defined values using several simple and straightforward rules. The space and location verifications that can be carried out with Solibri proved useful in checking the qualitative criterion SOC1.7. As the other qualitative criterion were also determined to be based largely on spatial/layout aspects, the majority will likely be verifiable using Solibri. That being said, accessing specific information based on location within the model, such as windows associated with certain rooms for example, was rather difficult. It is also not possible to verify the actual quality of a space in Solibri, but rather to check that certain components that have been previously determined to likely enhance the space have been included in the model. In this regard, writing the qualitative rules is far more complex than the quantitative ones, as they require an *a priori* determination of what elements, spaces and connections will have what subjective effect on the design and ultimately the user.

Overall, the rulesets created in Solibri showed that the model checker is especially useful in checking information that has intrinsically been stored in the model but also in verifying externally defined parameters. This makes it a great tool to use in evaluating both the qualitative and quantitative sustainability of a design. The nearly instant results provided by the software enable an iterative optimization process, that, if holistically developed, can be used on a variety of projects to enhance their overall sustainability.

5 Summary and Outlook

5.1 Summary

The goal of this thesis was to create a holistic sustainability optimization tool to be used in the early design stages, on the basis of the 2018 version of the DGNB criteria. Three supporting hypotheses were established to evaluate the integration potential of the criteria into the BIM workflow. It was postulated that for quantitative criteria, 80% of the BIM object information could be stored within the IFC data structure. For qualitative criteria, it was hypothesized that a successful integration would only be possible for 40% of the required information. The final hypothesis stated that model checking would be able to verify that overall 80% of the optimization relevant information had been stored within the model.

To achieve this goal and evaluate the hypotheses, it was necessary to carry out an in-depth analysis of the criteria to determine which could be considered in the early design stages and furthermore which would benefit from an integration into a digital model-based workflow. The analysis revealed that overall 17 criteria met these two requirements and these criteria could be split into those that were predominantly quantitative and those of qualitative nature. Based on this differentiation, one representative example criterion was selected from each, to be integrated into a building information model, and used to develop rulesets that formed the sustainability optimization tool.

Numerous BIM-sustainability integration approaches were evaluated. It was determined that the approach developed in the ONIB report had the greatest potential for adequately documenting and incorporating the sustainability requirements set forth by the DGNB. On the basis of this approach, Revit was used to create a building information model into which the sustainability information that had been prepared in the form of attribute matrices could be integrated, using both IFC and custom parameters. Solibri was then used to verify that the required parameters had been properly stored in the model and a custom ruleset was developed. The rules offered feedback regarding the information required to fulfill the selected DGNB criteria and enabled an iterative optimization process through straightforward and instant results.

It was found that, despite some limitations, the rules were able to successfully verify and provide feedback for both qualitative and quantitative criteria. The first hypothesis was confirmed, with approximately 84% of the required quantitative information successfully being added to the model. The second hypothesis was rejected, as it was found that significantly more qualitative information, nearly 95%, could be stored in the model than had been predicted. For the qualitative criteria the model layout, spaces and spatial relationships were important for determining if the DGNB requirements had been fulfilled, while the quantitative criteria depended more on the material and component-based information stored in the model. The third hypothesis was also confirmed, as over 80% of the optimization relevant information included in the model could be checked for both the quantitative and qualitative criteria. In summary, the ruleset created for the representative example criteria offers a good starting point for the future development of rulesets that could include and provide optimization feedback for all relevant DGNB criteria.

5.2 Outlook

5.2.1 Contributions

This thesis provides several new insights regarding research of BIM/Sustainability integration. The holistic analysis of all DGNB criteria found that over 80% of the criteria in the current system are applicable to be considered in the early stages. The analysis also revealed that over 75% of the criteria would benefit of an integration into a digital model-based workflow. This confirms the importance of including sustainability aspects as an integral part of the BIM methodology, especially in the early design stages when it is still easy and inexpensive to make design changes. Findings of this thesis also suggest that quantitative criteria can generally be included in the building information model through component attributes assigned to model objects as parameters. These can be checked against pre-defined values in the DGNB or the respective national rules and regulations using a rule-based model-checking software. Qualitative criteria can more easily be included in a digital workflow on the model-checking level than as component attributes, as the model checker allows for a greater freedom in defining subjective aspects. However, the question of how best to include subjective facets of sustainability is still open to discussion. Overall, this thesis represents a solid foundation for the future development of rule-based sustainability optimization on the basis of the DGNB building certification system.

5.2.2 Limitations and Recommendations for Further Developments

The results of this thesis have shown that model checking rulesets can be a valuable tool in verifying certain sustainability criteria and showing in which aspects a model can be optimized in regard to sustainability. However, there are several limitations to the methodology presented here. First and foremost, the integration of qualitative criteria is subjective, meaning the way in which these criteria are implemented and evaluated varies from designer to designer and auditor to auditor. Therefore, the qualitative, more subjectively defined criteria, require certification experts to assist in defining a type of subjective sustainability baseline for the qualitative rules to check. This poses the question if these types of generalizations are a beneficial approach in regard to sustainability or if they are actually more likely to limit innovation than support it. To answer this question, it would be necessary to create rulesets for all criteria and investigate how the range of implemented sustainability solutions differs between projects that use the rulesets to optimize the design and those that are left to their own devices on how and where to integrate sustainability. In the future, the model-checking ruleset results could also become linked with concrete improvement suggestions, instead of just pointing out issues or shortcomings. This could include suggestions about which materials to use, for example of the basis of the ÖKOBAUDAT or the BNB, or presenting possible changes to the room layout to benefit user interaction and communication or for sound insulation purposes. Investigating a connection between model checking and simulation results could also be very interesting for future research, as simulations generally provide very beneficial, concrete and actionable feedback about where a design can be optimized.

Further developing the model-checking rulesets past the optimization approach investigated in this thesis, to using them for actual BIM-based sustainability certifications, presents both opportunities and risks for the stakeholders in the certification process. On the one hand, it could streamline the documentation requirements and increase the efficiency of the overall certification process. However, this would require that the certification bodies accept 3rd party verification results, such as the output reports from Solibri, and ideally an automated or real-time link would need to be created between these reports and the certification systems internal verification platform. On the other hand, if the process becomes too automated, it could be seen as a threat to the existence of the certifying bodies altogether and the human element could become lost, that many find necessary for a meaningful evaluation.

Work on the implementation of rule-based sustainability assessments generally raises the question of how best to represent currently existing certification systems. Due to the existence of several certification systems and their different orientations in number, weighting and requirements of criteria, a standardization of sustainability requirements for building information models is imperative, but ultimately must be carried out directly by the certification bodies themselves. In this regard, standardized model content requirements for the attribute matrices should be created in collaboration between the certifying bodies and buildingSMART to encourage an openBIM approach. Ideally, the created attribute matrices could become a part of the publicly accessible certification system criteria catalogs, to be used as a general foundation for including sustainability aspects in building information models.

In summary, attribute matrices and rulesets should be developed for all criteria to better understand the full benefit of a holistic sustainability/BIM integration. To allow for a full integration of as many criteria as possible, and further extend the scope investigated in this thesis, FM and GIS models should also be included in the integration approach. Further research is necessary to determine how best to include qualitative criteria and simulation results in the overall sustainability optimization suggestions and to see how important the human element will be in carrying out sustainable building certifications in the future.

References

AEC (UK). (2012). AEC (UK) BIM Protocol Implementing UK BIM Standards for the Architectural, Engineering and Construction industry.

André Borrmann, Klaus Eschenbruch, Kerstin Hausknecht, Carsten Klempin, Thomas Liebich, Maciej Trzeciak, Bernd Wagner, Jan Tulke, Simon Vilgertshofer, Genia Schäferhoff, Ingo Schmidt, Daniel Hecker, Markus Hochmuth, Michael Kluge, Markus König, Christian Forster, & Robert Elixmann. (2019). Teil 6: Steckbriefe der wichtigsten BIM-Anwendungsfälle. Bundesministerium für Verkehr und digitale Infrastruktur.

ASHRAE (Ed.). (2006). ASHRAE greenguide: The design, construction, and operation of sustainable buildings (2nd ed). American Society of Heating, Refrigerating, and Air-conditioning Engineers.

Autodesk. (2018). Revit IFC Manual—Detailed instructions for handling IFC files.

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. Leadership and Management in Engineering, 11(3), 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2012). Application of life cycle assessment to early stage building design for reduced embodied environmental impacts. Building and Environment, 60, 81–92.

Bew, M., & Richards, M. (2011). A report for the Government Construction Client Group: Building Information Modelling (BIM) Working Party Strategy Paper.

BIMForum. (2018). LOD Specification 2018 Part I. 253.

BNP Paribas. (2018). Green Buildings: Nachhaltiges Bauen auf dem Vormarsch | BNP Paribas Real Estate. https://www.realestate.bnpparibas.de/blog/trends/green-buildings-nachhaltiges-bauen-auf-dem-vormarsch, date accessed: 05.07.2020

Borrmann, A. (2019). BIM VL 6 2019 BIM Project Execution [Lecture].

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). Building Information Modeling: Technology Foundations and Industry Practice (1st edition). Springer Berlin Heidelberg.

Bragança, L., Vieira, S. M., & Andrade, J. B. (2014). Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs. The Scientific World Journal, 2014, 1–8. https://doi.org/10.1155/2014/365364

BRE. (2016). BREEAM International New Construction 2016: Technical Manual.

BREEAM. (2020). How BREEAM Certification Works. BREEAM. https://www.breeam.com/discover/how-breeam-certification-works/, date accessed: 11.06.2020

Brooks-Church, G. (2012, June 12). Advantages and Disadvantages of Green Building Certifications. Gennaro Brooks-Church. https://brookschurch.com/advantages-disadvantages-green/

Brunsgaard, C., & Larsen, T. S. (2019). Perspectives on sustainability certification and design process – From evaluation tool to design tool. Indoor and Built Environment, 28(7), 869–872. https://doi.org/10.1177/1420326X19852782

buildingSMART. (2020). Information Delivery Manual (IDM). BuildingSMART Technical. https://technical.buildingsmart.org/standards/information-delivery-manual/, date accessed: 19.06.2020

Bynum, P., Issa, R. R. A., & Olbina, S. (2013). Building Information Modeling in Support of Sustainable Design and Construction. Journal of Construction Engineering and Management, 139(1), 24–34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560

Calquin, D. A. L. (2017). Automated Building Data Exchange between BIM and BPS Supporting Building Environmental Assessment Methods (BEAM). Building Simulation Conference Proceedings. 15th IBPSA Conference: Building Simulation 2017, San Francisco, CA.

DGNB. (2009). DGNB auf einen Blick. https://www.dgnb.de/de/aktuell/pressemitteilungen/2009/dgnb-auf-einen-blick, date accessed: 21.10.2020

DGNB. (2018a). DGNB System Criteria Set New Construction Building Version 2018. DGNB System.

DGNB. (2018b, July 19). DGNB & Co. compared – Part 1: Basic differences. DGNB Blog English. https://blog.dgnb.de/en/dgnb-co-part-1/, date accessed: 17.06.2020

DGNB. (2020a). DGNB System—Certification process. https://www.dgnb-system.de/en/certification/certification-process/index.php, date accessed: 15.05.2020

DGNB. (2020b). The DGNB System | DGNB System. https://www.dgnb-system.de/en/system/index.php, date accessed: 06.11.2020

Druhmann, C. K., & Ashworth, S. (2016). Rating Systems in Conjunction with BIM Deliver Outstanding Possibilities for Sustainable Construction. Journal of Civil Engineering and Architecture Reseach, 3(10), 1711–1717.

Dupuis, M., April, A., Lesage, P., & Forgues, D. (2017). Method to enable LCA analysis through each level of development of a BIM model. Creative Construction Conference 2017.

Eastman, C. M., Teicholz, P., Sacks, R., & Liston, K. (Eds.). (2008). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors. Wiley.

Ebert, T., Eßig, N., & Hauser, G. (2011). Green building certification systems: Assessing sustainability; international system comparison; economic impact of certifications. Institut für Internationale Architektur-Dokumentation.

Ernst, T., & Essig, B. (2016). Anwendung von BIM – Building Information Modeling für Zertifizierung von Gebäuden. Wissen, 3.

Essig, N., Eberl, S., & Beck, T. (2011). OPEN HOUSE – a European methodology for assessing the sustainability of buildings. 1st World Sustainability Forum.

Foliente, G., Luetzkendorf, T., Newton, P., & Paevere, P. (Eds.). (2008). SB08 book of abstracts: Connected viable liveable. ASN Events.

Grani, H. K. (2016, February 26). BIM objects—In the asset lifecycle. Areo Blog - Lifecycle BIM and Smart FM. https://blog.areo.io/bim-objects/, date accessed: 11.11.2020

GXN, & Statens Byggeforskningsinstitut. (2018). Guide to Sustainable Building Certifications. SBI : GXN.

Hjelseth, E. (2015a). Foundations for BIM-based model checking systems: Transforming regulations into computable rules in BIM-based model checking systems [PhD Thesis]. Norwegian University of Life Sciences.

Hjelseth, E. (2015b). BIM-based Model Checking (BMC). In R. R. A. Issa & S. Olbina (Eds.), Building Information Modeling: Applications and Practices. American Society of Civil Engineers. https://doi.org/10.1061/9780784413982

Hjelseth, E. (2016). Classification of BIM-based model checking concepts. ITcon, 21(Special), 354–369.

IEA. (2020). Buildings – Topics. IEA. https://www.iea.org/topics/buildings, date accessed: 17.09.2020

IISD. (2020). Sustainable Development. International Institute for Sustainable Development. https://www.iisd.org/about-iisd/sustainable-development, date accessed: 17.09.2020

Kats, G., Alevantis, L., Berman, A., Mills, E., & Perlman, J. (2003). The Costs and Financial Benefits of Green Buildings. Capital E.

Kreiner, H., Passer, A., & Wallbaum, H. (2015). A new systemic approach to improve the sustainability performance of office buildings in the early design stage. Energy and Buildings, 109, 385–396. https://doi.org/10.1016/j.enbuild.2015.09.040

Lanisa, A. O. (2018). Sustainable Green Building Certifications Supported by Building Information Modelling [Master's Thesis]. Metropolia, HTW Berlin.

LEED. (2019). LEED v4 for Building Design and Construction. U.S. Green Building Council (USGBC).

Liebich, T., Schweer, C.-S., & Wernik, S. (2011). Die Auswirkungen von Building Information Modeling (BIM) auf die Leistungsbilder und Vergütungsstruktur für Architekten und Ingenieure sowie auf die Vertragsgestaltung (Forschungsvorhaben | Zukunft Bau | BIM-HOAI) [End Report]. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumentwicklung (BBR).

Markelj, J., Kuzman, M. K., & Zbasnik-Senegacnik, M. (2013). A Review of Building Sustainability Assessement Methods. AR: Architecture, Research, XIV, 22-31.

ONIB. (2019). Optimierung der Nachhaltigkeit von Bauwerken durch die Integration von Nachhaltig- keitsanforderungen in die digitale Methode Building Information Modeling (ONIB) (End Report SWD-10.08.18.7-17.29; p. 84). Leibniz Universität Hannover.

OpenLearn. (2020). Systems thinking: Understanding sustainability. OpenLearn. https://www.open.edu/openlearn/science-maths-technology/computing-and-ict/systems-computer/systems-thinking-understanding-sustainability/content-section-0, date accessed: 22.09.2020

Panagiotidou, N. (2018, July 24). The difference between BIM and Revit. Breakwithanarchitect. https://www.breakwithanarchitect.com/post/the-difference-between-bim-and-revit, date accessed: 16.11.2020

Passer, A., Wall, J., Kreiner, H., Maydl, P., & Höfler, K. (2014). Sustainable buildings, construction products and technologies: Linking research and construction practice. The International Journal of Life Cycle Assessment, 20(1), 1–8. https://doi.org/10.1007/s11367-014-0820-4

Petrova, E. A., Romanska, I., Stamenov, M., Svidt, K., & Jensen, R. L. (2017). Development of an Information Delivery Manual for Early Stage BIM-based Energy Performance Assessment and Code Compliance as a Part of DGNB Pre-Certification. Building Simulation Conference Proceedings. 15th IBPSA Conference: Building Simulation 2017, San Francisco, CA.

Repo, 3D. (2019, March 12). What Are BIM Dimensions? 3D Repo BIM Online. https://3drepo.com/what-are-bim-dimensions/, date accessed: 22.06.2020

RICS, & IREBS. (2018). Grün Kommt! Europäische Nachhaltigkeitsstatistik 2017 [Study]. Royal Institution of Chartered Surveyors (RICS), IREBS Immobilienakademie.

Romano, S., & Riediger, N. (2019). BIM as a tool for Green Building Certifications: An evaluation of the energy category of LEED, BREEAM and DGNB. Journal of Physics: Conference Series, 1425, 012162. https://doi.org/10.1088/1742-6596/1425/1/012162

Schneider, L. (2018). Architecture Explained: The 6 Phases of Design. Schooley Caldwell. https://www.schooleycaldwell.com/architecture-explained-the-6-phases-of-design, date accessed: 07.07.2020

Schneider-Marin, P., & Abualdenien, J. (2019, September). A framework to facilitate an interdisciplinary design process using BIM. Forum Bauinformatik 2019, Berlin.

Solla, M., Ismail, L. H., & Yunus, R. (2016). Investigation on the Potential of Integrating BIM into Green Building Assessment Tools. ARPN Journal of Engineering and Applied Sciences, 11(4).

Soltani, S. (2016). The Contributions of Building Information Modelling to Sustainable Construction. World Journal of Engineering and Technology, 04(02), 193–199. https://doi.org/10.4236/wjet.2016.42018

Stella, A. (2018). Integrating DGNB into the BIM Process with special focus on LCA in the early stages of the design [Master's Thesis]. Technical University of Denmark.

Succar, B. (2015). UK BIM maturity model. http://changeagents.blogs.com/thinkspace/, date accessed: 13.07.2020

Tsikos, M., Negendahl, K., & Kauschen, J. S. (2017). LCA integration in BIM through the use of integrated dynamic models. 2046–2052.

UN Environment. (2017). Global Status Report 2017: UN Environment and International Energy Agency: Towards a zero-emission, efficient, and resilient buildings and construction sector.

UNEP-SBCI. (2012). Building Design and Construction: Forging Resource Efficiency and Sustainable Development.

VDI 2552. (2018). VDI 2552 Blatt 2: Building Information Modeling Begriffe. VEREIN DEUTSCHER INGENIEURE.

Vierra, S. (2019, August 5). Green Building Standards and Certification Systems. WBDG Whole Building Design Guide. https://www.wbdg.org/resources/green-building-standards-and-certification-systems/, date accessed: 11.06.2020

WBDG. (2020). Architectural Programming | WBDG - Whole Building Design Guide. https://www.wbdg.org/design-disciplines/architectural-programming

Wong, K., & Fan, Q. (2013). Building information modelling (BIM) for sustainable building design. Facilities, 31(3/4), 138–157. https://doi.org/10.1108/02632771311299412

WorldGBC. (2020). The benefits of green buildings. World Green Building Council. https://www.worldgbc.org/, date accessed: 05.07.2020

Appendices

Appendix A: Comparison of Certification Systems using Specific Indicators

Appendix B: BIM4INFRA2020 Use Cases

Appendix C: Early Design Stage Analysis

Appendix D: Digital Model-based Workflow Analysis

Appendix E: Overview of Criteria Analysis

Appendix F: Attribute Matrices

Appendix G: Revit Model Office Prototype *(Digital Appendix)*

Appendix H: Revit Custom Shared Parameter File *(Digital Appendix)*

Appendix I: Solibri Rulesets *(Digital Appendix)*

Appendix A: Comparison of Certification Systems using Specific Indicators

Comparison of Certification Systems using Specific Indicators (based on BRE, 2016; DGNB, 2018a; Ebert et al., 2011; LEED, 2019)

		BREEAM	LEED	DGNB
Ecological Aspects	Environmental loads/pollution	▪	▪	▪
	Materials/resources	▪	▪	▪
	Waste	▪	▪	▪
	Water	▪	▪	▪
Economic Aspects	Life cycle costs	▪	▪	▪
	Value stability			▪
Sociocultural Aspects	Safety and security	▪		▪
	Barrier-free accessibility	▪		▪
	Regional and social aspects	▪	▪	▪
Energy	CO$_2$ emissions	▪	▪	▪
	Energy efficiency	▪	▪	▪
	Renewable energy	▪	▪	▪
	Energy-efficient building envelope	▪	▪	▪
	Building services		▪	▪
	Energy monitoring	▪	▪	▪
	Submetering	▪	▪	
	Electrical building facilities	▪		▪
Health and Comfort	Thermal comfort	▪	▪	▪
	Indoor air quality	▪	▪	▪
	Acoustic comfort	▪	▪	▪
	Visual comfort	▪	▪	▪
	Occupants extent of control	▪	▪	▪
Functional Aspects	Site efficiency			▪
	Suitability for conversions			▪
Technical Aspects	Fire protection			▪
	Durability	▪		▪
	Suitability for upkeep and repair			▪
	Resistance to weather/ environmental damage	▪		▪
Design/ Innovation	Architecture			▪
	Building-related artwork			▪
	Innovation	▪	▪	▪
Process/ Management	Design process	▪	▪	▪
	Construction management	▪	▪	▪
	Commissioning	▪	▪	▪
	Operation	▪		▪
Site	Micro location	▪	▪	▪
	Traffic connections	▪	▪	▪
	Suitability for cyclists	▪	▪	▪
	Neighborhood	▪	▪	▪
	Building regulations	▪		▪
	Suitability for extensions			▪
	Land consumption	▪	▪	▪
	Protection of nature and landscape	▪	▪	▪
	Biodiversity	▪	▪	▪

Appendix B: BIM4INFRA2020 Use Cases

BIM4INFRA2020 Use Cases (based on André Borrmann et al., 2019)

Nr.	Use Cases	Applicable HOAI Phases									
		Planning			*Award of Execution*			*Execution*			*Use*
		1	2	3	4	5	6	7	8	9	
1	Existing Condition Modeling	■	■								
2	Design Option Investigations		■								
3	Technical Visualizations		■	■	■	■			■		
4	Dimensioning and Verification			■	■	■					
5	Coordination of the Specialist Disciplines		■	■		■					
6	Progress Monitoring					■					
7	Derivation of Design and Building Approval Plans		■	■	■						
8	Occupational Health and Safety Planning and Testing			■		■			■		
9	Planning Approval		■	■	■	■					
10	Cost Estimation		■	■							
11	Specifications, Tender, Award						■	■			
12	Construction Process Modeling (Scheduling)			■	■	■			■		
13	Logistics Planning					■			■		
14	Derivation of Technical Drawings					■					
15	Construction Progress Monitoring								■		
16	Change Tracking and Management								■		
17	Billing of Construction Work								■		
18	Issues and Defects Management								■	■	
19	Building Documentation								■		
20	Building Operation and Maintenance										■

				APPLICABLE LIFE CYCLE STAGE STAGE					
TOPIC	CRITERIA SHORT CODE	CRITERIA NAME	WEIGHTING (office)	PLANNING ASPECTS	DESIGN ASPECTS	CONSTRUCTION ASPECTS	POST CONSTRUCTION/FACILITY MANAGEMENT ASPECTS	TYPE OF REQUIRED DOCUMENTATION	APPLICABLE IN EARLY DESIGN STAGES?
Environmental Quality	**ENV1.1**	**Building Life Cycle Assessment**	9,50%	- integration of life cycle assessments into the planning process (1.1) - life cycle assessment optimization during the planning process (2.1) - weighted environmental impacts (3.1) - potential to achieve climate neutrality (4.1) - use of reused components or structural elements (5.1) - building generates energy for other users (5.2) - GWP factor of refrigerants in refrigeration systems (6.1)	N/A	N/A	N/A	- confirmation by auditor that LCA was carried out in planning process and an optimization was done - documentation of the calculation in accordance with the simplified calculation method, the complete calculation method, the use scenario calculation method, the end of life scenario calculation method - project reporting for creating the building life cycle assessment - verification of the results	the LCA is carried out predominantly in the early design stages and is used as an optimization tool
	ENV1.2	**Local Environmental Impact**	4,70%	- environmentally friendly building elements catalog based on criteria matrix (1.1) *only QL 1 and 2 can be analyzed in the planning and design stages	- building elements catalog at different quality levels based on criteria matrix (HOAI phases 3-9) for phase 3: - load bearing internal wood components together with outward-facing overhangs - external load-bearing wood components - wooden windows and internal and external non-load-bearing wood components - products with film preservation and goods treated with biocides - all aluminum and stainless steel components in the building envelope with a total area as a component of > 5 m2 (sun protection slats, roller shutter boxes and stainless steel railings are not taken into account) - coated metal components: facade elements, radiators and heating/cooling ceilings (hot-dip galvanizing is not considered as a coating here) - roof covering, guttering and downpipes - cooling systems/building technology/split devices	- building elements catalog based on criteria matrix (HOAI phases 5-9) - construction site log for material inspections	- building elements catalog based on criteria matrix (HOAI phases 5-9) - target/achieved comparison	- complete declaration and verification of relevant components/materials in points or lines using the criteria matrix -building elements catalog that includes environmental qualities in the obligatory quality level - for QL 1 and 2: construction product, manufacturer, area information if applied across surfaces), for QL 3 and 4: description of individual layers	Only partially analyzed/ limited to what is applicable in the early design stages (up to HOAI 3)
	ENV1.3	**Sustainable Resource Extraction**	2,40%	*materials to be used should be discussed early on	*product documentation requirements should be communicated with the contractors and manufacturers	N/A	- products permanently installed meet the requirements (1.1) - certified sustainable resource extraction (1.2, 1.3) - use of secondary raw materials with self-declaration (2.1) with certification (2.2)	- documentation by the manufacturer/processor - assessment of risk with the necessary excerpts - material specifications of what was installed - product certification proof	DGNB documentation requires the construction process to be complete

	ENV2.2	**Potable Water Demand and Waste Water Volume**	2,40%	N/A	- determine the "water use value" for estimating how much water will be used in the building (not including water needed during construction) (1.1)*based on established assumptions regarding technologies and user behavior - rainwater retention and water devices are planned (2.1) - water system is integrated into the district infrastructure (3.1)	N/A	- photo documentation of implemented measures	- calculation of water use value (WUV) - potable water demand and waste water volume by users - waste water due to rainwater diverted into drainage system - rainwater used for watering and flushing toilets - documentation regarding water retention and watering (plans or photos) - documentation of rainwater and waste water disposal system in building and district (including photos of implemented measures)	The majority of these calculations can be carried out in the planning and design development stages, some documentation after construction is required for full points
	ENV2.3	**Land Use**	2,40%	N/A	- outer development area (new development in a newly allocated area) (1.1.1) - inner development area (new development in a previously allocated area, redensification) (1.1.2) - brownfield area (1.1.3) - soil sealing factors are considered by percentage (2.1.1) - compensatory measures (rainwater infiltration, green roofs/walls, landscaping) (2.1.2)	N/A	N/A	- excerpts from land registry - documentation of previous contamination in the form of excerpts from a site or contamination survey with mapping of contaminants, professional assessment of the contaminated area - calculation of soil sealing factor - site plan with land and land covers - documentation of compensatory measures	*only relates to the building once it has been completed but the only changes can be made in the planning and design stages
	ENV2.4	**Biodiversity at the Site**	1,20%	- biotope area quality (calculated using DGNB excel tool) (1.1)	- specific measures to support existing species and introduce new species to the outdoor area (2.1) - specific measures to support existing species and introduce new species on the building itself (3.1) - invasive species are not included in the design (4.1) - migration paths are investigated and measures are planned to maintain them (5.1)	N/A	- outdoor areas are tended to for a further, limited period of time (1-2 years) (6.1) - outdoor areas are well maintained as part of the maintenance provisions (6.2) - a long term biodiversity strategy is developed and implemented for the building and its surrounding areas (7.1) - as built/success documentation	- brief explanation and photos of implemented measures - site plan, urban design concept and aerial photos - excel tool results - "animal aided design" should be shown to be implemented in the planning process from the start - presentation of planned and/or implemented measures - evidence of successful integration - statement from an expert regarding invasive species - excerpt from development and upkeep agreement	all plans and concepts can be developed, just the documentation of implemented measures will not be included
	ECO1.1	**Life Cycle Cost**	10,00%	- creation of an LCC model (including a variant comparison), integration of calculations of the life cycle assessment costs into the planning process (1.1)	- Life cycle costs are determined at regular intervals during the planning process and costs are optimized (work stages 2 and 3) (2.1)	- Life cycle costs are determined at regular intervals during the planning process and costs are optimized (work stages 4+) (2.1) - building related follow-up costs are integrated in later phases	- building related life cycle costs must be determined (3.1)	- evidence that a life cycle cost model was used in planning (at the latest in work stage 3) and that variant comparisons were carried out and that all building-related follow-up costs were considered - proof of cost optimization based on alternatives - table showing production and operation costs via cost calculation according to DIN 276-1 and DIN 18960 - final energy and water demands for the building - justification of category 1,2, or 3	costs and alternative comparisons can be carried out in the planning phase

Economic Quality	**ECO2.1**	**Flexibility and Adaptability**	7,50%	N/A	- space efficiency factor (≤ 0.48 - ≥0.75 for offices) (1.1) - ceiling height (≥3.0 m for offices) (2.1) - building depth (based on case) (3.1) - vertical access (≤1200 m2 to ≤400 m2 for offices) (4.1) - floor layout (sanitary and shaft connections for units ≤400 m2) (5.1) - flexibility aspects of the structure (non-load bearing internal walls, partition wall installation without floor or ceiling interference, re-use of partition walls, structural engineering allows for future load increases) (6.1) - technical building services (modifications in case of building adaptation) (7.1)	N/A	- photo documentation of as built components	- calculations of required values and factors - plans and floor layouts, including possible future alternatives - detailed drawings of load-bearing and non-load-bearing components - proof of load calculations - photo documentation with explanations	all relevant aspects can be considered and implemented in the planning and design stages
	ECO2.2	**Commercial Viability**	5,00%	- relationship between planned area and existing office area is either low or high (in regards to value based on city) (3.1)	- entrance situation is readily identifiable and easy to find (1.1) - routing and sign posting are provided (1.2) - delivery zones and parking spaces are clearly designated (2.1) - drop off and pick up areas (2.2) - the required amount of parking spaces are provided (1 per 200 m2 or 50 m2) (2.3) - bicycle parking is provided in line with requirements (2.4) - public parking within 200 m of entrance is provided as required (1 or 500 m2 or 200 m2) (2.5)	- excerpts from building permit documents	- degree of utilization/occupancy rate (evidence of signed rental agreements) (4.1) - photo documentation of implemented measures	- excerpts from plans with photo documentation - excerpts from building permit documents - evidence of a market analysis (can also be done by a professional) - signed rental agreements and evidence of collaboration between users/tenants and other companies occupying the building	the planning of the required measures can be done, however much of the evidence and documentation parts will not be included
	SOC1.1	**Thermal Comfort**	4,10%	N/A	- operative temperature in accordance with DIN EN 15251 Category I, II, III (1.1) - drafts in accordance with Category B of DIN EN ISO 7730 (2.1 and 6.1) - radiant temperature asymmetry and floor temperature (meet given values) (3.1 and 7.1) - relative humidity of >25% for at least 95% of the time (4.1 and 8.1) - operative temperatures meet DIN 4108-2 (5.1) *all of the above for both heating and cooling period *simulations can be carried out for a sample of rooms and not the whole building	N/A	N/A	- basis and results of thermal building simulation - characteristics of air outlets (regarding drafts) and basis and results of flow simulations) - radiant temperature verification using design documentation, U-values, thermal simulations and heat flow calculations - humidity verified based on verification of the selected system	most relevant results can be obtained in the planning and design stages with the help of simulations, some system verification can only be carried out after construction or selection of final systems
	SOC1.2	**Indoor Air Quality**	5,10%	N/A	- evaluation and prediction of indoor air concentration of VOCs (1.1) - air exchange rates based DINs for mechanical or natural ventilation or zonal flow simulations (2.1)	N/A	- measurement of indoor air concentration of VOCs	- determination of VOC and semi-VOC levels - confirmation of rooms selected for measurement and time the time of measurement - share of rooms with which furnishings - assessment of air changes per person according to EN 15251 - documentation of air changes in accordance with workplace regulations - completion of zonal flow simulation	simulations and predictions based on planned materials can be carried out but obviously tests after occupation cannot be carried out

Sociocultural and Functional Quality	**SOC1.3**	**Acoustic Comfort**	2,00%	- creation of room acoustic concept, updated during the planning process (1.1)	- compliance with requirements for reverberation times, based on classes A, B or C and room/office sizes of less than or greater than 40 m2 (2.1 and 3.1) - compliance for rooms with special requirements (4.1) - compliance with frequency ranges (5.1) *evaluation based on DIN 18041:2016-03 or VDI 2569: 2016-02 or through a detailed acoustic simulation	N/A	- acoustic measurements of finished constructions	- room acoustics concept with detailed description of measures - basis and results of reverberation time calculations as well as measurements of reverberation times - documentation of compliance with DIN and VDI through calculations or measurements - basis and result of completed detailed acoustic simulation	detailed concept can be created and calculations can be carried out, however no measurements can be taken
	SOC1.4	**Visual Comfort**	3,10%	N/A	- determination of daylight factor (DF) and useable areas via simulation or DIN V 18599 (1.1) - annual relative motive exposure via simulation or DIN V 18599 (2.1) - available lines of sight to the outside determined via floor plans (3.1) - sun/glare protection system, classified according to DIN 14501 (4.1) - minimum requirements for artificial light according to DIN EN 12464-1 (5.1) - artificial light over fulfillment (5.2) - daylight color rendering index (6.1) - duration of exposure to daylight (7.1)	N/A	- data sheets for installed systems and photo documentation	- basis and results of completed simulations - documentation using floor plans and calculations - data sheets for installed systems and photo documentation - light calculations and later measurements - manufacturer specifications for glazing and protection systems used	simulations and calculations can be performed but later documentation is not included
	SOC1.5	**User Control**	2,00%	N/A	- ventilation control (1.1) - shade and glare protection control (2.1) - room temperature control (heating and cooling period) (3.1 and 4.1) - artificial light control (5.1)	N/A	- data sheets from manufacturers regarding all systems implemented for shading and glare protection, temperature controls and lighting controls	- excerpts from ventilation concept, outlining essential features and assumptions - documentation of allocation of windows to workstations - data sheets from manufacturers regarding all systems implemented for shading and glare protection, temperature controls and lighting controls	the concepts can be incorporated and evaluated but no final documentation or data sheets
	SOC1.6	**Quality of Indoor and Outdoor Spaces**	2,00%	N/A	- communication zones of primary use incorporated into the interior design (1.1) - planning of additional provisions and services (gym, sauna, library, etc.) (2.1) - incorporation of a navigation information (2.2) - provisions for families in the building (3.1) - consideration of the quality of interior access and circulation areas (4.1) - design concept for outdoor facilities (5.1) - incorporation of roof surfaces and the facade into the design (6.1 and 6.2) - adding of useful fixtures and equipment in the useable outdoor areas (7.1)	N/A	- photo documentation after construction	- excerpts from floor plans and sections, including furnishings where appropriate - photo documentation - interior design concept - open space plan - outdoor space and roof space design concepts - site plans, views and 3D visualizations	floor plans, sections and rendering can be used to evaluate this criteria in the early stages but photo documentation will not be possible
	SOC1.7	**Safety and Security**	1,00%	N/A	- consider level of visibility and level of lighting (1.1 and 1.2) - include necessary technical safety equipment and preventative safety measures in the design (1.3)	N/A	- photo documentation after construction	- detailed design plans showing visual relationships - written explanation of the plans - photo documentation - plan of paths, light concept for paths - documentation showing light intensity, location of parking spaces, and bike parking - list and evidence of technical safety installations present, location on plans and photo documentation	all safety plans can be considered in the early design stages but documentation in the as-built condition will come later

	SOC2.1	**Design for All**	3,10%	- desired quality level should be decided and expert help should be sought if uncertain	Level 1 - access routes to entrances and circulation areas - barrier-free infrastructure for all units - dedication circulation areas for disabled passenger car parking spaces - operating information in "more-sense principle" - at least one barrier-free toilet cubicle to be accessed from a public area (1.1) Level 2 + at least 10% barrier-free workspaces (2.1) Level 3 + at least 50% barrier-free workspaces and 25% accessible outdoor areas (3.1) Level 4 + at least 95% barrier-free workspaces and 75% accessible outdoor areas (4.1)	N/A	- photo documentation and proof of concept verification at random locations	- general description of barrier-free design including relevant plans, details, photo documentation and expert/architect confirmation - random proof of concept can be requested after construction	the barrier-free concept design can be verified including plans and descriptions but photo documentation and proof of concept verification cannot be provided in the early design stages
	TEC1.2	**Sound Insulation**	2,30%	*the appropriate sound insulation levels are determined in the planning phase to help later design the proper wall constructions	*wall constructions, doors and ceilings are designed to meet sound insulation requirements - airborne sound insulation requirements are considered in the design (1.1, 1.2, 1.3 and 1.4) - footfall sound insulation requirements are considered in the design (2.1) - outside noise levels are considered in the design (3.1) - technical installation noise levels are considered in the design (4.1)	** retrospective improvements to the sound insulation are not possible or only to a very limited extent so the greatest significance lies in the project development and planning phases*	- verification of the sound insulation values in the actual construction	- documentation that critical components meet the requirements - comparison of achieved values with DIN 4109 requirements - construction plan for the documented components - German Acoustical Society insulation certificate - mathematical sound insulation documentation in accordance with DIN 4109 - measurement-based test certificates	the compliance with the requirements is verified based on the planned components, compliance in completed building can be checked at random in critical locations
	TEC1.3	**Quality of the Building Envelope**	3,00%	N/A	- calculate heat transfer coefficients of different building components (1.1) - calculate thermal heat bridge correction factors (2.1) - determine the solar transmittance parameter using either the simplified method or a simulation (4.1)	N/A	- determine the air change rate based on interior building volume (3.1) - determine joint permeability of windows and doors (3.2)	- declarations by specialist planners regarding condensation water amounts and heat insulation for thermal heat bridges - list of heat transfer coefficients for specific building components - details about selection of thermal heat bridge correction factor - catalog of thermal heat bridges - documentation of airtightness measurement results - documentation of joint permeability (details from technical data sheets) - documentation of solar transmittance parameter S - dynamic thermal simulation	calculation of specific values and declarations by specialist planners are possible in the early design stages but measures can only be taken in the later stages

Technical Quality	**TEC1.4**	**Use and Integration of Building Technology**	2,30%	- planning for a passive building concept including at least five of the following: compactness, window area proportion, daylight use, solar output use, sun protection, storage mass and insulation standard, natural ventilation, passive heating and cooling (1.1)	- implementation of a passive building concept based on the listed aspects (1.2) - heating and cooling distribution and transfer system (2.1 and 2.2) - technical facilities are designed to be easily accessible for later retrofit and replacement (3.1) - shafts/routes/distribution are adequately accessible (3.2) - design for expandability of system integration (4.1), for integration in a higher level system (4.2) and for integration into surrounding systems/the district (4.3)	N/A	- photo documentation after construction - verification of systems using data sheets	- description of the energy concept specifically with details regarding the passive solutions - excerpts from heating and cooling transfer system design/planning documents - dimensions from plans and data sheets - documentation of accessibility via plans and photo documentation - contract excerpts for commissioned system integration works - excerpts from building technology concept - plausibility checks	- concepts and layouts can already be evaluated in the early design stages but final documentation won't come until later
	TEC1.5	**Ease of Cleaning Building Components**	1,50%	- possible and necessary measures for ensuring ease of cleaning are taken into account in the planning process (7.1) - a detailed cleaning concept is created (7.2)	- façade cleaning feasibility is considered in the design (1.1) - measures are designed to reduce the costs of cleaning both interior and exterior surfaces (2.1 and 2.2) - easy to clean flooring is selected (3.1) - dirt traps are designed at building entrances (using 3 or 5-step principle) (4.1) - obstructions are placed to reduce their impact on cleaning activities (5.1) - frequently used surfaces are designed in a way that is easy to access and clean (6.1)	N/A	- photo documentation after construction - verification of systems using data sheets	- formulated cleaning concept - photo documentation of window accessibility - list of exterior glass surfaces and other interior and exterior surfaces, including cost and cleaning effort - product data sheets for exterior glass surfaces - evaluation of floor coverings with regard to contamination tolerance (including specification/documentation of lifetime) - floor plans of dirt traps and unobstructed layouts - documentation and classification of surfaces - confirmation from owner regarding the submission of an ease of cleaning concept	the majority of the decisions for this criteria are made in the early design stages, only documentation comes at a later time
	TEC1.6	**Ease of Recovery and Recycling**	3,00%	- ease of recovery, conversion and recycling in the planning process to optimize resource efficiency (3.1)	- selection of easy-to-recycle construction materials (1.1) - easy-to-recover building structure (2.1) - ease of recovery, conversion and recycling in the detailed design process to optimize resource efficiency (3.2)	N/A	- manufacturer verification of materials and recycling/reuse capabilities	- list classifying all relevant building component groups with component layers - verification of material recovery (QL 0 and 1) - documentation regarding product/material take-back or product leasing - confirmation from building owner confirming SBC understanding - confirmation that building components can be removed using non-destructive methods - statement regarding the consideration of ease of recovery and recycling in the planning process and the detailed design process	statements regarding the consideration of reusable and recyclable materials in the planning and design process can be provided in the early design stages but further verification comes at a later time

	TEC1.7	**Immissions Control**	0,80%	N/A	- noise pollution reduction measures (compliance/exceeding technical requirements) (1.1) - light pollution reduction measures (lighting concept with optimization simulation) (2.1)	N/A	- proof of lighting with data sheets and photo documentation	- noise protection expert report - expert report regarding noise in dB level - declaration by expert indicating that the immission locations are outside of the exposure zone - documentation of measures against light pollution - proof of lighting system with data sheets and photo documentation - lighting concept - if applicable, simulation results with methodology	in the early design stages the lighting concept can be created and potential simulations can be carried out but all expert verifications will come at a later time
	TEC3.1	**Mobility Infrastructure**	2,30%	N/A	- bicycle infrastructure is provided in or around the building, including anti-theft measures, maintenance facilities, weather protection and lighting (1.1) - parking spaces for mobility sharing are available in the immediate vicinity of the building (2.1) - parking spaces are provided with charging stations or are pre-fitted for installing charging stations (3.1) - electric bike parking spaces are provided with charging stations (3.2) - charging stations are integrated into the building energy management system (3.3) - showers, changing and drying and storage facilities are provided in the building (4.1) - parking spaces are provided for mobility aids (4.1)	N/A	- verification of implemented measures with site plans and photo documentation	- documentation of parking facilities with sufficient quality and quantity based on regional building regulations (including the number of bicycle stands and their location via floor plans and photo documentation) - documentation of bicycle maintenance facilities via site plan and photo documentation - rental systems documentation via screen shot of the areas of operation of the provider with photo documentation and a site plan - documentation of cable routing and assessment of power requirements via site plan and photo documentation - documentation of the charging stations - performance documentation of integration into billing system with roaming capability - documentation of user comfort inside the building with sire plan and photo documentation	mobility aspects can be included in the early planning and design but all verification will come at a later time
	PRO1.1	**Comprehensive Project Brief**	1,60%	- a requirements description has been written (1.1) - small-scale requirements planning has been undertaken (1.1) - large-scale requirements planning to determine the building owner's requirements has been undertaken (1.1) - various measures have been implemented to inform the general public (2.1) - people in the immediate neighborhood have been informed and a contact person as been appointed (2.1) - specifications have been drawn up regarding the building's sustainability and responsibilities have been defined (3.1)	N/A	N/A	N/A	- requirements planning documents and other documents that reveal the scope of the requirements planning undertaken and time at which it was undertaken (experts from logs) - filled out Appendix 2 including methods employed - documentation of measures implemented to inform the public - photo documentation of construction site sign - concrete objectives for sustainability aspects and responsibilities	this criteria is focused entirely on the early design stages

Process Quality	**PRO1.4**	**Sustainability Aspects in Tender Phase**	1,60%	N/A	N/A	- selected sustainability aspects with regard to impact on health or the environment are included in the tender phase in the form of general preliminary remarks (1.1) - requirements with regard to the impact of construction materials on health and the environment are integrated into the tender phase in the form of general preliminary remarks (1.1) - environmental, health and technical requirements have been set out for each of the trades (1.1)	N/A	- excerpts from the tender specifications such as sample service item texts, technical preliminary remarks and special contractual terms that demonstrate that sustainability aspects have been integrated as required	🟥 according to the HOAI the tender phase comes after the early design stage as defined in this thesis
	PRO1.5	**Documentation for Sustainable Management**	1,10%	- conducting of planning with BIM (4.1)	N/A	N/A	- production and provision of servicing, inspection, operating and upkeep instructions (1.1) - updating of plans, documentation and calculations to reflect how the building has actually been built (including provision of these to the building owner) (2.1) - production and provision of a facility management manual (3.1) - provision of BIM model to facility manager and building owner (4.1)	- use, servicing and upkeep instructions - servicing agreements - servicing and maintenance schedules - documentation that plans, documents and calculations reflect the building as it has actually been built - manual produced for the facility manager - confirmation that the facility manager and the owner have received an up-to-date version of the BIM model	🟥 the majority of this criteria is only applicable post-construction so it will not be included in the early design stage analysis of this thesis
	PRO1.6	**Procedure for Urban and Design Planning**	1,60%	- different design variants have been explored (1.1) OR a planning competition has been carried out (1.2) - recommendations by an independent design committee (2.1 and 2.2) - (alternatively: award in the form of an architecture prize) (3.1)	N/A	N/A	N/A	- presentation of different design variants - excerpts and documentation from the planning competition that was held - documentation of the commissioning of the prize winner - meeting minutes from the design committee meeting - documentation of the architecture prize or other recognition with a list of experts/judges	🟩 this criteria is focused specifically on creating a more sustainable planning process overall
	PRO2.1	**Construction Site/Construction Process**	1,60%	N/A	N/A	- low noise construction site concept (1.1) - training for the parties implementing the construction work (1.2, 2.2, 3.2, 4.2) - low-dust construction site concept (2.1) - soil and groundwater protection on the construction site (3.1) - low-waste construction site concept (4.1)	- review of work implemented (1.3, 2.3, 3.4, 4.3)	- documentation of implemented measures - tender documentation - detailed concept documents - site inspection reports - list of machinery - documentation of training/instructions provided - Photo documentation of implemented measures - declarations by specialists	🟥 this criteria is only concerned with the construction stage and none of its indicators fall into the early design stages

	PRO2.2	**Quality Assurance of the Construction**	1,60%	N/A	N/A	N/A	- a quality control plan has been drawn up for the completed building (1.1) - implementation of quality control measures (2.1) - quality assurance for the construction products used (3.1) - mould prevention plan has been created and implemented (4.1)	- submittal of quality assurance plan - DGNB template submitted for each indicator of quality control measures - documentation that site management has been instructed on the product requirements - documentation that a tailored ventilation program has been implemented	this criteria is only focused on the post-construction phase and none of its indicators fall into the early design stages
	PRO2.3	**Systematic Commissioning**	1,60%	N/A	N/A	N/A	- creation of a monitoring concept (4.1) - creation of a commissioning concept for scheduling (2.1) - performance of a preliminary function test (3.1) - performance and documentation of a function test and training for the operator (4.1) - creation of a detailed final commissioning report (5.1) - creation and handover of an integral operating concept (6.1) - readjustment of the system following the initial operating phase (7.1)	- commissioning plan including measurable objectives - excerpts from commissioning reports - handover certificated for preliminary and final function tests - list of completed tests and associated reports with results - concept for transforming commissioning into continuous monitoring and optimization - contract excerpts	this criteria is relevant for handover of the completed building and not in the early design stages
	PRO2.4	**User Communication**	1,10%	N/A	N/A	N/A	- provision of a sustainability guide for the user (1.1) - implementation of an information system on the sustainability of the building (2.1) - provision of a technical user manual (3.1)	- confirmation of receipt of the sustainability guide by the user - confirmation by auditor that information system has been installed - confirmation of receipt of the technical user manual by the user	the main focus of this criteria and its indicators is on the post construction and building use phase and not on the early design stages
	PRO2.5	**FM-compliant Planning**	0,50%	- performance of an FM check (1.1) - detailed operating cost projection (2.1) - optimization of user/use-related energy consumption (3.1)	N/A	N/A	N/A	- confirmation that FM check has been carried out appropriately - confirmation that an operating cost projection has been carried out appropriately - confirmation that an energy savings concept has been created	while this criteria is verified at a later time, the fulfillment of the indicators is included in the early design stages

Site Quality	**SITE1.1**	**Local Environment**	1,10%	- earthquake hazard level (1.1) and compensation measures (1.2) - volcanic eruption hazard level (2.1) and compensation measures (2.2) - avalanche hazard level (3.1) and compensation measures (3.2) - storm hazard level (4.1) and compensation measures (4.2) - flood hazard level (5.1) and compensation measures (5.2) - heavy rain hazard level (6.1) and compensation measures (6.2) - hail hazard level (7.1) and compensation measures (7.2) - landslide/subsidence hazard level (8.1) and compensation measures (8.2) - storm surge/tsunami hazard level (9.1) and compensation measures (9.2) - hazard level for extreme climates in accordance with ESPON map (10.1) and compensation measures (10.2) - forest fire hazard level (11.1) and compensation measures (11.2)	N/A	N/A	N/A	- plausible declaration of intent that measures will be implemented - brief explanation, photos, scans of implemented measures and mapping in an overall plan - project design - localization of the project on a risk map - risk statement by a qualified expert	the local environment must be considered in the early design stages to verify the plausibility of the project and site
	SITE1.2	**Influence on the District**	1,10%	- site classification and evaluation (1.1) - influence of the building on the site or district (2.1) - potential synergy due to clustering (3.1) - boost due to use (4.1) - boost due to spatial and design elements (4.2)	N/A	N/A	N/A	- excerpts from text and drawings defining the buildings specs and a reasonable evaluation of the public perception - characterization of the building according to its impact on the surrounding area (using press, articles, plans, photos, etc.) - documentation and description of synergistic effects - description and explanation of unique regional features, attraction of people from around the country, new uses and attractions	the indicators must be included in the early design stages even if they are only evaluated after the building is complete

Site Quality	**SITE1.3**	**Transport Access**	1,10%	- access to trunk roads, motorways and main roads (1.1) - building related parking spaces are integrated into a higher-level parking concept (1.2) - public transportation stops are within 350m air-line (2.1) - access to nearest railway station is less than a certain amount of time (2.2) - public transit frequency (2.3) - building related access to passenger information and maps (2.4) - cycle paths are close and clearly defined (3.1) - there is regional and national bike access (3.2) - there are bike access roads on the property leading to the building (3.3) - pedestrian path network (4.1) - pedestrian crossings (4.2) - pedestrian signage (4.3) - barrier free access to public transit (5.1)	N/A	N/A	N/A	- documentation of stops on an overall plan - description and calculation of public transit frequency - overall site plan with relevant elements - documentation and proof of planned services - overall routing plans - documentation (via photos) of signage - rough journey calculations - timetables	the transport access must be considered in the planning during the early design stages
	SITE1.4	**Access to Amenities**	1,70%	- education, leisure activities, playgrounds and sports facilities in the district/surrounding area (1.1) - opportunity to use rooms within the building and outdoor facilities (1.2) - local supply, food and catering, other services and medical services within the district/surrounding area (2.1) - variety of uses within the building (3.1)	N/A	N/A	N/A	- plausible declaration of intent that infrastructure will be implemented - photos of implemented measures - urban design concept including use and open space concept - site plan with mapping of the maximum permitted distance for each use category - depending on property: excerpts from text and drawings defining rooms that are available for third parties - depending on property: excerpts from text and drawings defining range of uses within the building	the access to amenities must be considered in the planning during the early design stages

TOPIC	CRITERIA SHORT CODE	CRITERIA NAME	WEIGHTING (office)	QUANTITATIVE/ QUALITATIVE?	PLAN (DWG)/EXCEL/SIMULATION/ DOCUMENT/PHOTO/OTHER?	ATTRIBUTES AND OUTPUTS	ADDED VALUE FROM DIGITAL WORK FLOW	DIGITAL MODEL-BASED WORKFLOW?
	ENV1.1	**Building Life Cycle Assessment**	9,50%					
		1.1 Integration of life cycle assessments into the planning process		quantitative	excel, software	material lists, material masses	quicker comparison of different variants, easier optimizations	🟩 this criteria can be represented digitally in the form of excel sheets or material lists that can be linked with a model or other downstream software solution
		1.1.1 A life cycle assessment model is created for the project in an early planning phase						
		1.1.2 Life cycle assessment results are determined for the building at regular intervals during the planning process						
		1.1.3 Life cycle assessment results are determined for the operating phase of the building, going beyond the statutory scope of the energy calculation						
		2.1 Life cycle assessment optimization during the planning process						
		2.1.1 The effects of significant alternative decisions on the expected life cycle assessment results are determined for the building						
		2.1.2 The effects of significant decisions on the expected life cycle assessment results are determined for the building						
		3.1 Weighted environmental impacts						
		3.1.1 Building life cycle assessment results provided						
		3.1.2 Evaluation of the building life cycle assessment results with limit, reference and target values						
		4.1 potential to achieve climate neutrality						
		4.1.1 climate-neutral building-related energy demand						
		4.1.2 climate-neutral energy demand of users						
		4.1.3 climate-neutral construction						
		5.1 use of reused components or structural elements						
		5.2 building generates energy for other users						
		6.1 GWP factor of refrigerants in refrigeration systems						
	ENV1.2	**Local Environmental Impact**	4,70%					
		1.1 Fulfilment of all requirements in the criteria matrix given the different QL levels		quantitative	building component catalogs, manufacturer data sheets, EPDs	materials, components/areas	building catalogs can be generated using a digital building model	🟨 building catalogs can be produced digitally but a manual evaluation with the criteria matrix and data sheets is still required
		1.3 Additional points in quality level 1, 2 and 3 in terms of cooling without halogenated refrigerants		quantitative	manufacturer data sheets, documentation of used products	type of refrigerant	N/A	🟥 verifying the type of refrigerant does not require digital representation
	ENV1.3	**Sustainable Resource Extraction**	2,40%					
		1.1 Corporate responsibility for resource extraction (quality level 1.1)		qualitative	manufacturer documentation regarding extraction and processing, excerpts from risk management, results reports, corporate guidelines, significance level	material catalog that is linked with manufacturer documentation	material catalogs can be created digitally and linked with the manufacturer data sheets once they become available	🟨 material catalogs can be produced digitally but a manual evaluation of the material data from manufacturers may still be necessary
		1.2 Certified sustainable resource extraction of a part of the value chain (quality level 1.2)		quantitative	building component catalogs, manufacturer data sheets, delivery notes or invoices, proof of DGNB recognized certification	building component catalog	material catalogs can be created digitally and linked with the manufacturer data sheets once they become available	🟨 material catalogs can be produced digitally but a manual evaluation of the material data from manufacturers may still be necessary
		1.3 Certified sustainable resource extraction (quality level 1.3)		quantitative	building component catalogs, manufacturer data sheets, delivery notes or invoices, proof of DGNB recognized certification	building component catalog	material catalogs can be created digitally and linked with the manufacturer data sheets once they become available	🟨 material catalogs can be produced digitally but a manual evaluation of the material data from manufacturers may still be necessary

Environmental Quality		2.1 Use of secondary raw materials with self-declaration (quality level 2.1)		quantitative	building elements catalog, proof of self-declaration of secondary raw material share	building elements catalog	material catalogs can be created digitally and linked with the self-declarations	material catalogs can be produced digitally but a manual evaluation of the self-declaration may still be necessary
		2.2 Use of certified secondary raw materials with self-declaration (quality level 2.2)		quantitative	building elements catalog, proof of DGNB recognized certification, delivery notes or invoices	building elements catalog	material catalogs can be created digitally and linked with the self-declarations	material catalogs can be produced digitally but a manual evaluation of the self-declaration may still be necessary
	ENV2.2	**Potable Water Demand and Waste Water Volume**	2,40%					
		1.1 Water use value		quantitative	calculation	value in m3/a for comparison	N/A	this indicator assess a calculated value that is based on the number of building users and the type of building use so it does not make sense to depict this indicator digitally
		2.1 Watering and retention		qualitative	plans, photos, description	answering of two qualitative questions regarding the intent to add water retention and if so, whether retention devices are included in the external works	N/A	this indicator is mainly focused on two qualitative questions however the second question can be answered with the help of digitally created plans
		3.1 Level of integration		qualitative	documents, photos	answering of the question whether the system is geared towards integration with existing infrastructure or not	N/A	this indicator is based on the answering of a question that does not require any form of digital information to answer
	ENV2.3	**Land Use**	2,40%					
		1.1 Extent of rededication		qualitative				
		1.1.1 Outer development area - undeveloped		qualitative	land registry records or cadaster and expert reports	determination of previous use and potential contamination	N/A	these indicators are based on land registry records and survey reports which are site specific and do not make sense to integrate digitally
		1.1.2 Inner development area - undeveloped		qualitative	land registry records or cadaster and expert reports	determination of previous use and potential contamination	N/A	
		1.1.3 Brownfield		qualitative	land registry records or cadaster and expert reports	determination of previous use and potential contamination	N/A	
		1.1.4 Circular Economy Bonus		qualitative	land registry records or cadaster and expert reports, soil and contamination survey and professional assessment	determination of previous use and potential contamination	N/A	
		2.1 Soil sealing factor and compensatory measures		qualitative				
		2.1.1 Soil sealing factor		quantitative	calculation	determination of different land sealing on the site (full, partial or underground)	the different types of sealings can be added on the site around the building using a digital model	the different types of soil sealing and their percentages can be gathered from a digital model however the final soil sealing factor is still most easily calculated manually using excel for example
		2.1.2 Implementation of compensatory measures		qualitative	plans, photos, description	evaluation of rainwater management and infiltration measures, green roofs and walls and landscaping	N/A	the verification of this indicator is best done manually after construction is complete
	ENV2.4	**Biodiversity at the Site**	1,20%					
		1.1 Biodiversity index		quantitative	calculation using excel, site plan, photos of implemented measures, brief explanation	property-specific biodiversity index	the site plan can be created digitally and potentially linked with as built/implemented documentation	the index value is determined using an excel tool which can potentially be supplemented with area information from a digital model
		2.1 Specific measures for the active introduction of new and native animal species in the outdoor area		qualitative	plan for each selected species, concept within the framework of "animal-aided design", presentation of planned or implemented measures, evidence of integration	presentation of planned or implemented measures	N/A	the plans submitted for this indicator must be evaluated manually

	3.1 Specific measures for the active introduction of new and native species on the building		qualitative	plan for each selected species, concept within the framework of "animal-aided design", presentation of planned or implemented measures, evidence of integration	presentation of planned or implemented measures	N/A	🟥 the plans submitted for this indicator must be evaluated manually
	4.1 Avoidance of invasive plant species		quantitative	plans and list of plants	expert statement that the land does not contain any invasive species	N/A	🟥 this indicator must be evaluated manually by an expert who submits a statement
	5.1 Measures for habitat connectivity		qualitative	site plan, photos, brief explanation, expert statement	expert statement, design concept and photos	site plan can be created digitally and certain design elements can be integrated	🟨 the site plan can be created digitally and certain aspects of the design concept can potentially be integrated into the digital model but the overall success of the connectivity plan must be evaluated by an expert with a written statement
	6.1 Development agreement		quantitative	written statement	excerpt from development and upkeep agreement	N/A	🟥 this indicator is evaluated using a written statement that must be checked manually
	6.2 Maintenance area		quantitative	written statement	excerpt from development and upkeep agreement	N/A	🟥 this indicator is evaluated using a written statement that must be checked manually
	7.1 Devising and implementing a biodiversity strategy		quantitative	finalized written strategy	excerpt from the strategy plan	N/A	🟥 this indicator is evaluated using a written statement that must be checked manually
ECO1.1	**Life Cycle Cost**	10,00%					
	1.1 Integration of calculations of the life cycle costs into the planning process		quantitative				
	1.1.1 A LCC system/model is drawn up for the project in an early planning phase		quantitative	LCC model created in work stage 3	LCC model	LCC can be linked with LCA and the building components which will then update automatically every time the digital model is updated	🟩 link with the LCA, both can be built on information contained within the digital model
	1.1.2 The life cycle costs are determined at regular intervals during the planning process and are communicated within the planning team		quantitative	LCC model that includes relevant building-related follow-up costs	target values used for comparison	LCC results can easily be produced at different stages as the model is updated and expanded during the design process	🟩 link with the LCA, both can be built on information contained within the digital model
	2.1 Life cycle cost optimization during the planning process		qualitative				
	2.1.1 The effects of significant alternative decisions on the expected LCC are determined for the building		qualitative	LCC model	type of analysis, time (work phase) of analysis, number of alternatives, type of alternatives	N/A	🟥 to achieve points for this indicator it must simply be shown that numerous LCC alternatives were investigated
	2.1.2 The effects of significant decisions on the expected LCC are determined for the building		qualitative	LCC model	type of analysis, time (work phase) of analysis, number of alternatives, type of alternatives	N/A	🟥 to achieve points for this indicator it must simply be shown that numerous LCC alternatives were investigated
	2.2 Circular Economy Bonus		qualitative	documentation showing relevance of implemented solution	documentation of specific solutions	N/A	🟥 To achieve points for this indicator documentation of the solutions must be provided
	3.1 Assessment and comparison of the building-related life cycle costs		quantitative				
	3.1.1 Office buildings - medium standard and buildings with increased representativeness requirements		quantitative	specification of life cycle costs in accordance with DIN 276-1 and 18960	value below certain limits defined in the indicator	a digital model can be used to produce material/component lists that are the basis for the cost calculations that need to be carried out	🟩 link with the LCA, both can be built on information contained within the digital model
ECO2.1	**Flexibility and Adaptability**	7,50%					

Economic Quality		1.1 Space efficiency ≤ 0.48 - ≥ 0.75 (UA/GFA)		quantitative	plan, calculation	space efficiency = proportion of usable floor area (UA)/gross floor areas (GFA)	changes in the plans can immediately be seen in this value	the values needed to fulfill these indicators can all be gathered from a digital model
		2.1 Shell dimensions ≥ 3.00 m		quantitative	plan	ceiling heigh in meters (m)	changes in the plans can immediately be seen in this value	
		3.1 Building depth case 1 or 2 case 1: 10 to 16.5 or 12.5 to 14.5 case 2: 5 to 8.25 or 6.25 to 7.25		quantitative	plan	building depth in meters (m)	changes in the plans can immediately be seen in this value	
		4.1 Relationship between the gross floor area and the number of building access cores, on a per-story basis ≤ 1200 m2 to ≤ 400 m2		quantitative	plan, calculation	GFA story/ (n) building access cores	changes in the plans can immediately be seen in this value	
		5.1 Flexibility aspects of the floor plan, units less than 400 m2		quantitative	plan	sanitary facilities or connections provided for ≤ 400 m2 units	changes in the plans can immediately be seen in this value	
		6.1 Flexibility aspects of the structure, points per items achieved		qualitative	plan, calculation	non-load bearing partition walls that can be reused and easily installed, structural calculations that account for future loading	the information regarding the capabilities of the partition walls can be stored in a digital model as semantic information	the information regarding the future use of the partition walls can be stored in a digital model
		7.1 Flexibility aspects of the technical building services		qualitative				
		7.1.1 Ventilation/HVAC		qualitative	excerpts from technical building services plans, photo documentation	documentation regarding the distribution system	simulations can be carried out and future building configurations can be examined using a digital model to show how the technical building installations could be adapted in the future	a digital model can be used to show future changes that impact the technical building installations
		7.1.2 Cooling		qualitative	excerpts from technical building services plans, photo documentation	documentation regarding the distribution system		
		7.1.3 Heating		qualitative	excerpts from technical building services plans, photo documentation	documentation regarding the distribution system		
		7.1.4 Water - vertical WC connections		qualitative	excerpts from technical building services plans, photo documentation	documentation regarding the distribution system		
		8 Circular Economy Bonus		qualitative	more intense usage concepts have been considered and implemented in the design	high intensity usage concepts	high intensity usage concepts can be shown within a digital model through increased loading or alternate floor plan layouts	a digital model can be used to show how different usages would be possible within the building
	ECO2.2	**Commercial Viability**	5,00%					
		1.1 Entrance situation		qualitative	floor and site plans	floor plan with easily identifiable entrances	changes in the plans can be seen immediately	plan excerpts are required to verify these indicators and these plans can be generated and easily updated using a digital model
		1.2 Routing and signposting		qualitative	floor and site plans	floor plans with route and signage locations marked	changes in the plans can be seen immediately	
		2.1 Delivery zone		qualitative	site plan	site plan with clearly discernable parking spaces in the immediate vicinity of the entrance	changes in the plans can be seen immediately	
		2.3 Passenger car parking space capacity allocated to the building		quantitative	floor and site plans, calculation	number of required parking spaces per building unit areas	the parking spaces around the building can be indicated within the site of the digital model	
		2.4 Bicycle parking capacity allocated to the building		quantitative	site plan	number of required bike parking spaces per guideline figures for required bicycle parking from ADFC	N/A	
		2.5 Public parking spaces 200 m from the main or side entrance		quantitative	floor and site plans, calculation	number of parking spaces within 200 m from entrance	the parking spaces around the building can be indicated within the site of the digital model	
		3.1 Market risk (high or low)		quantitative	calculations	relationship (%) between planned and existing office area and rental performance	N/A	a market risk analysis is typically carried out by an expert and does not require a digital model
		4.1 Degree of utilization/occupancy rate (in percentage)		quantitative	documentation of users and rental agreements	proportion of rented spaces within the building	N/A	the rental agreements do not require a digital model to verify
		4.2 Circular Economy Bonus		qualitative	verification of collaboration between users and other companies occupying the building and contributing to a circular economy	verification of users and companies	N/A	the collaboration between users and companies cannot be verified using a digital model
	SOC1.1	**Thermal Comfort**	4,10%					

	1.1 Operative temperature (heating period)		quantitative	thermal simulation	compliance with DIN EN 15251 Category I, II or III using a degree C value and PMV index	the simulation can be run directly using the digital model and any changes can instantly be checked	thermal building simulations can be run directly using a digital model
	2.1 Drafts (heating period)		quantitative	manufacturer data sheets, flow simulations	air speed comparison between data sheet and value in accordance with Category B of DIN EN ISO 7730 using results from a flow simulation	the simulation can be run directly using the digital model and any changes can instantly be checked	flow simulations can be run directly using a digital model
	3.1 Radiant temperature asymmetry and floor temperature (heating period)		quantitative	data sheets, simulations	surface temperature values in degree C	the simulation can be run directly using the digital model and any changes can instantly be checked	U-values can be integrated in to the digital model and zonal simulations can also be run directly using a digital model
	4.1 Relative humidity (heating period)		quantitative	data sheets, simulations	indoor humidity ≥ 25% for at least 95% of the operating time	the simulation can be run directly using the digital model and any changes can instantly be checked	zonal moisture simulations can be run using the digital model
	5.1 Operative temperature (cooling period)		quantitative	thermal simulation	compliance with DIN 4108-2 and with DIN EN 15251 Category I, II or III using a degree C value and PMV index	the simulation can be run directly using the digital model and any changes can instantly be checked	thermal building simulations can be run directly using a digital model
	6.1 Drafts (cooling period)		quantitative	manufacturer data sheets, flow simulations	air speed comparison between data sheet and value in accordance with Category B of DIN EN ISO 7730 using results from a flow simulation	the simulation can be run directly using the digital model and any changes can instantly be checked	flow simulations can be run directly using a digital model
	7.1 Radiant temperature asymmetry and floor temperature (cooling period)		quantitative	data sheets, simulations	surface temperature values in degree C	the simulation can be run directly using the digital model and any changes can instantly be checked	U-values can be integrated in to the digital model and zonal simulations can also be run directly using a digital model
	8.1 Indoor humidity (cooling period)		quantitative	data sheets, simulations	absolute moisture content < 12 g/kg	the simulation can be run directly using the digital model and any changes can instantly be checked	zonal moisture simulations can be run using the digital model
SOC1.2	**Indoor Air Quality**	5,10%					
	1.1 Measurement of volatile organic compounds		quantitative	measurement	micrograms/m3 of TVOC and Formaldehyde	N/A	the measurement required for this indicators does not need a digital model
	2.1 Air exchange rate		quantitative	simulation, documentation, calculation	simulation results, or evaluation according to EN 15251, total ventilation rate q(tot)	a digital model can be used to perform the flow simulation	flow simulations can be run directly using a digital model
SOC1.3	**Acoustic Comfort**	2,00%					
	1.1 Room acoustics concepts		qualitative	concept	detailed concept in accordance with DIN 18041:2016-03	N/A	the overall concept does not require a digital model
	2.1 Compliance with the requirements for reverberation times in individual offices and multi-person offices up to 40 m2		quantitative	calculation, simulation	calculation and measurement results of reverberation time, values for sound absorption of people and furnishings, acoustic simulation	a digital model can be used to perform the acoustics simulation	acoustics simulations can be run directly using a digital model
	3.1 Compliance with the requirements for reverberation times in multi-person offices greater than 40 m2		quantitative	calculation, simulation	calculation and measurement results of reverberation time, values for sound absorption of people and furnishings, acoustic simulation	a digital model can be used to perform the acoustics simulation	acoustics simulations can be run directly using a digital model
	4.1 Compliance with the requirements for reverberation time T(target) and the requirements for inclusion		quantitative	calculation, simulation	calculation and measurement results of reverberation time, values for sound absorption of people and furnishings, acoustic simulation	a digital model can be used to perform the acoustics simulation	acoustics simulations can be run directly using a digital model
	5.1 Compliance with the recommendations for the A/V ratio in the frequency range 250-2000 Hz		quantitative	calculation, simulation	calculation and measurement results of reverberation time, values for sound absorption of people and furnishings, acoustic simulation	a digital model can be used to perform the acoustics simulation	acoustics simulations can be run directly using a digital model
SOC1.4	**Visual Comfort**	3,10%					

Sociocultural and Functional Quality		1.1 Daylight Factor (DF)		quantitative	calculation, simulation	daylight factor (%) for 50% of the useable area in accordance with DIN V 18599-4 or simulation	a digital model can be used to perform the daylight simulation	a digital model can be used as the basis for the simulation
		2.1 Annual relative motive exposure		quantitative	calculation, simulation	annual relative motive exposure (%) in accordance with DIN V 18599-4 or simulation	a digital model can be used to perform the daylight simulation	a digital model can be used as the basis for the simulation
		3.1 Available lines of sight to the outside		qualitative	floor plans, calculations	analysis of visual links to the outdoors	all changes to the floor plan and layout can be see immediately	the analysis can be carried out using floor plans generated within the digital model
		4.1 Absence of glare due to sun/glare protection system		quantitative	manufacturer data sheets	classification of sun glare protection system	N/A	the data sheets need to be checked manually as they differ for each project/product used
		5.1 Minimum requirements for artificial light		quantitative	calculation, product data sheets	requirements of DIN EN 12464-1 (Maintained illuminance level, glare limitation, uniformity of illuminance, color rendering, illuminance of the walls, luminance limits for lights at workstations with monitors)	a digital model can be used to perform the daylight simulation	a digital model can be used as the basis for the simulation
		5.2 Artificial light overfulfilment		quantitative	calculation, product data sheets	requirements of DIN EN 12464-1 (Maintained illuminance level, glare limitation, uniformity of illuminance, color rendering, illuminance of the walls, luminance limits for lights at workstations with monitors)	a digital model can be used to perform the daylight simulation	a digital model can be used as the basis for the simulation
		6.1 Color rendering index R(a)		quantitative	spectral calculation, manufacturer data sheets	color rendering index Ra	N/A	this indicator is based on data sheets and a calculation that do not require a digital model
		7.1 Duration of exposure to daylight		quantitative	floor and site plans, calculations, sun progression chart	duration of exposure to daylight on 17.01 and 21.03/21.09 in accordance with DIN 5034	N/A	the sun path can be overlayed in the digital model
	SOC1.5	**User Control**	2,00%					
		1.1 Ventilation control		qualitative	floor plans, concept	excerpts describing ventilation concept, spatial allocation of windows to workstations	spatial allocations can be adjusted easily using a digital model	a digital model can be used to generate the required floor plans
		2.1 Shading and glare protection control		quantitative	data sheets	user control based on data sheets	N/A	this indicator is based on data sheets and does not require a digital model
		3.1 Room temperature control during the heating period		quantitative	data sheets, photos	overall heating concept and user control based on data sheets	N/A	this indicator is based on data sheets and does not require a digital model
		4.1 Temperature control outside of the heating period		quantitative	data sheets	overall cooling concept and user control based on data sheets	N/A	this indicator is based on data sheets and does not require a digital model
		5.1 Artificial light control		quantitative	data sheets	user control based on data sheets	N/A	this indicator is based on data sheets and does not require a digital model
	SOC1.6	**Quality of Indoor and Outdoor Spaces**	2,00%					
		1.1 Communication zones of primary use		qualitative	floor plans	different types of meeting areas	different floor plan variations can be tried out and visualized more easily using a digital model	floor plans can easily be generated using a digital model as well as renderings
		2.1 Additional provisions/services		qualitative	floor plans	additional services provided	floor plans can more easily be adjusted to accommodate additional services using a digital model	easy editing of floor plans using a digital model

	2.2 Navigation/information		qualitative	concept	navigation system provided	N/A	it is difficult to analyze a navigation concept before it has been installed but certain elements can be added to the digital model
	3.1 Provisions for families in the building		qualitative	floor and site plans	childcare facilities, rooms with baby changing options, play areas, senior citizen rec areas, larger parking spaces	floor plans can more easily be adjusted to accommodate family services using a digital model	easy editing of floor plans using a digital model
	4.1 Quality of the interior access and circulation areas		qualitative	floor plans	number of circulation features provided	the different features can be implemented and easily updated in a digital model	the digital model can be easily updated to include more features
	5.1 Design concept for the outdoor facilities		qualitative				
	5.1.1 The design concept integrates the clever use of materials, lighting, navigation, greening and the necessary technical installations…		qualitative	floor plans, materials concepts, green plans	all encompassing outdoor design concept	the outdoor concept can be integrated into a digital model to help with visualizations	the digital model can be used to show elements of the concept
	5.1.2 Quality of outdoor areas		qualitative	site plan	playgrounds, green spaces, integrated technical infrastructure, social control, …	the outdoor concept can be integrated into a digital model for easier analysis	the digital model can be used to show elements of the concept
	6.1 Roof surfaces can be used		quantitative	roof plan	percentage of roof surface that can be used (>5m2)	the useable roof areas can be more easily adjusted using a digital model	areas can be generated using the digital model
	6.2 Façades can be used with balconies or are greened		quantitative	floor plans	balconies, loggias > 3m2 useable area per unit, green facades over >10% and at least 20 m2 in total	balcony and loggia areas can be easily calculated from a digital model	areas can be generated using the digital model
	6.3 Outdoor spaces (ground level)		quantitative	floor and site plans	communal outdoor seating, 80% of rooms have doors to the outdoors	number of doors can be easily counted and updated in a digital model	door schedules can be generated using the digital model
	7.1 Fixtures and equipment in the usable outdoor areas		qualitative	floor and site plans	number of fixture and equipment features provided	the different features can be implemented and easily updated in a digital model	the digital model can be easily updated to include more features
SOC1.7	**Safety and Security**	1,00%					
	1.1 Level of visibility		qualitative	floor and site plans	visibility in areas around the building	N/A	renderings can be used from a digital model to show visibility in certain areas
	1.2 Level of lighting		qualitative	site plans and simulations	lighting of thoroughfares, paths and parking areas	simulations can be carried out more easily	lighting simulations of the outdoor space can be carried out using a digital model
	1.3 Technical safety equipment		quantitative	floor and site plans	number of technical safety installation	installations can be depicted and quickly updated in a digital model	a digital model can show the different installations
SOC2.1	**Design for All**	3,10%					
	1.1 Degree of barrier-free design (level 1, DGNB minimum requirement)		quantitative	floor plans, photo documentation, details	internal and external infrastructure meet MBO barrier-free requirements, all units are barrier-free regardless of users, circulation areas for disabled passenger parking spaces, operating information is provided in "more-senses principle", at least one public barrier-free toilet cubicle	all requirements regarding widths and access can easily be determined using a digital model	a digital model can be used to quickly make adjustments to the floor plans to make them more accessible
	2.1 Degree of barrier-free design (level 2)		quantitative	floor plans, photo documentation, details	+ 10% designated barrier-free workspaces	all requirements regarding widths and access can easily be determined using a digital model	a digital model can be used to quickly make adjustments to the floor plans to make them more accessible
	3.1 Degree of barrier-free design (level 3)		quantitative	floor plans, photo documentation, details	+ 50% designated barrier-free workspaces + 25% barrier-free outdoor areas	all requirements regarding widths and access can easily be determined using a digital model	a digital model can be used to quickly make adjustments to the floor plans to make them more accessible

	4.1 Degree of barrier-free design (level 4)		quantitative	floor plans, photo documentation, details	+ 95% designated barrier-free workspaces + 75% barrier-free outdoor areas	all requirements regarding widths and access can easily be determined using a digital model	a digital model can be used to quickly make adjustments to the floor plans to make them more accessible
TEC1.2	**Sound Insulation**	2,30%					
	1.1 Airborne sound insulation between rooms within the own area - separating walls R'w and corridor doors Rw		quantitative	plans, building element constructions (partition walls and doors)	dB value for partition walls and doors	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	1.2 Airborne sound insulation between separating walls R'w and doors Rw		quantitative	plans, building element constructions (separating walls)	dB value for separating walls according to DIN 4109-1	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	1.3 Airborne sound insulation between separating ceilings R'w		quantitative	plans, building element constructions (ceilings)	dB values for separating ceilings in accordance with DIN 4109	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	1.4 Airborne sound insulation between standard flanking transmission level differences Rl,w,R or Dn,f,w,R		quantitative	plans, building element constructions (flanking components of each wall grid)	dB values for all flanking components	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	2.1 Footfall insulation of dividing ceilings and stairs		quantitative				
	2.1.1 In the own area (use of the same building)		quantitative	plans, building element constructions (ceilings and stairs)	dB values horizontal and vertical	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	2.1.2 Insulation against noise from other areas		quantitative	plans, building element constructions (ceilings and stairs)	dB values in accordance with DIN 4109, Supplement 2	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	3.1 Airborne sound insulation against outside noise		quantitative	plans, building element constructions (walls)	dB values according to DIN 4109-1	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
	4.1 Airborne sound insulation against building technical installations		quantitative	plans, building element constructions (walls)	dB values according to DIN 4109-1	building element constructions/layers can more easily be updated in a digital model	the sound insulation values associated with an element can be stored and checked within a digital model
TEC1.3	**Quality of the Building Envelope**	3,00%					
	1.1 Heat transfer coefficients		quantitative	plans, building element constructions/types of transparent surfaces, specialist confirmation or stationary or non-stationary calculations	heat transfer coefficient in W/m2K for all listed components	components can more easily be adjusted in a digital model	a digital model can be used to accurately depict the different wall constructions and can include U-values for the different elements
	2.1 Thermal heat bridge correction factors		quantitative	specialist planner declaration or two-dimensional isothermal calculation	thermal bridge correction factor in W/m2K according to DIN 4108-6	N/A	the floor plans and element components in the digital model can potentially be used in the calculation
	3.1 Airtightness measurement		quantitative	measurement of final construction	air change rate in h-1	N/A	the measurements do not require a digital model
	3.2 Joint permeability of windows and doors		quantitative	measurement of final construction	joint permeability class	N/A	the measurements do not require a digital model
	4.1 Summer heat protection (simplified method or simulation)		quantitative	calculation according to DIN 4108-2 or simulation	solar transmittance parameter	simulations can be carried out more easily	the digital model can be used as the basis for the simulation
TEC1.4	**Use and Integration of Building Technology**	2,30%					

Technical Quality		1.1 Planning for a passive building concept		qualitative	floor and site plans, simulation	window area proportion, building compactness, daylight use, sun protection, storage mass, natural ventilation, passive heating and cooling	different passive elements can be tested using a building simulation	the digital model can be used as the basis for the simulation
		1.2 Implementation of a passive building concept		quantitative	floor and site plans, simulation	window area proportion, building compactness, daylight use, sun protection, storage mass, natural ventilation, passive heating and cooling	different passive elements can be tested using a building simulation	the digital model can be used as the basis for the simulation
		2.1 Heat distribution and transfer system		quantitative	HVAC plan, documentation	hot water temperature of heat transfer system	system can be overlayed and clash checked with the works of other disciplines	Clash detection can easily be carried out using a digital model
		2.2 Cooling distribution and transfer system		quantitative	HVAC plan, documentation	cold water temperature of cooling transfer system	system can be overlayed and clash checked with the works of other disciplines	Clash detection can easily be carried out using a digital model
		3.1 Technical facilities/generation		qualitative	floor plans, photo documentation	accessibility analysis	can be visualized and altered using a digital model	dimension and visualizations can be generated using a digital model
		3.2 Shafts/routes/distribution		qualitative	floor plans, photo documentation	accessibility analysis	can be visualized and altered using a digital model	dimension and visualizations can be generated using a digital model
		4.1 Condition and expandability of system integration		quantitative				
		4.1.1 Open and standardized protocols in existing networks		qualitative	concept documentation	use of specific protocols	N/A	the type of protocols used are not influenced by the type of model
		4.1.2 Planning/implementation in accordance with DIN EN ISO 16484-1		quantitative	concept documentation	use of DIN EN ISO 16484-1 in planning and implementation	N/A	the DIN requirements are not influenced by a digital model
		4.2 Integrated functions in a higher-level system		qualitative	floor plan	implementation of certain functions	certain functions can be added to the system in the digital model	certain functions can be saved in the digital model which can help later on during FM
		4.3 Integration of the technical systems/media into the district/the immediate surroundings		qualitative				
		4.3.1 Planning of integration of the technical systems/media into the district/the immediate surroundings		qualitative	area analysis, calculations	analysis of surrounding area	potential connections to the district can be added to a digital model to act as proof of concept	the surrounding area and district systems can be added to the digital model
		4.3.2 Implementation of integration of the technical systems/media into the district/the immediate surroundings		qualitative	site plan	district integration	potential connections to the district can be added to a digital model to act as proof of concept	the surrounding area and district systems can be added to the digital model
		4.4 Integration of the energy infrastructure into the district/the immediate surroundings		qualitative				
		4.4.1 Circular Economy Bonus - District solution for renewable energy		qualitative	documentation, calculation	renewable energy used in district	N/A	the district energy is not influenced by the type of model
		4.4.2 Circular Economy Bonus - Grid-compatible energy system		quantitative	documentation, calculation	building storage capacity	N/A	the building storage is not influenced by the type of model
	TEC1.5	**Ease of Cleaning Building Components**	1,50%					
		1.1 Feasibility of façade cleaning		quantitative	floor plans, elevations	exterior glass surface share	changes in the plans can be seen immediately	elevation and 3D views can be generated using a digital model
		2.1 Cost and effort required for cleaning exterior components		quantitative	floor plans, list of building components and cleaning concepts	list of exterior building components with cleaning effort and type	building component lists can be generated automatically	component schedules and lists can be generated using a digital model
		2.2 Cost and effort required for cleaning interior components		quantitative	floor plans, list of building components and cleaning concepts	list of interior building components with cleaning effort and type	building component lists can be generated automatically	component schedules and lists can be generated using a digital model
		3.1 Ease of cleaning floor covering		qualitative	floor plans and interior design plan	floor covering type	floor type lists can be generated automatically	component schedules and lists can be generated using a digital model
		4.1 Dirt trap at building entrances I		quantitative	floor plans	existence of dirt traps	changes to the dirt traps can be carried out easily	dirt traps can be verified using a digital model
		4.2 Dirt trap at building entrances II		quantitative	floor plans	types of dirt traps	changes to the dirt traps can be carried out easily	dirt traps can be verified using a digital model
		5.1 Obstacle prevention in the floor plan		quantitative	floor plans	locations of obstacles	clashes can be detected early on and objects can more easily be moved	easy editing of floor plans and clash detection using a digital model

	6.1 Surfaces that are frequently used and difficult to access		qualitative	floor plans and interior design plan	list of areas with classifications	different surfaces and areas can be stored in the digital model	areas can be attributed relevant characteristics in the digital model
	7.1 Concept for ease of cleaning considered in the planning process		qualitative	cleaning concept	submission of cleaning concept	the cleaning concept can be integrated into the model on a component/element basis for potential later access by the FM	concept can be integrated into a digital model for FM use
	7.2 Cleaning concept		qualitative	cleaning concept	submission of cleaning concept	the cleaning concept can be integrated into the model on a component/element basis for potential later access by the FM	concept can be integrated into a digital model for FM use
TEC1.6	**Ease of Recovery and Recycling**	3,00%					
	1.1 Selection of easy-to-recycle construction materials and building components		quantitative	plans	material and component lists with SBC percentages in accordance with DIN 276	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
	1.2 Circular Economy Bonus - Reuse or material recovery		quantitative	plans	material and component lists with SBC percentages in accordance with DIN 276	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
	1.3 Circular Economy Bonus - Avoiding use of building components		quantitative	plans	material and component lists with SBC percentages	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
	2.1 Easy-to-recover building structure and building components		quantitative	plans	material and component lists with SBC percentages	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
	3.1 Recovery, conversion and ease of recycling in the early planning process		qualitative	concept	material and component lists that show changes in the planning process	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
	3.2 Recovery, conversion and ease of recycling in the detailed design		qualitative	concept	material and component lists that show changes in the design process	building component lists can be generated automatically	a digital model can be used to generate the required building component lists
TEC1.7	**Immissions Control**	0,80%					
	1.1 Noise pollution reduction measures		quantitative	technical values, documentation, reports	immission values and compliance with guidelines (noise emissions level, sound power level, sound power level with immission effect, operational period of the systems, assessed level as additional pollution, immissions guide value)	N/A	the immission compliance must be checked by an expert and does not require a digital model
	2.1 Light pollution reduction measures		quantitative	simulation, concept, documentation, data sheets	types of lighting and light spread	a digital model can be used to perform potential simulations	a digital model can be used as the basis for the simulation of outdoor lighting conditions
TEC3.1	**Mobility Infrastructure**	2,30%					
	1.1 Parking facilities		qualitative	plans	easily accessible and protected parking areas near building	plans can be easily updated using a digital model	a digital model can be used to generate the required floor plans
	2.1 Circular Economy Bonus - Mobility sharing		quantitative	plans	mobility sharing parking spaces near building	plans can be easily updated using a digital model	a digital model can be used to generate the required floor plans
	3.1 Electromobility - motorized individual transport (MIT)		quantitative	plans	parking spaces with charging stations	plans can be easily updated using a digital model	a digital model can be used to generate the required floor plans
	3.2 Electric bikes		quantitative	plans	electric bike parking spaces with charging stations	plans can be easily updated using a digital model	a digital model can be used to generate the required floor plans
	3.3 Electromobility - integration of charging stations		qualitative	concept	charging station and management system integration	N/A	the management system is not influenced by a digital model
	4.1 User comfort inside the building		quantitative	floor plans	different types of rooms with specific uses are available	plans can be easily updated using a digital model	a digital model can be used to generate the required floor plans
PRO1.1	**Comprehensive Project Brief**	1,60%					
	1.1 Scope of requirements planning		qualitative	documentation	architectural brief - requirements descriptions based on Appendix 1a, 1b and 1c of the criterion	N/A	the indicators in this criteria do not

	2.1 Measures for working with the public		qualitative	documentation, photos	measures to inform the general public	N/A	the indicators in this criteria do not require a digital model
	3.1 Sustainability requirements in the specifications		qualitative	documentation	specifications including sustainability aspects	N/A	
PRO1.4	**Sustainability Aspects in Tender Phase**	1,60%					
	1.1 Scope of integration of sustainability aspects in tender phase		qualitative	documentation	general preliminary remarks	N/A	preliminary remarks do not require a digital model
	1.2 Circular Economy Bonus - Recycling Materials		qualitative	documentation	explicit inclusion of secondary or recycled material suggestions for mineral construction products	N/A	preliminary remarks do not require a digital model
PRO1.5	**Documentation for Sustainable Management**	1,10%					
	1.1 Production and provision of servicing, inspection, operating and upkeep instructions		qualitative	documentation and scheduling	instructions for service providers	the instructions and cleaning/maintenance schedules can be added into a digital building model on a component basis	detailed information can be stored in the digital model
	2.1 Updating of plans, documentation and calculations to reflect the building as it has actually been built, and provision of these to the building owner		qualitative	documentation, simulations, calculations	up-to-date plans, calculations, simulations, documentation reflecting the as built situation	the digital model provides a location to store all as built documentation in one place	as built information can be linked with the digital model
	3.1 Production and provision of a facility management manual		qualitative	documentation	facility management manual	N/A	the manual is a separate submittal from the digital model
	4.1 Conducting of planning with BIM and provision of the BIM model		qualitative	BIM model	up-to-date BIM model	using a digital model fulfils this	the digital model itself fulfils this indicator
PRO1.6	**Procedure for Urban and Design Planning**	1,60%					
	1.1 Prior exploration of different design variants		qualitative	plans, concepts, documentation	documentation of different design options	N/A	different versions of the model can be saved to show alternative design ideas and general design progress
	1.2 (alternatively) Planning competition		qualitative				
	1.2.1 Scope and quality of the planning competition		qualitative	documentation	holding of a planning competition	N/A	A holding of a planning competition does not require a digital model
	1.2.2 Type of competition held		qualitative	documentation	type of planning competition	N/A	A holding of a planning competition does not require a digital model
	1.2.3 Implementation of a prize-winning design		qualitative	documentation	prize winning design implemented	N/A	A holding of a planning competition does not require a digital model
	1.2.4 Commissioning of the planning team		quantitative	documentation	winning team is commissioned	N/A	A holding of a planning competition does not require a digital model
	2.1 A design recommendation by the DGNB commission has been held or the project was presented before and architectural advisory board		qualitative	documentation	DGNB design recommendation	N/A	Design recommendations do not require a digital model
	2.2 The design recommendations by the DGNB commission or the architectural advisory board were implemented		qualitative	documentation	DGNB design recommendation implemented	N/A	Design recommendations do not require a digital model
	3.1 Recognition/Award		qualitative				
	3.1.1 Recognition in terms of good design "Baukultur"		qualitative	documentation	award documentation	N/A	Awards and recognition do not require a digital model
	3.1.2 Award for the completed project (DGNB Diamond award)		qualitative	documentation	DGNB Diamond award	N/A	Awards and recognition do not require a digital model
PRO2.1	**Construction Site/Construction Process**	1,60%					
	1.1 Low-noise construction site concept		quantitative	documentation	reports and documentation	N/A	construction site concepts and the
	1.2 Training for the parties implementing the construction work		qualitative	documentation	training	N/A	
	1.3 Reviewing the work implemented		qualitative	documentation, photos, measurements	reports and documentation	N/A	
	2.1 Low-dust construction site concept		quantitative	documentation, photos	reports and documentation	N/A	
	2.2 Training for the parties implementing the construction work		qualitative	documentation	training	N/A	

Process Quality		2.3 Reviewing the work implemented		qualitative	documentation, photos, measurements	reports and documentation	N/A	implementation of these concepts can potentially be integrated into a digital model in terms of scheduling and detailed information regarding specific components or areas of the model
		3.1 Soil and groundwater protection concept		quantitative	documentation, photos	reports and documentation	N/A	
		3.2 Training for the parties implementing the construction work		qualitative	documentation	training	N/A	
		3.3 Reviewing the work implemented		qualitative	documentation, photos, measurements	reports and documentation	N/A	
		4.1 Low-waste construction site concept		quantitative	documentation, photos	reports and documentation	N/A	
		4.2 Training for the parties implementing the construction work		qualitative	documentation	training	N/A	
		4.3 Reviewing the work implemented		qualitative	documentation, photos	reports and documentation	N/A	
		4.4 Circular Economy Bonus - Waste prevention on the construction site		quantitative	documentation, photos	reports and documentation	N/A	
	PRO2.2	**Quality Assurance of the Construction**	1,60%					
		1.1 Quality assurance plan		qualitative	documentation	quality assurance plan	N/A	the quality assurance plan is a separate submittal from the digital model
		2.1 Implementation of quality control measures		quantitative				
		2.1.1 Differential pressure has been measured before fitting work is implemented		quantitative	measurement	differential pressure values	N/A	a digital model is not required for measurement taking, however the measurements could potentially be stored in the digital model
		2.1.2 Thermal imaging measurement		quantitative	measurement	thermal imaging values	N/A	
		2.1.3 Reverberation period has been measured		quantitative	measurement	reverberation times	N/A	
		2.1.4 Sound reduction index pertaining to external noise		quantitative	measurement	sound reduction index (external)	N/A	
		2.1.5 Sound reduction index pertaining to interior noise		quantitative	measurement	sound reduction index (internal)	N/A	
		2.1.6 Measurements of footfall sound level for the ceilings		quantitative	measurement	footfall sound level	N/A	
		2.1.7 Other building relevant measurements		quantitative	measurement	relevant measurements	N/A	
		3.1 Quality assurance for the construction products used		qualitative	construction product lists	product requirement lists based on ENV1.2, ENV1.3 and SOC1.2	N/A	
		4.1 Mould prevention		qualitative	documentation	mould prevention/ventilation program for the building	N/A	
	PRO2.3	**Systematic Commissioning**	1,60%					
		1.1 Creation of a monitoring concept		quantitative	documentation	monitoring concept (on a monthly basis)	the monitoring concept can be integrated into the FM digital model	FM digital model
		2.1 Creation of a commissioning concept for scheduling		qualitative	documentation	commissioning reports and contracts	N/A	the commissioning report is a separate submittal from the digital model
		3.1 Performance of a preliminary function test		quantitative	documentation	function test reports and certificates	function test results can be saved in the digital model for later access	FM digital model
		4.1 Performance and documentation of a function test and training for the operator		quantitative	documentation	function test reports and certificates	function test results can be saved in the digital model for later access	FM digital model
		5.1 Creation of a detailed final commissioning report		qualitative	documentation	final commissioning report	N/A	the commissioning report is a separate submittal from the digital model
		6.1 Creation and handover of an integral operation concept		quantitative	documentation	operation concept	the operation concept can be integrated into the FM digital model	FM digital model
		7.1 Readjustment of the system following initial operating phase		qualitative	documentation	contract confirming optimizations	readjustments can be documented in the digital FM model	FM digital model
	PRO2.4	**User Communication**	1,10%					
		1.1 Provision of a sustainability guide for the user		qualitative	documentation	user sustainability guide	N/A	the user guide is a separate submittal from the digital model
		2.1 Implementation of an information system on the sustainability of the building		qualitative	documentation	information system in the building	the information system can be added to the digital model for monitoring	the information system can be integrated into the digital model
		3.1 Provision of a technical user manual		qualitative	documentation	technical user manual	N/A	the technical manual is a separate submittal from the digital model

PRO2.5	**FM-compliant Planning**	0,50%					
	1.1 Performance of an FM check		qualitative	plans, documentation	FM check results	a digital model can be used as the basis for this check and to record the results	FM digital model
	2.1 Detailed operating cost projection		quantitative	calculations	cost projection results considering GEFMA 200 and 100	cost information can be integrated into the digital model for easy tracking and updating	5D digital model
	3.1 Optimization of user/use-related energy consumption		qualitative	documentation	metering concept	the metering of different areas can be integrated in the digital model	FM digital model
SITE1.1	**Local Environment**	1,10%					
	1.1 Earthquake hazard level		quantitative	documentation	Earthquake hazard level according to DIN EN 1998-1/NA	by including the surroundings in the model and including the exact building location it can be easier to find the site on a map which allows different risk maps to be digitally overlaid resulting in more precise results	GIS digital model
	1.2 Earthquake compensation measures		qualitative	documentation, concept, floor plans	earthquake-proof shelters, risk analysis, early warning system		GIS digital model
	2.1 Volcanic eruption hazard level		quantitative	documentation	last known volcanic eruption		GIS digital model
	2.2 Volcanic eruption compensation measures		qualitative	documentation, structural details	lava and debris safe site, risk analysis, early warning system		GIS digital model
	3.1 Avalanche hazard level		quantitative	documentation	avalanche hazard level color		GIS digital model
	3.2 Avalanche compensation measures		qualitative	documentation	risk analysis, structural measures		GIS digital model
	4.1 Storm hazard level		quantitative	documentation	winter storm 50-year event		GIS digital model
	4.2 Storm compensation measures		qualitative	documentation, site plans	surrounding area analysis, risk analysis		GIS digital model
	5.1 Flood hazard level		quantitative	documentation	flood hazard level		GIS digital model
	5.2 Flood compensation measures		qualitative	concept, documentation	structural measures, safe distances, retention areas, risk analysis		GIS digital model
	6.1 Heavy rain hazard level		quantitative	documentation	KOSTRA-DWD-2010R rainfall even catalog		GIS digital model
	6.2 Heavy rain compensation measures		qualitative	expert report, documentation	risk analysis, depths and rates based on recurrence interval		GIS digital model
	7.1 Hail hazard level		quantitative	documentation	hail zone according to BBK		GIS digital model
	7.3 Hail compensation measures		qualitative	documentation	risk analysis		GIS digital model
	8.1 Landslide/subsidence hazard level		quantitative	documentation	local risk areas or site inclination		GIS digital model
	8.2 Landslide/subsidence compensation measures		qualitative	documentation	soil survey, risk assessment, structural measures		GIS digital model
	9.1 Storm surge/tsunami hazard level		quantitative	documentation	storm surge risk from map		GIS digital model
	9.2 Storm surge/tsunami compensation measures		qualitative	documentation, site plans	surrounding area analysis, risk analysis		GIS digital model
	10.1 Hazard level for extreme climates in accordance with ESPON map		quantitative	documentation	risk level from ESPON map		GIS digital model
	10.2 Extreme climate compensation measures		qualitative	documentation	structural measures, risk analysis		GIS digital model
	11.1 Forest fire hazard level		quantitative	documentation	last known forest fire		GIS digital model
	11.2 Forest fire compensation measures		qualitative	documentation	warning system, site and risk analysis		GIS digital model
	12.1 Compliance with legally required limit values for air quality characteristics		quantitative	documentation	PM10 and NO2 limit values	N/A	meeting the requirements does not require a digital model
	12.2 Air quality compensation measures		qualitative	documentation	decrease in emissions levels, risk analysis	N/A	meeting the requirements does not require a digital model
	13.1 Outdoor noise level		quantitative	documentation	dB value in accordance with DIN 4109	by including the surroundings in the model and including the exact building location it can be easier to find the site on a map which allows different risk maps to be digitally overlaid resulting in more precise results	GIS digital model
	13.2 Outdoor noise compensation measures		qualitative	documentation, site and floor plans, expert report	building orientation, noise protection measures in floor plan	floor plans can more easily be adjusted to accommodate noise protection measures	GIS digital model

Site Quality		13.3 Reduction factors apply to air traffic noise		quantitative	documentation	noise protection zones	N/A	meeting the requirements does not require a digital model
		14.1 Radon concentration levels		quantitative	documentation	radon ground air concentration	N/A	meeting the requirements does not require a digital model
	SITE1.2	**Influence on the District**	1,10%					
		1.1 Site classification and evaluation		qualitative	documentation	site image and impact	N/A	meeting the requirements does not require a digital model
		2.1 Influence of the building on the site or the district		qualitative	documentation	building image and impact	N/A	meeting the requirements does not require a digital model
		3.1 Potential synergy due to clustering		qualitative	documentation	cluster configuration, technical or economic synergies	N/A	meeting the requirements does not require a digital model
		4.1 Boost in attraction due to use		qualitative	documentation	unique features that attract users and/or employees	N/A	meeting the requirements does not require a digital model
		4.2 Boost in attraction due to spatial and design aspects		qualitative	documentation	"stimulation" to the district	N/A	meeting the requirements does not require a digital model
	SITE1.3	**Transport Access**	1,10%					
		1.1 Surrounding private transportation access in the area		qualitative	site plan, documentation	roadway access	site plans can be combined with GIS data to store information about the transportation options in the area	GIS digital model
		1.2 Building-related private transportation access		qualitative	site plan	parking spaces		
		2.1 Public transit stops		quantitative	site plan, documentation	distances to stops		
		2.2 Access to nearest railway station		quantitative	site plan	time to stations (minutes)		
		2.3 Public transport frequency		quantitative	timetables/ schedules	frequency (minutes)		
		2.4 Building-related public transportation access		qualitative	documentation	information displays		
		3.1 Cycle paths		quantitative	site plan, documentation	types of bike paths		
		3.2 Bicycle access		qualitative	regional plans	regional and national access		
		3.3 Building-related bicycle access		qualitative	site plan	access roads around building		
		4.1 Pedestrian path network		qualitative	site plan	percentage of covered walking possibilities		
		4.2 Pedestrian crossing possibilities		qualitative	site plan	percentage of crossing possibilities		
		4.3 Pedestrian signage		qualitative	site plan	signage		
		5.1 Barrier-free access to nearby public transport stops		quantitative	site plan	height differences and clearances, access points, weather protection		
		5.2 Barrier-free design of the path to the building and the area surrounding it		qualitative	site plan, documentation	visual obstructions, guiding elements, uncrossed areas		
	SITE1.4	**Access to Amenities**	1,70%		plans, photo documentation, timetables/schedules			
		1.1 Social infrastructure within the district/surrounding area (education, leisure, playgrounds, sports facilities)		quantitative	district plan	types of local facilities and distances	site plans can be combined with GIS data to store information about the facility options in the area	GIS digital model
		1.2 Opportunity to use rooms within the building and outdoor facilities		qualitative				
		1.2.1 Opportunities to hire rooms and use spaces within the building		qualitative	floor plans	rental opportunities for rooms within the building	different room uses can be added to the digital model	floor plans can be linked with use information in the digital model
		1.2.2 Opportunities to use spaces in the building's outdoor facilities		qualitative	site plans	public use of outdoor facilities	different outdoor space uses can be added to the digital model	site plans can be linked with use information in the digital model
		2.1 Commercial infrastructure within the district/surround area (local supply, food and catering, other services - bank, post office, etc., medical services)		quantitative	district plan	types of local facilities and distances	site plans can be combined with GIS data to store information about the facility options in the area	GIS digital model
		3.1 Variety of uses within the building		qualitative	floor plans	variety of uses in the building	different building uses can be added to the digital model	floor plans can be linked with use information in the digital model
		3.2 Circular Economy Bonus - Facilities that cater for people's day-to-day needs and provide meeting points for interactions		qualitative	floor and site plans	social interaction spaces and activities	N/A	meeting the requirements does not require a digital model

TOPIC	CRITERIA SHORT CODE	CRITERIA NAME	APPLICABLE IN EARLY DESIGN STAGES?	DIGITAL MODEL-BASED WORKFLOW?	CATEGORY	INCLUDED IN THIS THESIS?
Environmental Quality	ENV1.1	**Building Life Cycle Assessment**				
		1.1 integration of life cycle assessments into the planning process	🟩	🟩	quantitative	NO, this topic has already been thoroughly investigated in other research papers and constitutes its own thesis topic. For insight into research regarding LCA and BIM integration see the following sources: [1] Stella, A. (2018). Integrating DGNB into the BIM Process (with special focus on LCA in the early stages of the design) [2] Hollberg, et. al. (2017).Design-integrated LCA using early BIM [3] Santos, et. al. (2019). Integration of LCA and LCC analysis within a BIM-based environment
		1.1.1 LCA is created in the early planning phase	🟩	🟩	quantitative	
		1.1.2 LCA results are determined at regular intervals during the planning process	🟩	🟩	quantitative	
		1.1.3. LCA results are determined for the operating phase of the build	🟩	🟩	quantitative	
		2.1 life cycle assessment optimization during the planning process	🟩	🟩	quantitative	
		2.1.1 effects of significant alternative decisions on the expected LCA results are determined	🟩	🟩	quantitative	
		2.1.2 effects of significant decisions on the expected LCA results are determined	🟩	🟩	quantitative	
		3.1 weighted environmental impacts	🟩	🟩	quantitative	
		3.1.1 building LCA results provided	🟩	🟩	quantitative	
		3.1.2 evaluation of the LCA results	🟩	🟩	quantitative	
		4.1 potential to achieve climate neutrality	🟩	🟩	quantitative	
		4.1.1 climate-neutral building-related energy demand	🟩	🟩	quantitative	
		4.1.2 climate-neutral energy demand of users	🟩	🟩	quantitative	
		4.1.3 climate-neutral construction	🟩	🟩	quantitative	
		5.1 use of reused components or structural elements	🟩	🟩	quantitative	
		5.2 building generates energy for other users	🟩	🟩	quantitative	
		6.1 GWP factor of refrigerants in refrigeration systems	🟩	🟩	quantitative	
	ENV1.2	**Local Environmental Impact**				
		1.1 Fulfilment of all requirements in the criteria matrix given the different QL levels	🟨	🟨	quantitative	YES, this criteria falls under the quantitative category of this thesis
		1.3 Additional points in quality level 1, 2 and 3 in terms of cooling without halogenated refrigerants	🟨	🟥	quantitative	
	ENV1.3	**Sustainable Resource Extraction**				
		1.1 Corporate responsibility for resource extraction (quality level 1.1)	🟥	🟨	qualitative	NO, this criteria is not applicable in the early design stages and requires manual checking that cannot be done with a digital model
		1.2 Certified sustainable resource extraction of a part of the value chain (quality level 1.2)	🟥	🟨	quantitative	
		1.3 Certified sustainable resource extraction (quality level 1.3)	🟥	🟨	quantitative	
		2.1 Use of secondary raw materials with self-declaration (quality level 2.1)	🟥	🟨	quantitative	
		2.2 Use of certified secondary raw materials with self-declaration (quality level 2.2)	🟥	🟨	quantitative	
	ENV2.2	**Potable Water Demand and Waste Water Volume**				
		1.1 Water use value	🟩	🟥	quantitative	NO, this criteria is not reasonable to depict digitally
		2.1 Watering and retention	🟩	🟨	qualitative	
		3.1 Level of integration	🟩	🟥	qualitative	
	ENV2.3	**Land Use**				
		1.1 Extent of rededication	🟩	🟥	qualitative	NO, this criteria is not reasonable to depict digitally
		1.1.1 Outer development area - undeveloped	🟩	🟥	qualitative	
		1.1.2 Inner development area - undeveloped	🟩	🟥	qualitative	
		1.1.3 Brownfield	🟩	🟥	qualitative	
		1.1.4 Circular Economy Bonus	🟩	🟥	qualitative	
		2.1 Soil sealing factor and/or compensatory measures	🟩	🟨	qualitative	
		2.1.1 Soil sealing factor	🟩	🟨	quantitative	
		2.1.2 Implementation of compensatory measures	🟩	🟥	qualitative	
	ENV2.4	**Biodiversity at the Site**				
		1.1 Biodiversity index	🟩	🟨	quantitative	NO, this criteria is not reasonable to depict digitally
		2.1 Specific measures for the active introduction of new and native animal species in the outdoor area	🟩	🟥	qualitative	
		3.1 Specific measures for the active introduction of new and native species on the building	🟩	🟥	qualitative	
		4.1 Avoidance of invasive plant species	🟩	🟥	quantitative	
		5.1 Measures for habitat connectivity	🟩	🟨	qualitative	
		6.1 Development agreement	🟨	🟥	quantitative	
		6.2 Maintenance area	🟨	🟥	quantitative	
		7.1 Devising and implementing a biodiversity strategy	🟨	🟥	quantitative	
	ECO1.1	**Life Cycle Cost**				
		1.1 Integration of calculations of the life cycle costs into the planning process	🟩	🟩	quantitative	NO, the topic LCC is closely linked with LCAs which are not included in this thesis and ultimately an LCC cannot be performed without also performing an LCA. Additionally this topic has already been covered in depth in other research, for example in the following sources: [1] Santos, et. al. (2019). Integration of LCA and LCC analysis within a BIM-based environment [2] Haugbølle and Raffnsøe. (2018) Rethinking life cycle cost drivers for sustainable office buildings in Denmark [3] Dermot and Kehily. (2017). Embedding Life Cycle Costing in 5D
		1.1.1 A LCC system/model is drawn up for the project in an early planning phase	🟩	🟩	quantitative	
		1.1.2 The life cycle costs are determined at regular intervals during the planning process and are communicated within the planning team	🟩	🟩	quantitative	
		2.1 Life cycle cost optimization during the planning process	🟩	🟥	qualitative	
		2.1.1 The effects of significant alternative decisions on the expected LCC are determined for the building	🟩	🟥	qualitative	
		2.1.2 The effects of significant decisions on the expected LCC are determined for the building	🟩	🟥	qualitative	
		2.2 Circular Economy Bonus	🟩	🟥	qualitative	
		3.1 Assessment and comparison of the building-related life cycle costs	🟩	🟩	quantitative	
		3.1.1 Office buildings - medium standard and buildings with increased representativeness requirements	🟩	🟩	quantitative	
		Flexibility and Adaptability				
		1.1 Space efficiency ≤ 0.48 - ≥ 0.75 (UA/GFA)	🟩	🟩	quantitative	
		2.1 Shell dimensions ≥ 3.00 m	🟩	🟩	quantitative	

Economic Quality	ECO2.1	3.1 Building depth case 1 or 2 case 1: 10 to 16.5 or 12.5 to 14.5 case 2: 5 to 8.25 or 6.25 to 7.25	🟩	🟩	quantitative	NO, already covered in ONIB Report, conclusion: about 30% could be depicted geometrically in the BIM model Source: ONIB (2019).
		4.1 Relationship between the gross floor area and the number of building access cores, on a per-story basis ≤ 1200 m2 to ≤ 400 m2	🟩	🟩	quantitative	
		5.1 Flexibility aspects of the floor plan, units less than 400 m2	🟩	🟩	quantitative	
		6.1 Flexibility aspects of the structure, points per items achieved	🟩	🟩	qualitative	
		7.1 Flexibility aspects of the technical building services	🟩	🟩	qualitative	
		7.1.1 Ventilation/HVAC	🟩	🟩	qualitative	
		7.1.2 Cooling	🟩	🟩	qualitative	
		7.1.3 Heating	🟩	🟩	qualitative	
		7.1.4 Water - vertical WC connections	🟩	🟩	qualitative	
		8 Circular Economy Bonus	🟩	🟩	qualitative	
	ECO2.2	**Commercial Viability**				
		1.1 Entrance situation	🟨	🟩	qualitative	YES, this criteria falls under the quantitative category of this thesis
		1.2 Routing and signposting	🟨	🟩	qualitative	
		2.1 Delivery zone	🟨	🟩	qualitative	
		2.3 Passenger car parking space capacity allocated to the building	🟨	🟩	quantitative	
		2.4 Bicycle parking capacity allocated to the building	🟨	🟩	quantitative	
		2.5 Public parking spaces 200 m from the main or side entrance	🟨	🟩	quantitative	
		3.1 Market risk (high or low)	🟨	🟥	quantitative	
		4.1 Degree of utilization/occupancy rate (in percentage)	🟥	🟥	quantitative	
		4.2 Circular Economy Bonus	🟥	🟥	qualitative	
Sociocultural and Functional Quality	SOC1.1	**Thermal Comfort**				
		1.1 Operative temperature (heating period)	🟩	🟩	quantitative	YES, this criteria falls under the quantitative category of this thesis
		2.1 Drafts (heating period)	🟩	🟩	quantitative	
		3.1 Radiant temperature asymmetry and floor temperature (heating period)	🟩	🟩	quantitative	
		4.1 Relative humidity (heating period)	🟩	🟩	quantitative	
		5.1 Operative temperature (cooling period)	🟩	🟩	quantitative	
		6.1 Drafts (cooling period)	🟩	🟩	quantitative	
		7.1 Radiant temperature asymmetry and floor temperature (cooling period)	🟩	🟩	quantitative	
		8.1 Indoor humidity (cooling period)	🟩	🟩	quantitative	
	SOC1.2	**Indoor Air Quality**				
		1.1 Measurement of volatile organic compounds	🟩	🟥	quantitative	YES, this criteria falls under the quantitative category of this thesis
		2.1 Air exchange rate	🟩	🟩	quantitative	
	SOC1.3	**Acoustic Comfort**				
		1.1 Room acoustics concepts	🟩	🟥	qualitative	YES, this criteria falls under the quantitative category of this thesis
		2.1 Compliance with the requirements for reverberation times in individual offices and multi-person offices up to 40 m2	🟩	🟩	quantitative	
		3.1 Compliance with the requirements for reverberation times in multi-person offices greater than 40 m2	🟩	🟩	quantitative	
		4.1 Compliance with the requirements for reverberation time T(target) and the requirements for inclusion	🟩	🟩	quantitative	
		5.1 Compliance with the recommendations for the A/V ratio in the frequency range 250-2000 Hz	🟩	🟩	quantitative	
	SOC1.4	**Visual Comfort**				
		1.1 Daylight Factor (DF)	🟩	🟩	quantitative	YES, this criteria falls under the quantitative category of this thesis
		2.1 Annual relative motive exposure	🟩	🟩	quantitative	
		3.1 Available lines of sight to the outside	🟩	🟩	qualitative	
		4.1 Absence of glare due to sun/glare protection system	🟩	🟥	quantitative	
		5.1 Minimum requirements for artificial light	🟩	🟩	quantitative	
		5.2 Artificial light overfulfilment	🟩	🟩	quantitative	
		6.1 Color rendering index R(a)	🟩	🟥	quantitative	
		7.1 Duration of exposure to daylight	🟩	🟨	quantitative	
	SOC1.5	**User Control**				
		1.1 Ventilation control	🟩	🟩	qualitative	NO, this criteria is not reasonable to depict digitally
		2.1 Shading and glare protection control	🟩	🟥	quantitative	
		3.1 Room temperature control during the heating period	🟩	🟥	quantitative	
		4.1 Temperature control outside of the heating period	🟩	🟥	quantitative	
		5.1 Artificial light control	🟩	🟥	quantitative	
	SOC1.6	**Quality of Indoor and Outdoor Spaces**				
		1.1 Communication zones of primary use	🟩	🟩	qualitative	YES, this criteria falls under the qualitative category of this thesis
		2.1 Additional provisions/services	🟩	🟩	qualitative	
		2.2 Navigation/information	🟩	🟨	qualitative	
		3.1 Provisions for families in the building	🟩	🟩	qualitative	
		4.1 Quality of the interior access and circulation areas	🟩	🟩	qualitative	
		5.1 Design concept for the outdoor facilities	🟩	🟩	qualitative	
		5.1.1 The design concept integrates the clever use of materials, lighting, navigation, greening and the necessary technical installations…	🟩	🟩	qualitative	
		5.1.2 Quality of outdoor areas	🟩	🟩	qualitative	
		6.1 Roof surfaces can be used	🟩	🟩	quantitative	
		6.2 Façades can be used with balconies or are greened	🟩	🟩	quantitative	
		6.3 Outdoor spaces (ground level)	🟩	🟩	quantitative	
		7.1 Fixtures and equipment in the usable outdoor areas	🟩	🟩	qualitative	
	SOC1.7	**Safety and Security**				
		1.1 Level of visibility	🟩	🟩	qualitative	YES, this criteria falls under the qualitative category of this thesis
		1.2 Level of lighting	🟩	🟩	qualitative	
		1.3 Technical safety equipment	🟩	🟩	quantitative	
	SOC2.1	**Design for All**				
		1.1 Degree of barrier-free design (level 1, DGNB minimum requirement)	🟩	🟩	quantitative	NO, already covered in ONIB Report, conclusion: about 30% could be

	SOC2.1	2.1 Degree of barrier-free design (level 2)	🟩	🟩	🟩 quantitative	🟥 depicted geometrically in the BIM model Source: ONIB (2019)
		3.1 Degree of barrier-free design (level 3)	🟩	🟩	🟩 quantitative	
		4.1 Degree of barrier-free design (level 4)	🟩	🟩	🟩 quantitative	
Technical Quality	TEC1.2	**Sound Insulation**				
		1.1 Airborne sound insulation between rooms within the own area - separating walls R'w and corridor doors Rw	🟩	🟩	🟩 quantitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		1.2 Airborne sound insulation between separating walls R'w and doors Rw	🟩	🟩	🟩 quantitative	
		1.3 Airborne sound insulation between separating ceilings R'w	🟩	🟩	🟩 quantitative	
		1.4 Airborne sound insulation between standard flanking transmission level differences Rl,w,R or Dn,f,w,R	🟩	🟩	🟩 quantitative	
		2.1 Footfall insulation of dividing ceilings and stairs	🟩	🟩	🟩 quantitative	
		2.1.1 In the own area (use of the same building)	🟩	🟩	🟩 quantitative	
		2.1.2 Insulation against noise from other areas	🟩	🟩	🟩 quantitative	
		3.1 Airborne sound insulation against outside noise	🟩	🟩	🟩 quantitative	
		4.1 Airborne sound insulation against building technical installations	🟩	🟩	🟩 quantitative	
	TEC1.3	**Quality of the Building Envelope**				
		1.1 Heat transfer coefficients	🟩	🟩	🟩 quantitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		2.1 Thermal heat bridge correction factors	🟩	🟩	🟩 quantitative	
		3.1 Airtightness measurement	🟥	🟥	🟩 quantitative	
		3.2 Joint permeability of windows and doors	🟥	🟥	🟩 quantitative	
		4.1 Summer heat protection (simplified method or simulation)	🟩	🟩	🟩 quantitative	
	TEC1.4	**Use and Integration of Building Technology**				
		1.1 Planning for a passive building concept	🟩	🟩	🟨 qualitative	🟨 YES, this criteria falls under the qualitative category of this thesis
		1.2 Implementation of a passive building concept	🟩	🟩	🟩 quantitative	
		2.1 Heat distribution and transfer system	🟩	🟩	🟩 quantitative	
		2.2 Cooling distribution and transfer system	🟩	🟩	🟩 quantitative	
		3.1 Technical facilities/generation	🟩	🟩	🟨 qualitative	
		3.2 Shafts/routes/distribution	🟩	🟩	🟨 qualitative	
		4.1 Condition and expandability of system integration	🟩	🟥	🟩 quantitative	
		4.1.1 Open and standardized protocols in existing networks	🟩	🟥	🟨 qualitative	
		4.1.2 Planning/implementation in accordance with DIN EN ISO 16484-1	🟩	🟥	🟩 quantitative	
		4.2 Integrated functions in a higher-level system	🟩	🟨	🟨 qualitative	
		4.3 Integration of the technical systems/media into the district/the immediate surroundings	🟩	🟨	🟨 qualitative	
		4.3.1 Planning of integration of the technical systems/media into the district/the immediate surroundings	🟩	🟨	🟨 qualitative	
		4.3.2 Implementation of integration of the technical systems/media into the district/the immediate surroundings	🟩	🟨	🟨 qualitative	
		4.4 Integration of the energy infrastructure into the district/the immediate surroundings	🟩	🟥	🟨 qualitative	
		4.4.1 Circular Economy Bonus - District solution for renewable energy	🟩	🟥	🟨 qualitative	
		4.4.2 Circular Economy Bonus - Grid-compatible energy system	🟩	🟥	🟩 quantitative	
	TEC1.5	**Ease of Cleaning Building Components**				
		1.1 Feasibility of façade cleaning	🟩	🟩	🟩 quantitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		2.1 Cost and effort required for cleaning exterior components	🟩	🟩	🟩 quantitative	
		2.2 Cost and effort required for cleaning interior components	🟩	🟩	🟩 quantitative	
		3.1 Ease of cleaning floor covering	🟩	🟩	🟨 qualitative	
		4.1 Dirt trap at building entrances I	🟩	🟩	🟩 quantitative	
		4.2 Dirt trap at building entrances II	🟩	🟩	🟩 quantitative	
		5.1 Obstacle prevention in the floor plan	🟩	🟩	🟩 quantitative	
		6.1 Surfaces that are frequently used and difficult to access	🟩	🟩	🟨 qualitative	
		7.1 Concept for ease of cleaning considered in the planning process	🟩	🟨	🟨 qualitative	
		7.2 Cleaning concept	🟩	🟨	🟨 qualitative	
	TEC1.6	**Ease of Recovery and Recycling**				
		1.1 Selection of easy-to-recycle construction materials and building components	🟨	🟩	🟩 quantitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		1.2 Circular Economy Bonus - Reuse or material recovery	🟨	🟩	🟩 quantitative	
		1.3 Circular Economy Bonus - Avoiding use of building components	🟨	🟩	🟩 quantitative	
		2.1 Easy-to-recover building structure and building components	🟨	🟩	🟩 quantitative	
		3.1 Recovery, conversion and ease of recycling in the early planning process	🟨	🟩	🟨 qualitative	
		3.2 Recovery, conversion and ease of recycling in the detailed design	🟨	🟩	🟨 qualitative	
	TEC1.7	**Immissions Control**				
		1.1 Noise pollution reduction measures	🟨	🟥	🟩 quantitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		2.1 Light pollution reduction measures	🟨	🟨	🟩 quantitative	
	TEC3.1	**Mobility Infrastructure**				
		1.1 Parking facilities	🟨	🟩	🟨 qualitative	🟩 YES, this criteria falls under the quantitative category of this thesis
		2.1 Circular Economy Bonus - Mobility sharing	🟨	🟩	🟩 quantitative	
		3.1 Electromobility - motorized individual transport (MIT)	🟨	🟩	🟩 quantitative	
		3.2 Electric bikes	🟨	🟩	🟩 quantitative	
		3.3 Electromobility - integration of charging stations	🟨	🟥	🟨 qualitative	
		4.1 User comfort inside the building	🟨	🟩	🟩 quantitative	
		Comprehensive Project Brief				

Process Quality	PRO1.1	1.1 Scope of requirements planning	🟩	🟥	qualitative	NO, this criteria is not applicable to be depicted digitally
		2.1 Measures for working with the public	🟩	🟥	qualitative	
		3.1 Sustainability requirements in the specifications	🟩	🟥	qualitative	
		Sustainability Aspects in Tender Phase				
	PRO1.4	1.1 Scope of integration of sustainability aspects in tender phase	🟥	🟥	qualitative	NO, this criteria is not applicable in the early design stages nor is it applicable to be depicted digitally
		1.2 Circular Economy Bonus - Recycling Materials	🟥	🟥	qualitative	
		Documentation for Sustainable Management				
	PRO1.5	1.1 Production and provision of servicing, inspection, operating and upkeep instructions	🟥	🟨	qualitative	NO, this criteria is not applicable in the early design stages
		2.1 Updating of plans, documentation and calculations to reflect the building as it has actually been built, and provision of these to the building owner	🟥	🟨	qualitative	
		3.1 Production and provision of a facility management manual	🟥	🟥	qualitative	
		4.1 Conducting of planning with BIM and provision of the BIM model	🟩	🟩	qualitative	
		Procedure for Urban and Design Planning				
	PRO1.6	1.1 Prior exploration of different design variants	🟩	🟨	qualitative	NO, this criteria is not applicable to be depicted digitally
		1.2 (alternatively) Planning competition	🟩	🟥	qualitative	
		1.2.1 Scope and quality of the planning competition	🟩	🟥	qualitative	
		1.2.2 Type of competition held	🟩	🟥	qualitative	
		1.2.3 Implementation of a prize-winning design	🟥	🟥	qualitative	
		1.2.4 Commissioning of the planning team	🟩	🟥	quantitative	
		2.1 A design recommendation by the DGNB commission has been held or the project was presented before and architectural advisory board	🟩	🟥	qualitative	
		2.2 The design recommendations by the DGNB commission or the architectural advisory board were implemented	🟩	🟥	qualitative	
		3.1 Recognition/Award	🟥	🟥	qualitative	
		3.1.1 Recognition in terms of good design "Baukultur"	🟥	🟥	qualitative	
		3.1.2 Award for the completed project (DGNB Diamond award)	🟥	🟥	qualitative	
		Construction Site/Construction Process				
	PRO2.1	1.1 Low-noise construction site concept	🟥	🟨	quantitative	NO, this criteria is not applicable in the early design stages
		1.2 Training for the parties implementing the construction work	🟥	🟨	qualitative	
		1.3 Reviewing the work implemented	🟥	🟨	qualitative	
		2.1 Low-dust construction site concept	🟥	🟨	quantitative	
		2.2 Training for the parties implementing the construction work	🟥	🟨	qualitative	
		2.3 Reviewing the work implemented	🟥	🟨	qualitative	
		3.1 Soil and groundwater protection concept	🟥	🟨	quantitative	
		3.2 Training for the parties implementing the construction work	🟥	🟨	qualitative	
		3.3 Reviewing the work implemented	🟥	🟨	qualitative	
		4.1 Low-waste construction site concept	🟥	🟨	quantitative	
		4.2 Training for the parties implementing the construction work	🟥	🟨	qualitative	
		4.3 Reviewing the work implemented	🟥	🟨	qualitative	
		4.4 Circular Economy Bonus - Waste prevention on the construction site	🟥	🟨	quantitative	
		Quality Assurance of the Construction				
	PRO2.2	1.1 Quality assurance plan	🟥	🟥	qualitative	NO, this criteria is not applicable in the early design stages
		2.1 Implementation of quality control measures	🟥	🟨	quantitative	
		2.1.1 Differential pressure has been measured before fitting work is implemented	🟥	🟨	quantitative	
		2.1.2 Thermal imaging measurement	🟥	🟨	quantitative	
		2.1.3 Reverberation period has been measured	🟥	🟨	quantitative	
		2.1.4 Sound reduction index pertaining to external noise	🟥	🟨	quantitative	
		2.1.5 Sound reduction index pertaining to interior noise	🟥	🟨	quantitative	
		2.1.6 Measurements of footfall sound level for the ceilings	🟥	🟨	quantitative	
		2.1.7 Other building relevant measurements	🟥	🟨	quantitative	
		3.1 Quality assurance for the construction products used	🟥	🟨	qualitative	
		4.1 Mould prevention	🟥	🟨	qualitative	
		Systematic Commissioning				
	PRO2.3	1.1 Creation of a monitoring concept	🟥	🟨	quantitative	NO, this criteria is not applicable in the early design stages
		2.1 Creation of a commissioning concept for scheduling	🟥	🟥	qualitative	
		3.1 Performance of a preliminary function test	🟥	🟨	quantitative	
		4.1 Performance and documentation of a function test and training for the operator	🟥	🟨	quantitative	
		5.1 Creation of a detailed final commissioning report	🟥	🟥	qualitative	
		6.1 Creation and handover of an integral operation concept	🟥	🟨	quantitative	
		7.1 Readjustment of the system following initial operating phase	🟥	🟨	qualitative	
		User Communication				
	PRO2.4	1.1 Provision of a sustainability guide for the user	🟥	🟥	qualitative	NO, this criteria is not applicable in the early design stages
		2.1 Implementation of an information system on the sustainability of the building	🟥	🟩	qualitative	
		3.1 Provision of a technical user manual	🟥	🟥	qualitative	
		FM-compliant Planning				
	PRO2.5	1.1 Performance of an FM check	🟩	🟨	qualitative	YES, this criteria falls under the qualitative category of this thesis
		2.1 Detailed operating cost projection	🟩	🟨	quantitative	
		3.1 Optimization of user/use-related energy consumption	🟩	🟨	qualitative	
		Local Environment				
		1.1 Earthquake hazard level	🟩	🟨	quantitative	🟥
		1.2 Earthquake compensation measures	🟩	🟨	qualitative	
		2.1 Volcanic eruption hazard level	🟩	🟨	quantitative	

Site Quality	SITE1.1	2.2 Volcanic eruption compensation measures	🟩	🟨	qualitative	NO, these topics are more adequately represented using GIS models which are not investigated as a part of this research
		3.1 Avalanche hazard level	🟩	🟨	quantitative	
		3.2 Avalanche compensation measures	🟩	🟨	qualitative	
		4.1 Storm hazard level	🟩	🟨	quantitative	
		4.2 Storm compensation measures	🟩	🟨	qualitative	
		5.1 Flood hazard level	🟩	🟨	quantitative	
		5.2 Flood compensation measures	🟩	🟨	qualitative	
		6.1 Heavy rain hazard level	🟩	🟨	quantitative	
		6.2 Heavy rain compensation measures	🟩	🟨	qualitative	
		7.1 Hail hazard level	🟩	🟨	quantitative	
		7.3 Hail compensation measures	🟩	🟨	qualitative	
		8.1 Landslide/subsidence hazard level	🟩	🟨	quantitative	
		8.2 Landslide/subsidence compensation measures	🟩	🟨	qualitative	
		9.1 Storm surge/tsunami hazard level	🟩	🟨	quantitative	
		9.2 Storm surge/tsunami compensation measures	🟩	🟨	qualitative	
		10.1 Hazard level for extreme climates in accordance with ESPON map	🟩	🟨	quantitative	
		10.2 Extreme climate compensation measures	🟩	🟨	qualitative	
		11.1 Forest fire hazard level	🟩	🟨	quantitative	
		11.2 Forest fire compensation measures	🟩	🟨	qualitative	
		12.1 Compliance with legally required limit values for air quality characteristics	🟩	🟥	quantitative	
		12.2 Air quality compensation measures	🟩	🟥	qualitative	
		13.1 Outdoor noise level	🟩	🟨	quantitative	
		13.2 Outdoor noise compensation measures	🟩	🟨	qualitative	
		13.3 Reduction factors apply to air traffic noise	🟩	🟥	quantitative	
		14.1 Radon concentration levels	🟩	🟥	quantitative	
	SITE1.2	**Influence on the District**				
		1.1 Site classification and evaluation	🟩	🟥	qualitative	NO, these topics are more adequately represented using GIS models which are not investigated as a part of this research
		2.1 Influence of the building on the site or the district	🟩	🟥	qualitative	
		3.1 Potential synergy due to clustering	🟩	🟥	qualitative	
		4.1 Boost in attraction due to use	🟩	🟥	qualitative	
		4.2 Boost in attraction due to spatial and design aspects	🟩	🟥	qualitative	
	SITE1.3	**Transport Access**				
		1.1 Surrounding private transportation access in the area	🟩	🟨	qualitative	NO, these topics are more adequately represented using GIS models which are not investigated as a part of this research
		1.2 Building-related private transportation access	🟩	🟨	qualitative	
		2.1 Public transit stops	🟩	🟨	quantitative	
		2.2 Access to nearest railway station	🟩	🟨	quantitative	
		2.3 Public transport frequency	🟩	🟨	quantitative	
		2.4 Building-related public transportation access	🟩	🟨	qualitative	
		3.1 Cycle paths	🟩	🟨	quantitative	
		3.2 Bicycle access	🟩	🟨	qualitative	
		3.3 Building-related bicycle access	🟩	🟨	qualitative	
		4.1 Pedestrian path network	🟩	🟨	qualitative	
		4.2 Pedestrian crossing possibilities	🟩	🟨	qualitative	
		4.3 Pedestrian signage	🟩	🟨	qualitative	
		5.1 Barrier-free access to nearby public transport stops	🟩	🟨	quantitative	
		5.2 Barrier-free design of the path to the building and the area surrounding it	🟩	🟨	qualitative	
	SITE1.4	**Access to Amenities**				
		1.1 Social infrastructure within the district/surrounding area (education, leisure, playgrounds, sports facilities)	🟩	🟨	quantitative	YES, this criteria falls under the qualitative category of this thesis
		1.2 Opportunity to use rooms within the building and outdoor facilities	🟩	🟩	qualitative	
		1.2.1 Opportunities to hire rooms and use spaces within the building	🟩	🟩	qualitative	
		1.2.2 Opportunities to use spaces in the building's outdoor facilities	🟩	🟩	qualitative	
		2.1 Commercial infrastructure within the district/surround area (local supply, food and catering, other services - bank, post office, etc., medical services)	🟩	🟨	quantitative	
		3.1 Variety of uses within the building	🟩	🟩	qualitative	
		3.2 Circular Economy Bonus - Facilities that cater for people's day-to-day needs and provide meeting points for interactions	🟩	🟥	qualitative	

Information Requirements for SOC1.7 - Safety and Security - Office Buildings

Indicator	Indicator Explanation	Documented via	Check via	Logical Check	Additional Parameters Required?	Type of Parameter	Model Object Type	IFC Entity	IFC Type	IFC Parameter	Attribute Name	Attribute Explanation	Attribute Data Type	Units	Default Value	Discipline	LOD
1.1	Level of Visibility	model checking	model check of distance between components	Check 1: are there visual obstructions within 10 m of entrances?	no	IFC Parameter	Door	IfcDoor	IfcDoorStyle	[-]	[-]	[-]	double	[m]	10 m	Architecture	LOD 200
		model checking	model check of distance between components	Check 2: are there visual obstructions within 5 m of main paths and thoroughfares?	no	IFC Parameter	Path	IfcRoof *the sidewalk element was added as a roof in order to be able to give it a	[-]	[-]	[-]	[-]	double	[m]	5 m	Architecture	LOD 200
		model checking	model check of distance between components	Check 3: are there visual obstructions within 5 m of parking areas?	no	IFC Parameter	Parking Lot	IfcSlab	[-]	[-]	[-]	this attribute defines if there are any obstructions within 10 m of parking areas	double	[m]	5 m	Architecture	LOD 200
		[-]	[-]	Check 4: is there comprehensive sign posting around the building?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	LOD 500
		model checking	visual check	Check 5: is there a visual link between offices and general spaces?	no	IFC Parameter	Window Space	IfcWindow IfcSpace	IfcWindowStyle	[-]	[-]	[-]	boolean	[yes/no]	yes	Architecture	LOD 200
		model checking	visual check	Check 6: is there a visual link between meeting rooms and general spaces?	no	IFC Parameter	Window Space	IfcWindow IfcSpace	IfcWindowStyle	[-]	[-]	[-]	boolean	[yes/no]	yes	Architecture	LOD 200
		spatial attribute	visual check	Check 7: is there a visual link from entrances to the parking areas?	yes	Custom - Shared Parameter	Door	IfcDoor	IfcDoorStyle	[-]	SOC1.7_VisualLinkParkingArea	this attribute defines if there is a visual link between entrances and parking areas	boolean	[yes/no]	yes	Architecture	LOD 200
		spatial attribute	visual check	Check 8: is there a visual link from entrances to public transit stations?	yes	Custom - Shared Parameter	Door	IfcDoor	IfcDoorStyle	[-]	SOC1.7_VisualLinkPublicTransit	this attribute defines if there is a visual link between entrances and public transit stations	boolean	[yes/no]	yes	Architecture	LOD 200
				If yes, safety and security in the building and on the site is improved													
1.2	Level of Lighting	spatial attribute	simulation	Check 1: do all thoroughfares have a minimum lighting of at least 5 lux? (based on DIN EN 12464-1)	no	IFC Parameter	Exterior Lighting	IfcFlowTerminal	IfcLightFixtureType	illuminance	[-]	[-]	double	[lux]	5	Electrical	LOD 300
		spatial attribute	simulation	Check 2: do all paths to carparks have a minimum lighting of at least 10 lux? (based on DIN EN 12464-1)	no	IFC Parameter	Exterior Lighting	IfcFlowTerminal	IfcLightFixtureType	illuminance	[-]	[-]	double	[lux]	10	Electrical	LOD 300
		spatial attribute	simulation	Check 3: do all paths to bicycle parking have a minimum lighting of at least 15 lux? (based on DIN EN 12464-1)	no	IFC Parameter	Exterior Lighting	IfcFlowTerminal	IfcLightFixtureType	illuminance	[-]	[-]	double	[lux]	15	Electrical	LOD 300
		spatial attribute	simulation	Check 4: do all publicly accessible outdoor spaces have a minimum lighting of at least 10 lux? (based on DIN EN 12464-1)	no	IFC Parameter	Exterior Lighting	IfcFlowTerminal	IfcLightFixtureType	illuminance	[-]	[-]	double	[lux]	10	Electrical	LOD 300
				if yes, there is adequate lighting in outdoor areas to improve safety and security													
1.3	Technical Safety Equipment	model checking	model check of presence of component	Check 1: has at least one emergency telephone been installed in the building?	no	IFC Parameter	Telephone	IfcFlowTerminal	[-]	[-]	[-]	[-]	[-]	[-]	[-]	Electrical	LOD 300
		model checking	model check of presence of component	Check 2: has CCTV been installed to cover the entire exterior of the building?	no	IFC Parameter	CCTV	IfcFlowTerminal	[-]	[-]	[-]	[-]	[-]	[-]	[-]	Electrical	LOD 300
		model checking	model check of presence of component	Check 3: has a PA system been provided in the offices?	no	IFC Parameter	Speaker	IfcFlowTerminal	[-]	[-]	[-]	[-]	[-]	[-]	[-]	Electrical	LOD 300
		model checking	model check of presence of component	Check 4: has a voice alarm system been installed in the building?	no	IFC Parameter	Voice Alarm	IfcDistributionControlElement	IfcAlarmType	[-]	[-]	[-]	[-]	[-]	[-]	Electrical	LOD 300
				if one of these measures has been implemented half the points are awarded (15 pts) *if ≥ 2 of these measures have been implemented all points are awarded (30 pts)*													
1.4	Preventative Safety Measures	**does not apply to office buildings according to DGNB*															

Information Requirements for TEC1.5 - Ease of Cleaning Building Components - Office Buildings

Indicator	Indicator Explanation	Documented via	Check via	Logical Check	Additional Parameters Required?	Type of Parameter	Model Object Type	IFC Entity	IFC Type	IFC Parameter	Attribute Name	Attribute Explanation	Attribute Data Type	Units	Default Value	Discipline	LOD
1.1	Feasibility of façade cleaning with or without aids	component attribute	logical check of component attribute	Check 1: does window open inwards?	yes	Custom - Shared Parameter	Window	IfcWindow	IfcWindowStyle	[-]	TEC1.5_WindowOpeningInwards	this attribute defines if it is true that the window opens inwards	boolean	[yes/no]	yes	Architecture	LOD 200
		component geometry	model geometry	Check 2: is distance from floor to top of window approx. 4 m?	no	IFC Parameter	Window Curtain Wall	IfcWindow IfcCurtainWall	IfcWindowType IfcCurtainWallType	Top Elevation	[-]	[-]	double	[m]	4 m	Architecture	LOD 200
				If yes, window can be cleaned without aid (determine total %) *if no, window requires cleaning aid (determine total %)*													
2.1	Cost and effort required for cleaning exterior components	component attribute	logical check of component attribute	Check 1: is the component an exterior surface?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	Pset_WallCommon	IsExternal	[-]	[-]	boolean	[yes/no]	yes	Architecture	LOD 200
		component attribute	logical check of component attribute	Check 2: does exterior component have dirt-repellent surface properties?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	IfcWallType	Material	[-]	this attribute defines a dirt-repellent surface layer on exterior walls	List <string>	[Dirt-Repellent Exterior Coating]	= Dirt-Repellent Exterior Coating	Architecture	LOD 300
		component geometry	visual model check	Check 3: are there drip edges or eaves above the exterior surface?	yes	Custom - Shared Parameter	Roof	IfcRoof	[-]	[-]	TEC1.5_RoofEaves	this attribute defines if there are eaves included as a part of the roof structure	boolean	[yes/no]	yes	Architecture	LOD 200
		component attribute	logical check of component attribute	Check 4: are there splash protectors (skirting boards) around the bottom of the exterior walls?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	IfcWallType	Material	[-]	this attribute defines if certain exterior walls have a splash protectant surface coating	List <string>	[Splash Protector]	= Splash Protector	Architecture	LOD 300
				if yes, there can be a reduction of cleaning agents, a reduction of cleaning process duration, and an increase in intervals between cleaning													
2.2	Cost and effort required for cleaning interior components	component attribute	logical check of component attribute	Check 1: is the component an interior surface?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	Pset_WallCommon	IsExternal	[-]	[-]	boolean	[yes/no]	no	Architecture	LOD 200
		component attribute	logical check of component attribute	Check 2: does interior component have dirt-repellent surface properties?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	IfcWallType	Material	[-]	this attribute defines a dirt-repellent surface layer on interior walls	List <string>	[Dirt-Repellent Interior Coating]	= Dirt-Repellent Interior Coating	Architecture	LOD 300
		component attribute	logical check of component attribute	Check 3: are there splash guards around water areas?	no	IFC Parameter	Surface/Wall	IfcWallStandardCase	IfcWallType	Material	[-]	this attribute defines if certain interior walls have a splash guard surface coating	List <string>	[Splash Guard]	= Splash Guard	Architecture	LOD 300
				if yes, there can be a reduction of cleaning agents, a reduction of cleaning process duration, and an increase in intervals between cleaning													
3.1	Ease of cleaning floor coverings	component attribute	logical check of component attribute	Check 1: is the flooring located in a circulation area?	yes	Custom - Shared Parameter	Floor	IfcSlab	[-]	[-]	TEC1.5_FloorCirculationZone	this attribute defines if the floor is located in a circulation zone	List <string>	[Carpet Circulation Zones]	= Carpet Circulation Zones	Architecture	LOD 200
		component attribute	logical check of component attribute	Check 2: is the floor covering patterned, mottled or structured?	yes	Custom - Shared Parameter	Floor	IfcCovering	[-]	[-]	TEC1.5_FlooringPatternedMottled Structured	this attribute defines if the flooring can be classified as either patterned, mottled or structured	boolean	[yes/no]	yes	Architecture	LOD 300
		component attribute	logical check of component attribute	Check 3: are carpet tiles used?	yes	Custom - Shared Parameter	Floor	IfcCovering	[-]	[-]	TEC1.5_FloorCarpetTiles	this attribute defines if carpet tiles were used in applicable areas	boolean	[yes/no]	yes	Architecture	LOD 300
				If yes, the floor covering can be cleaned more easily													
4.1	Dirt traps at all main building entrances	component attribute	logical check of several component attributes	Check 1: are there grates or mats located directly at every entrance?	yes	Custom - Shared Parameter	Door	IfcDoor	IfcDoorStyle	[-]	TEC1.5_DirtTrapAtEntrance	this attribute defines if there is a dirt trap located at each external door	boolean	[yes/no]	yes	Architecture	LOD 300
				If yes, there are suitable dirt traps at every entrance													
4.2	dirt traps with a multi-step principle	component geometry	model geometry	Check 1: is the dirt trap approx. 2.4 m in length?	no	IFC Parameter	Floor	IfcCovering	[-]	Dimensions.Lengte	[-]	[-]	double	[m]	2.4 m	Architecture	LOD 300
		component geometry	model geometry	Check 2: is the dirt trap approx. 4 m in length?	no	IFC Parameter	Floor	IfcCovering	[-]	Dimensions.Lengte	[-]	[-]	double	[m]	4.0 m	Architecture	LOD 300
				If yes, the dirt trap meets either the 3 or 5-step principle													
5.1	Obstacle Prevention	component attribute	logical check of component attribute and model geometry	Check 1: are there radiators? Check 2: if yes, do they have a ground clearance ≥ 15 cm?	no	IFC Parameter	Radiator	IfcFlowTerminal	[-]	bottom elevation	[-]	[-]	double	[m]	> 0.15	MEP	LOD 300
		component attribute	logical check of component attribute	Check 3: are railing supports attached laterally?	yes	Custom - Shared Parameter	Railings	IfcRailing	[-]	[-]	TEC1.5_RailingSupportsAttached Laterally	this attribute defines if the railing supports are attached laterally to minimize horizontal components that could make cleaning the floors more difficult	boolean	[yes/no]	yes	Architecture	LOD 300
		component attribute	logical check of component attribute	Check 4: are toilets attached to the wall and not the floor?	no	IFC Parameter	Toilet	IfcFlowTerminal	[-]	bottom elevation	[-]	[-]	double	[m]	> 0.15	MEP	LOD 300
		component attribute	logical check of component attribute	Check 5: are sinks attached to the wall and not the floor?	no	IFC Parameter	Sink	IfcFlowTerminal	[-]	bottom elevation	[-]	[-]	double	[m]	> 0.15	MEP	LOD 300
		component attribute	logical check of several component attributes	Check 6: are separating walls created without floor support points?	no	IFC Parameter	Wall	IfcWallStandardCase	IfcWallType	bottom elevation	[-]	[-]	double	[m]	> 0.15	Architecture	LOD 300
		model checking	model check of several component attributes	Check 7: are free-standing supports at least 20 cm from surrounding components?	no	IFC Parameter	Column/Support	IfcColumn	[-]	location	[-]	[-]	double	[m]	> 0.20	Architecture	LOD 200
		component attribute	logical check of component attribute	Check 8: is the lighting recesses in ceiling?	no	IFC Parameter	Lighting	IfcFlowTerminal	IfcLightFixtureType	[-]	[-]	[-]	boolean	[yes/no]	yes	MEP	LOD 350
		zone attribute	visual model check	Check 9: are there built-in closets available?	no	IFC Parameter	Room	IfcZone	[-]	Name	[-]	[-]	List <string>	[Storage]	= Storage	Architecture	LOD 200

				if yes, then obstacles are adequately prevented													
6.1	Surfaces that are frequently used and difficult to clean	component attribute	visual model check	Check 1: are work surfaces uninterrupted?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	LOD 400
		component attribute	visual model check	Check 2: are durable handles and doorknobs without intricate details used?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	LOD 400
		component attribute	visual model check	Check 3: are light switches and lift buttons flat with space between them?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	LOD 400
		component attribute	logical check of component attribute	Check 4: can hanging lights be reached with a small ladder/step-stool (less than 4 m from floor)?	no	IFC Parameter	Lighting	IfcFlowTerminal	IfcLightFixtureType	bottom elevation	[-]	[-]	double	[m]	< 4.0	MEP	LOD 300
		component attribute	logical check of component attribute	Check 5: can sun protection be reached with a small ladder/step-stool (less than 4 m from floor)?	no	IFC Parameter	Sun Shade	IfcBuildingElementProxy	IfcBuildingElementProxy Type	bottom elevation	[-]	[-]	double	[m]	< 4.0	Architecture	LOD 300
		component attribute	logical check of component attribute	Check 6: can shelves, cabinets and ledges be reached with a small ladder/step-stool (less than 4 m from floor)?	no	IFC Parameter	Furniture	IfcFurnishingElement	IfcSystemFurnitureElement Type	top elevation	[-]	[-]	double	[m]	< 4.0	Architecture	LOD 300
				if yes, then frequently used surfaces have been made easier to clean													
7.1	Consideration in the planning process	[-]	[-]	Check 1: was cleaning considered in the planning phase?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
				if yes, then this indicator is fulfilled													
7.2	Cleaning concept	[-]	[-]	Check 1: was a detailed cleaning concept created?	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
				if yes, then this indicator is fulfilled													

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Master-Thesis selbstständig angefertigt habe. Es wurden nur die in der Arbeit ausdrücklich benannten Quellen und Hilfsmittel benutzt. Wörtlich oder sinngemäß übernommenes Gedankengut habe ich als solches kenntlich gemacht.

Ich versichere außerdem, dass die vorliegende Arbeit noch nicht einem anderen Prüfungsverfahren zugrunde gelegen hat.

München, 25. November 2020 [redacted]

Vorname Nachname

Lena Drewes

[redacted]

[redacted]

[redacted]