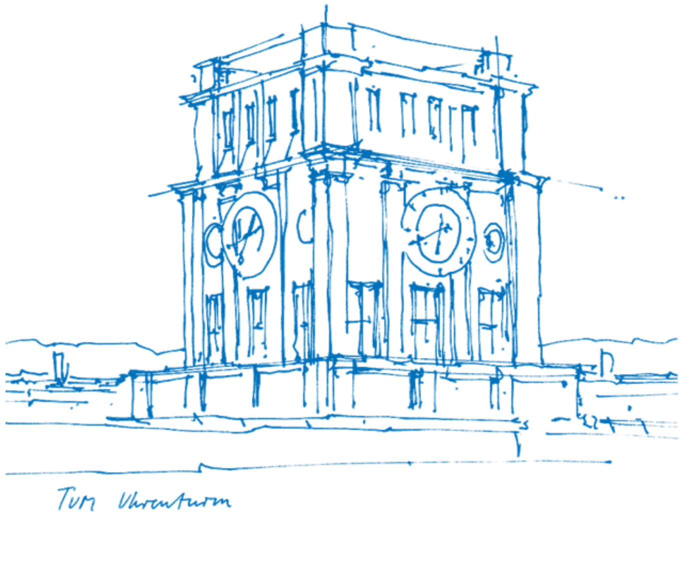
Technische Universität München
TUM School of Engineering and Design

Machine-Interpretable BIM-based Communication and Design Decisions Documentation

Ata Zahedi



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Abstract

Construction projects are characterized by their interdisciplinary and collaborative nature, requiring consideration of various criteria, regulations, and standards during the design process. The increasing complexity of information in building design necessitates the involvement of multidisciplinary design teams. However, the exchange of vast amounts of information among domain specialists and stakeholders poses challenges to decision-making.

Efficient management of information and knowledge in building design has become a pressing issue due to the wide range of stakeholders involved and the need for effective representation, documentation, and communication. Particularly in the early stages of design, when information is limited and uncertainty is high, critical design decisions must be made without sufficient data.

Without comprehensive design process documentation, valuable insights and solutions from previously finished projects are lost, leading to increased time and cost, errors, and redundant work. To address these challenges, this dissertation aims to leverage the BIM methodology to achieve minimized model-based design communication and machine-interpretable documentation of design decisions. This will facilitate partial reusability and enhance transparency in the BIM-based building design process.

This dissertation proposes a framework for comprehensive digital documentation of the design process by introducing the concepts of ***Design Episodes*** and ***Explanation Tags***. Additionally, the concept of ***Feedback Mechanism*** enables adaptive detailing of design models by incorporating model-based suggestions from domain experts during the early stages of design. By harnessing the capabilities of BIM methodology and introducing these novel concepts, the dissertation seeks to improve communication, documentation, and decision-making in the building design process.

Zusammenfassung

Bauprojekte zeichnen sich durch ihren interdisziplinären und kooperativen Charakter aus und erfordern die Berücksichtigung verschiedener Kriterien, Vorschriften und Normen während des Entwurfsprozesses. Die zunehmende Komplexität der Informationen in der Gebäudeplanung macht die Einbeziehung multidisziplinärer Planungsteams erforderlich. Der Austausch großer Informationsmengen zwischen Fachleuten und Projektbeteiligten stellt jedoch eine Herausforderung für die Entscheidungsfindung dar.

Effizientes Informations- und Wissensmanagement in der Gebäudeplanung ist zu einem dringenden Problem geworden, da eine Vielzahl von Projektbeteiligten involviert ist und eine effektive Darstellung, Dokumentation und Kommunikation erforderlich ist. Besonders in den frühen Entwurfsphasen, wenn die Informationen begrenzt und die Unsicherheit groß ist, müssen kritische Entwurfsentscheidungen ohne ausreichende Daten getroffen werden.

Ohne eine umfassende Dokumentation des Entwurfsprozesses gehen wertvolle Erkenntnisse und Lösungen aus bereits abgeschlossene Projekten verloren, was zu einem erhöhten Zeit- und Kostenaufwand, Fehlern und redundanter Arbeit führt. Um diesen Herausforderungen zu begegnen, zielt diese Dissertation darauf ab, die BIM-Methodik zu nutzen, um eine minimierte modellbasierte Entwurfskommunikation und eine maschineninterpretierbare Dokumentation von Entwurfsentscheidungen zu erreichen. Dies wird die Teilwiederverwendbarkeit erleichtern und die Transparenz im BIM-basierten Bauplanungsprozess erhöhen.

Durch die Einführung der Konzepte Design Episoden und Explanation Tags wird in dieser Dissertation ein Rahmen für die vollständige digitale Dokumentation des Entwurfsprozesses vorgeschlagen. Darüber hinaus ermöglicht der Feedback-Mechanismus die adaptive Detaillierung von Entwurfsmodellen durch die Einbeziehung modellbasierter Vorschläge von Fachleuten. Durch die Nutzung der Möglichkeiten der BIM-Methodik und die Einführung dieser neuen Konzepte soll die Dissertation die Kommunikation, Dokumentation und Entscheidungsfindung im Gebäudeentwurfsprozess verbessern.

Acknowledgment

This dissertation was written during my work as a research assistant at the Chair of Architectural Informatics at the Technical University of Munich. Many people have supported me in this process, and I would like to express my sincere gratitude to all of them.

First and foremost, to my beloved wife Katharina, your unwavering love, encouragement, and patience have been the bedrock of my strength throughout this endeavor. Your belief in me, even at the most challenging times, has been a source of inspiration and motivation. Thank you, my love, for being my biggest supporter. And to my soon to be born angel, the anticipation of your arrival has filled my heart with joy and hope. You are a constant reminder of why I strive to be the best version of myself.

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To my colleagues, whether in the Early-BIM research group or at the chair of Architectural Informatics, and friends, thank you for your support, intellectual stimulation and shared experiences that have enriched this journey. Your support, whether through collaboration or simply lending an ear, has made this process more manageable and enjoyable.

Finally, I would like to express my gratitude to all the students who participated in different projects and theses or worked as assistants at the chair of Architectural Informatics. Your hard work, enthusiasm, and dedication have played a crucial role in bringing these ideas to life.

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Glossary

AEC (Architecture, Engineering, and Construction)

An industry that encompasses the fields of architecture, engineering, and construction, focusing on the design, planning, and development of buildings and infrastructure.

BCF (BIM Collaboration Format)

A standardized format used in Building Information Modeling (BIM) to facilitate communication, collaboration, and issue tracking within construction projects.

BDL (Building Development Level)

A new concept, which was introduced by Abualdenin & Borrmann (Abualdenien and Borrmann 2019) to describe the maturity of the overall building model. “A BDL can be conceived as a milestone where specific decisions need to be made. At the same time, each BDL can be used by engineers to specify the required building elements and their maturity to carry out a model analysis.”

BIM (Building Information Modeling)

A digital representation of a building's physical and functional characteristics allowing for enhanced collaboration, visualization, and data management in the AEC industry.

CAD (Computer-Aided Design)

The use of computer software to assist in the creation, modification, and optimization of design and engineering processes.

CBD (Case-Based Design)

A design approach that leverages previous design cases as references to inform and inspire new design solutions.

CBR (Case-Based Reasoning)

A problem-solving method that uses past cases and their solutions as a basis for solving new, similar problems.

Common Data Environment (CDE)

A centralized digital platform in BIM that facilitates collaborative storage, access, and management of project data to ensure accuracy and consistency among project stakeholders.

DDD (Design Documents' Deficiencies)

Refers to the identification of flaws or shortcomings in design documents and drawings in the context of construction projects.

DE (Design Episode)

A new concept introduced in this dissertation that embodies a specific chapter or episode within the design BIM-model, often characterized by addressing a specific design challenge or dilemma and a set of distinct design elements joined with an explanatory description that illustrates the solution to that design task or milestone.

DFG (Deutsche Forschungsgemeinschaft)

The German Research Foundation, responsible for promoting and supporting research in Germany.

DIKW (Data Information Knowledge Wisdom)

A hierarchy that represents the stages of knowledge evolution, from raw data to information, knowledge, and ultimately wisdom.

ET (Explanation Tag)

A new concept, introduced in this dissertation, to provide explanations or additional context within a design BIM-model to document and elaborate on the design decisions' rationale and reasoning.

HOAI (Honorarordnung für Architekten und Ingenieure)

A fee scale in Germany that governs the compensation of architects and engineers for their services.

IBIS (Issue-Based Information System)

A system that focuses on the organization and management of information related to issues, typically within the context of a project.

IFC (Industry Foundation Classes)

A standardized data format used in BIM to exchange and share information across different software applications.

IP (Intellectual Property)

Legal rights associated with creations of the mind, such as inventions, designs, and artistic works.

LOD (Level of Development)

A term used in BIM to describe the level of detail and accuracy of a building model at various stages of a project.

LPH (Leistungsphasen)

A German term referring to the different phases in the architectural design process.

NER (Named Entity Recognition)

A natural language processing technique used to identify and categorize named entities, such as names of people, places, and organizations, within text.

NIBS (National Building Information Modeling Standard)

A set of guidelines and standards developed to promote consistent practices in BIM within the United States.

NLP (Natural Language Processing)

A field of artificial intelligence that focuses on the interaction between computers and human language, enabling machines to understand and generate human language.

OWL (Web Ontology Language)

A computer language used to represent and reason about knowledge and data in a machine-readable format.

PCM (Propose-Critique-Modify)

A design methodology that involves proposing design solutions, receiving feedback or critiques, and making modifications accordingly.

POS (Part-of-Speech)

A linguistic term used to classify words into categories like nouns, verbs, adjectives, and adverbs based on their grammatical functions.

RDF (Resource Description Framework)

A framework for representing information about resources on the web, often used in the context of semantic web technologies.

RFP (Request for Proposal)

A formal document used to solicit proposals, bids, or quotations from potential vendors or contractors for a specific project.

SNAP (Systematik für Nachhaltigkeitsanforderungen in Planungswettbewerben)

A German term that refers to a system for sustainability requirements in planning competitions.

TDK (Tacit Design Knowledge)

Design knowledge that is not explicitly documented but exists within the minds of designers based on their experiences and expertise.

UI (User Interface)

The point of interaction between a user and a computer system, often involving elements like menus, buttons, and screens that facilitate user interaction.

1. Introduction

This chapter explains the research question and problem definition, followed by the approach and contributions of this dissertation. The chapter starts by describing the current situation and follows by addressing the research gap and critical remarks. Afterward, the goal of this work, the proposed approach to tackle the research gap, and the structure of this dissertation will be explained.

The core of the present work is the architectural design process and the question of how to facilitate machine-interpretable communications and documentation of design decisions rationale. Above all, this work is motivated by the fact that various architectural design projects contain valuable design knowledge and expertise that can be used as sources of inspiration or as possible answers to repeating design challenges (Gallagher 2022). This work follows an interdisciplinary approach and deals with topics from architecture and design, building information modeling, model-based communication, and knowledge management. First, the situation as it is today will be discussed to understand this better. Based on this discussion, relevant questions and the goals of the work will be formulated.

1.1. The current situation

Architectural building design is a crucial part of the Architecture, Engineering, and Construction (AEC) industry, as it is responsible for designing and creating the built environment. The AEC industry is a vital sector of the global economy. Based on research by Market Business Insights[1], the worldwide AEC (Architecture, Engineering, and Construction) market is on track for substantial growth in the coming decade. They predict a solid annual growth rate of 10.2%. This growth is expected to translate into a market size of around $16.5 billion by 2030, a significant jump from the $8.9 billion recorded in 2022. According to data from the US Census Bureau (U.S. Census Bureau 2023), the AEC industry was valued at over $1.8 trillion in 2022 in the USA alone, making it a significant contributor to the national economy. In addition, the AEC industry employs millions of people worldwide, with the construction sector alone employing over 9 million people just in the United States, according to data from the Bureau of Labor Statistics (Gallagher 2022). The importance of the AEC industry goes beyond its economic contributions, as it plays a crucial role in the design, development, and maintenance of infrastructure, buildings, and other structures essential to modern society, providing shelter and a sense

[1] https://www.linkedin.com/pulse/architecture-engineering-construction-aec-market-size-rahul-dhabe/

of place. From offices and residential buildings to hospitals and schools, architectural design plays a vital role in shaping our built environment.

Designing a building is a problem-solving activity starting with the client's needs which are translated into a design task. Throughout the design process, the design task and its solutions co-evolve. The reason is that as the design progresses, much more knowledge about the design task and the client's requirements is gathered compared to the beginning. It involves a complex and iterative process that requires the coordination of numerous factors and stakeholders. Designing a building is a time-consuming process that necessitates careful planning and attention to detail in order to deliver a successful solution.

Several intermediary states and design phases must be completed before reaching the final detailed construction documents. The architect initiates the process with program development and site analysis based on the client's needs, derived from the design brief or request for proposal (RPF). The next step is the schematic design, which involves outlining the features and functions of the intended building, along with a rough idea of its size, shape, and layout. Next, the architect refines the schematic design and creates more detailed plans, including floor plans, sections, and elevations.

The design development phase is an iterative process, and the designs may undergo several revisions as they are refined. During this phase, the architect generates and manipulates various design variants, evaluates and compares them to determine which variant best meets the requirements and goals, and selects the most suitable variants at each step. The chosen variants at each stage are further detailed until the final design solution is reached.

Moreover, architectural design ideas and goals are often subjective and constantly evolving during the design process. Due to the widespread social engagement of architectural design and planning, design goals are several and sometimes express inconsistent and even contradictory objectives and concerns. For instance, the objective of creating a highly energy-efficient building may conflict with the client's budget or the goal of creating a visually striking structure.

Another challenge arises from the subjective nature of design goals, which can vary or be interpreted differently by different stakeholders. The interests of diverse parties are frequently difficult to define and grasp, let alone combine into a single, conclusive position or viewpoint (Cao and Protzen 1999). Figure 1 shows the different interpretations of the same design among parties involved in the planning and construction. Thus, it is often problematic and requires compromises to reconcile these conflicting goals and develop a design that meets the needs and expectations of all stakeholders.

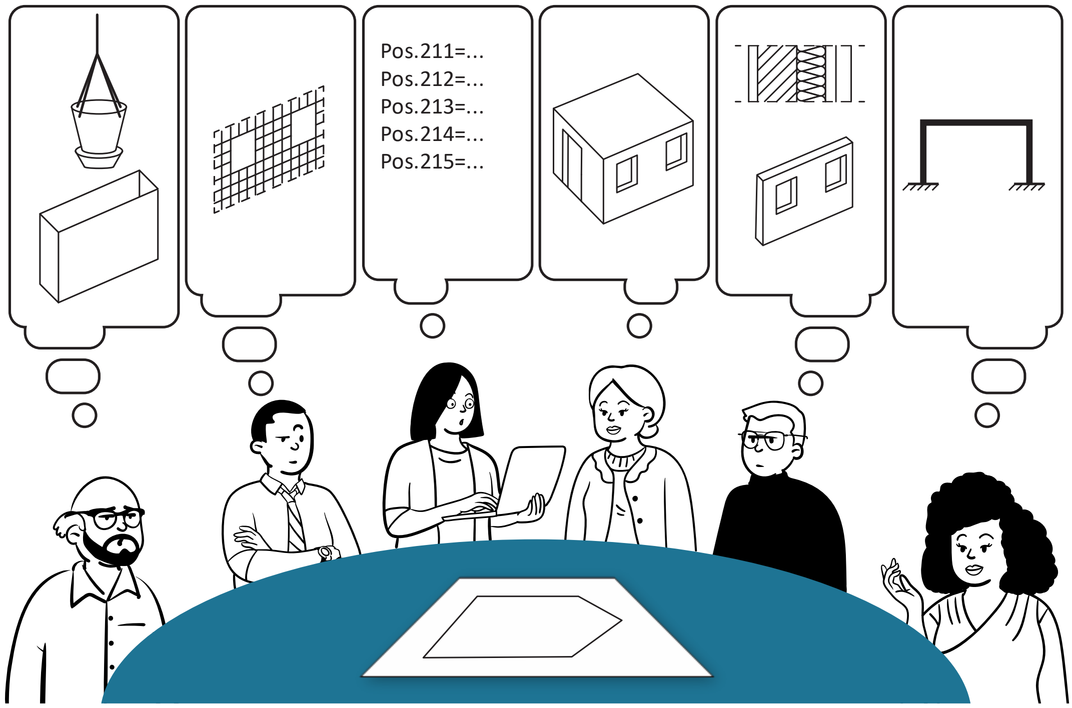

Figure 1 - Different interpretations of the same design among parties involved in the planning and construction based on (Junge and Liebich 1997)

Digitalization has altered a wide range of industrial sectors over the previous decade, resulting in massive increases in productivity, product quality, and product diversity. Likewise, the AEC nowadays is in the midst of a digital transformation, with many organizations adopting digital technologies to improve efficiency, accuracy, and collaboration. Some of the key areas where digitalization is having a significant impact on the AEC industry may include but are not limited to Building Information Modeling (BIM), additive manufacturing (3D printing), new project- and knowledge-management methods, Artificial Intelligence (AI), and data analytics. Digital technologies are rapidly being used in the AEC sector to plan, construct, and operate buildings. However, compared to other industry fields, the continuous utilization of digital information and knowledge throughout the planning and production chain lags substantially (Borrmann et al. 2018b, p. 2). All too often, important design decisions during the early stages of design are made based on the rule of thumb or general assumptions due to a lack of information, making it impossible to ask for expert opinion via analysis and simulation. Only the final design is often delivered, sometimes in BIM models, but the intermediate design variants are not stored or documented. All too frequently, essential information and knowledge are lost since important argumentations and design knowledge are rarely documented.

Furthermore, design information is still mostly communicated through drawings, either as printed plots on paper or in a constrained digital format. Such interruptions in information flow occur throughout the entire lifecycle of a building, including the design, construction, and operation, as well as during critical handovers between these phases (Eastman et al. 2011). Figure 6 in Chapter 3.3 shows this continuous loss of information caused by disruptions in the digital information flow (Borrmann et al. 2018b, p. 3).

1.2. Problem statement

Architectural design knowledge is mainly tacit and held by key individuals with extensive experience in various projects (Joe et al. 2013). These key individuals will leave their organizations sooner or later due to retirement or other reasons, taking their experience and expertise with them. Organizations must capture and document the tacit knowledge that older employees hold before their leave. Suppose a strategy to capture such tacit knowledge is not put in place. In that case, many knowledge-intensive organizations will constantly lose important knowledge that cannot be recovered when people depart (Calo 2008). Needless to say that construction engineering and architecture firms are among these knowledge-intensive organizations. In building design practice, accurate and unambiguous documentation and capturing of design reasoning and argumentation, as well as its transparent communication to diverse stakeholders and decision-makers, are yet missing to a large extent. A review and assessment study of the causes of deficiencies in design documents for large-scale construction projects done by Assaf et al. (Assaf et al. 2018) stated the lack of knowledge transfer mechanism and cross-disciplinary coordination among the most significant causes of design documents' deficiencies (DDD).

Moreover, the AEC industry faces some unique and challenging boundary conditions. Above all, in this industry, the process and value creation chain, comprising architectural offices, engineering consultancies, and construction companies, are distributed throughout a vast number of small or medium size companies rather than being controlled by a handful of large organizations (Borrmann et al. 2018b, p. 3). These various actors and companies usually only work together throughout a particular project and not for an extended period (Borrmann et al. 2018b, p. 3).

The move to digital, model-based product development and production has already been made by other industry sectors, like the automobile industry, allowing them to gain considerable efficiency benefits (Kagermann 2015). With the help of BIM methodology and cloud computing, we can centralize the storage and management of all design documents and plans and give the right people at the right place access to the most updated version of the project documents—for example, a domain expert to run analysis or on-site constructors to assemble some building parts.

However, due to the fragmented nature of the AEC industry, within this ad hoc network of companies exists various working methods and several software solutions and interfaces where digital information must be transferred. Even in more advanced companies already utilizing BIM authoring tools for design, most communications between architects and engineers still occur outside these BIM platforms through emails and telephone calls. Although some closed BIM solutions and platforms offer model-based communication and collaboration features, most of these communications remain human-interpretable, relying on screenshots, annotations, and comments that are not understandable to computers.

In summary, machine-interpretable and transparent documentation of design decisions, as well as effective communication with domain specialists, are lacking in today's architectural practices. These issues are the focus of the present work, and the aim is to address these challenges in this dissertation.

1.3. The goal of the work

The early stages of design often lack proper model-based communications among experts. Architects frequently rely on their experience and intuition to navigate the absence of objectifiable evaluations for critical early-stage design decisions when faced with insufficient details in their design models, which are required for analysis or simulations. Additionally, architects often struggle to articulate and document their design intentions, justifications, and logic because no standardized framework exists for defining, approving, and utilizing various subjective architectural assessment criteria. As a result, the tacit design knowledge in architecture is often undocumented and, therefore, inaccessible for reuse, given these unique characteristics and complexities.

The lack of a standardized framework for documenting the design process within architectural firms as well as the whole construction industry leads to a significant loss of the companies' intellectual property and collective design knowledge and expertise. This valuable knowledge becomes untraceable and unusable for other colleagues. Preserving intellectual property (IP) and managing knowledge in architectural firms remains a significant challenge due to the implicit nature of architectural design knowledge and the difficulty in capturing it.

Given the aforementioned critical remarks, this work aims to bridge the gap by introducing new concepts and methods that harness the existing capabilities of BIM methodology and enhance them, thus achieving model-based machine-interpretable communication among experts and documentation of design decisions. Consequently, this facilitates the partial reuse of architectural tacit design knowledge embedded within various design decisions.

It is essential to acknowledge the diverse requirements present in different architectural design projects as well as the architects' individuality. The strategy proposed in this work is an adaptive and modular system that offers the necessary flexibility to adjust to the specific demands of various design challenges and can be applied in various situations.

Importantly, these concepts are not intended to dominate or hinder the flow or authority of architects. Accordingly, the proposed concepts and methods aim to assist architects in preserving their design knowledge and provide them with new inspirations and a pool of ideas. This enhances the design process and promotes creative design. In other words, these concepts are intended to support architects without interfering with, disturbing, or patronizing their creative design activities.

In summary, the following are the main objectives and goals of this dissertation.

- Providing a BIM-based machine-interpretable feedback mechanism.
- Documenting design decisions’ reasoning and rationale.
- Preserving tacit design knowledge.
- Enabling the partial reuse of design knowledge.

1.4. Research questions

Based on the problem statement mentioned above and the overall goal of this dissertation, the following research questions will be addressed in this work.

- How to provide support for architects during the early stages of design when facing various essential design decisions and not having objectifiable assessments based on expert analysis and simulations due to insufficient information in early design models?
- How can other domain experts' opinions and feedback be delivered via model-based machine-interpretable communication?
- How to avoid the loss of tacit design knowledge when experienced employees leave the firm?

- How to capture, transfer and store tacit design knowledge?
- How can documentation of design decisions' reasoning and argumentation be made possible based on both subjective and objective criteria?
- What suitable approaches exist for translating and storing tacit design knowledge for future queries and reuse?
- How to avoid redundancies and re-inventing the wheel by providing previous design solutions as a source of inspiration when addressing similar design challenges?

1.5. Research hypothesis

The underlying hypothesis addressed in this dissertation is as follows:

Partial reusability and more transparency in BIM-based design process can be achieved through machine-interpretable documentation of design decisions and communications

1.6. Approach and methodology

The approach or methodology of this dissertation is centered around bridging the gap, as mentioned above, in the architectural design process by introducing new concepts and methods. These concepts and methods aim to leverage the capabilities of BIM methodology and enhance them to achieve model-based, machine-interpretable communication among experts as well as adequate digital documentation of design decisions. By doing so, the goal is to enable the partial reuse of architectural tacit design knowledge that is embedded within various design decisions.

A systematic literature review is followed to accomplish this goal, starting with a comprehensive understanding of BIM methodology, architectural design, communication among experts, and design decisions' documentation. This literature review has served as the foundation for developing a theoretical framework that builds upon and enhances the existing capabilities of BIM methodology.

Furthermore, this work uses empirical research to validate and evaluate the proposed concepts and methods in real-world architectural design scenarios. This involved collaborating with architectural firms, conducting case studies, and gathering data on communication practices, design decision documentation, and the potential for reusing tacit design knowledge. The collected data is then analyzed and interpreted to assess the effectiveness and impact of the introduced concepts and methods.

This dissertation's approach combines theoretical development with practical implementation, aiming to address the identified gap in architectural design process through the enhancement of BIM methodology and the facilitation of model-based, machine-interpretable communication and design decisions' documentation.

1.7. Contributions, impacts and values

The proposed concepts in this dissertation, focusing on model-based machine-interpretable design communication and decision documentation, offer significant impacts and value across various levels. These include but are not limited to:

- Clarity, transparency, and improved accuracy: Documenting design decisions clarifies the rationale behind specific choices, fostering understanding among team members and stakeholders. It promotes transparency, building trust and engagement. It also reduces errors and ambiguities, enhancing the quality of the design process.

- Enhanced collaboration and improved communication and interoperability: Machine-interpretable design communication and decision documentation enable clear and efficient collaboration among architects, engineers, and contractors. It facilitates better coordination, reduces errors, and speeds up decision-making. It can also be shared and integrated into other projects, enabling interoperability and knowledge transfer.

- Future reference and increased efficiency: Documenting design decisions supports future reference, informing subsequent design work and dispute resolution. Machine-interpretable documentation enhances efficiency compared to unstructured and scattered information like emails and annotations. It eliminates the need for teams to spend excessive time deciphering or recreating past work.

- Greater flexibility: The introduced adaptive frameworks offer flexibility in representing and documenting the design process across various projects and diverse requirements. They allow retrieval and querying in myriad ways.

- Informed decision-making: Feedback from domain experts ensures informed decision-making by evaluating different design alternatives and aligning with project goals and requirements.

- Preservation of knowledge: Design documentation safeguards intellectual property and shares knowledge inside an organization. It captures valuable knowledge and expertise that might otherwise be lost over time, ensuring continuity when team members leave the organization.

- Facilitating the onboarding process: Design documentation helps new team members quickly familiarize themselves with a project, providing insights into past decisions and guiding their work. It facilitates knowledge sharing and reuse among teams, promoting efficient collaboration and learning from previous projects.

- Interorganizational auditing: Comprehensive documentation allows for tracking progress, evaluating results, and facilitating self-criticism and improvement within the firm. Mistakes and successes in various projects can serve as valuable lessons.

- Sharing and learning: Design documentation enables companies to share or sell their designs, promoting knowledge exchange and rework when facing similar design challenges. It encourages collaboration and learning among architectural firms.

In conclusion, model-based machine-interpretable design communication and decision documentation are potent tools for enhancing design teams' communication, collaboration, and efficiency. It ensures project requirements are met, fosters transparency, and provides a valuable reference for future projects.

1.8. Limitations

In the context of this dissertation, it is important to acknowledge and clarify certain limitations to avoid any potential misunderstandings or misinterpretations regarding the results and contributions provided.

It should be noted that the early design stages referred to in this dissertation are specifically LPH 2 & 3, as defined by the ‘Honorarordnung für Architekten und Ingenieure’ (HOAI) (Wiesbaden 2013). However, it is worth mentioning that the requirements criteria specified during LPH 0 & 1 could be used as benchmarks for evaluating and comparing design variants. However, it should be mentioned that the LPH 0 precedes the classical HAOI phases and is used to develop spatial concepts and utilization scenarios. These provide the architect with the necessary foundations for further planning of the building[2]. Furthermore, an overview of the structured design process based on three prominent sets of standards, HOAI (Germany), RIBA (United Kingdom), and AIA (United States), will be discussed in chapter 2.6.

Additionally, the concepts and methods proposed within this dissertation are intended to assist architects rather than dominate or hinder their flow or authority. The proposed feedback mechanism aims to provide objective assessments for architects during the early design stages based on feedback from consultants and other domain experts. Feedback loops are also an essential part of lean management and lean development processes, as they help create value faster and more efficiently. Feedback loops are mechanisms that allow information to be gathered, analyzed, and acted upon from multiple sources, such as various domain experts and stakeholders. However, accepting or rejecting these suggestions remains solely in the architect's authority. The use of Explanation Tags empowers architects to explain and document both subjective and objective aspects of their design decisions while avoiding any negative impact on their creative design flow or excessive workload. The proposed methods aim to enable architectural firms to capture and record tacit design knowledge, making it visible and accessible for transfer to new recruits and reuse in future projects.

It is important to note that the concepts and methods presented in this dissertation are not meant to completely solve the problem of inefficient design communications and insufficient design process documentation. They may bring additional work or minor changes to the working procedures of architectural firms, which may face resistance in the workplace. Therefore, it is crucial to further test and survey the effectiveness and consequences of these methods and concepts through future research in this field.

1.9. Structure of the work

This chapter started by assessing the current situation in the AEC industry, specifically the architectural practices, and stated the research gap and problem definition. Then, the main goals of this dissertation, followed by the research hypotheses, were discussed. The approach and methodology outlined in this chapter necessitate a systematic examination of the given framework conditions. This is reflected in the following areas: Architectural Building Design, Building Information Modelling, and Knowledge Management in Architecture. Furthermore, a discussion of the related research followed by a deficit

[2] - https://www.conceptk.org/leistungsphase-0

analysis is provided. Based on the knowledge gained from this, the appropriate concepts and methods are derived and verified in sub-fields using prototypes. The structure of the work is divided into the following chapters:

1.9.1. Chapter 2 – Architectural building design process

This chapter focuses on architectural building design and provides detailed information on how to approach and understand this process effectively. This chapter also covers a wide range of topics related to the process of planning and designing. The chapter commences by defining key terminologies related to planning and designing. It then delves into the intricacies of the design process and emphasizes the complexity and difficulty associated with solving design problems. The chapter categorizes design problems as "wicked problems" and outlines the challenges of addressing them. It highlights the importance of the decision-making process in architectural design and how it is a continuous dialogue and argumentation with oneself or other stakeholders. This chapter emphasizes the iterative nature of the architectural design process, where the iteration between problem, solution, and evaluation is crucial in achieving the final design. The main focus is on theories that see the design process as a series of argumentations and communications between experts and oneself, which lays the theoretical foundation for the proposed concepts in chapter 7.1.

1.9.2. Chapter 3 – Building information modeling (BIM)

This chapter delves into the essential topic of Building Information Modeling (BIM) and its critical application in the design process. It begins with an introduction to BIM and highlights its significance in modern construction projects. The chapter then explores why traditional Computer-Aided Design (CAD) methods are no longer adequate and provides an overview of what BIM is and how it can revolutionize the design process.

The chapter comprehensively analyses the various aspects of BIM and explains how it can improve the design process. It delves into the use of BIM models and the Industry Foundation Classes (IFC) open data format for BIM.

Overall, this chapter provides a detailed exploration of BIM methodology and its essential role in modern construction projects. It lays the groundwork for the proposed concepts and methods in chapter 7 and emphasizes the importance of integrated design processes and collaborative efforts to achieve a successful design outcome. In this regard, the chapter highlights the significance of the Integrated Design Process (IDP), also known as “Integrale Planung”, which is an approach that emphasizes the collaboration and integration of all stakeholders in the design process. The IDP provides the foundation for the concept of adaptive detailing strategies and the minimized BIM-based machine-interpretable feedback mechanism, both introduced in this work and discussed in chapter 7.1.

1.9.3. Chapter 4 – Knowledge management in architecture

This chapter is focused on knowledge management in architecture and its importance in the design process. The chapter starts by defining knowledge and its importance in the design process. It then goes on to discuss architectural design knowledge and the distinction between objective/quantitative and subjective/qualitative design decisions. Special emphasis is given to architectural tacit knowledge, its unique features, and how to preserve and represent it. This chapter then delves into formal knowledge representation techniques, such as graph structures and Case-Based Design (CBD), which is an approach for reusing previous design solutions for similar problems. This chapter also covers the use of Natural Language Processing (NLP) as a tool for knowledge management, which can be used to extract, understand, and manage information from text data.

In particular, the Case-Base Design methodology, knowledge graphs, and NLP are important since they are later used as the basis for the concepts discussed in chapters 7.3 and 7.4. Furthermore, some fundamentals regarding Natural Language Processing (NLP) and various similarity measures are covered to provide background on searching for desired design intentions among several stored design episodes using free-text as input, later discussed in chapter 8.3.

1.9.4. Chapter 5 – Discussion of the related work

This chapter will present a literature review of the related work and state-of-the-art research associated with this dissertation's proposed concepts and contributions. Firstly, the chapter will discuss the work of the EarlyBIM research group, which focuses on using BIM in the early design stages.

The chapter will then delve into model-based issue management, communication, and collaboration in the design process. Specifically, it focuses on machine-interpretable model-based design issue management and communications, which are becoming increasingly important in the field.

Additionally, the chapter will cover the use of formal knowledge representation and the semantic web, as well as the various graph representations used in the AEC industry.

Next, the use of references and knowledge extraction from semantic models and the application of NLP in the context of BIM will be discussed.

Moreover, the chapter will focus on the objective and subjective design criteria, the documentation of design decisions, as well as subgraph matching in searching for design references. It is essential to understand the current state-of-the-art research in the field to comprehend better the topics covered in the rest of this dissertation.

1.9.5. Chapter 6 – Deficit analysis

This chapter addresses the research gap that exists due to the unique characteristics of tacit design knowledge in architecture, as well as the need for effective model-based communications and documentation of design decisions, as discussed in chapters 2, 2.5 & 4. Additionally, the potential benefits of the BIM methodology highlighted in Chapter 3 are considered. The chapter emphasizes the deficiencies in the current practices of architectural design and the loss of intellectual property resulting from them. It sheds light on the overlooked aspects of model-based design communications and decision documentation and the significant potential they offer. When reviewing this chapter, it becomes apparent that the argument for the importance of these aspects is well-supported and compelling.

1.9.6. Chapter 7 – Proposed methods and concepts

This chapter provides a detailed explanation of the applied research methodology used in this dissertation and the introduced concepts to support the design process during the early design stages. The chapter explains how a minimized machine-interpretable BIM-based communication protocol can be used for this purpose, as well as how digital design knowledge documentation can be achieved through the use of explanation tags and design episodes. Additionally, the chapter discusses the proposed graph representation concepts for design episodes. Finally, the chapter presents several demonstrative examples to showcase the proposed novel methods and concepts. Overall, this chapter is an essential part of the dissertation, as it outlines the research methodology and the novel concepts introduced, setting the stage for the subsequent chapters that delve deeper into these concepts and their implementations.

1.9.7. Chapter 8 – Implementations as proof-of-concept

Subsequently, in this chapter, the partial implementations, together with some real-world use cases, will be discussed to demonstrate the proof of concept and applicability of the developed methods and concepts. In particular, two plugins for Autodesk Revit (as an example of a BIM authoring tool) will be explained and examined. One of which supports the machine-interpretable communication protocol for the early design stages, and the other enables the documentation of design decisions for both objective and subjective assessments as well as capturing and storing various design episodes and then transforming them into knowledge graphs. Furthermore, multiple search methods and similarity measures to extract knowledge from graphs representing design episodes and semantic models will be examined and explained using real-world projects as examples.

1.9.8. Chapter 9 – Discussion and outlook

This concluding chapter will present a comprehensive overview of the research findings and contributions, followed by a critical self-reflection and discussion of the proposed concepts and their limitations. To begin with, a summary of the research hypothesis and the proposed approach will be provided. Then, the hypothesis will be put to the test based on the findings and outcomes of the novel concepts and methods presented in chapters 7 & 8. Furthermore, the proposed approach's practical implications and potential benefits will be outlined.

Moreover, this chapter will also highlight the limitations and constraints of the research, including the scope and methodology used and the potential biases and assumptions that may have influenced the results. A critical reflection on these limitations will be provided, along with suggestions for future research that could address these gaps and expand on the findings. Lastly, this dissertation will conclude by offering an outlook on the future steps to expand this research and continue its results. This will include recommendations for further study, practical applications, and potential collaborations with industry partners.

1.9.9. Chapters 10 to 12 – Appendix

Chapter 10 includes a detailed list of all the publications that are written and published in the context of this dissertation. Followed by chapter 11 which includes a detailed list of some explanation tags (representing only an exemplary set of ETs) that are presented and explained in detail to help readers understand their potential applications in building design and construction. This list of explanation tags is an essential aspect of the proposed approach and is meant as a starting point to serve as a means of documenting design decisions and rationale in a structured and standardized way. And finally chapter 12 lists all the publication bibliography that are cited throughout this discussion.

Figure 2 summarizes and demonstrates the outline and structure of this dissertation based on the chapters and their relationship with each other.

Introduction

- Chapter 1: Introduction

Analysis

- Chapter 2: Architectural building design process
- Chapter 3: Building information modeling (BIM)
- Chapter 4: Knowledge management in architecture
- Chapter 5: Discussion of the related work

Deficit

- Chapter 6: Deficit analysis

Concept

- Chapter 7: Proposed concepts and methods
- Chapter 8: Implementations as proof-of-concept

Discussion

- Chapter 9: Discussion and outlook

Apendix

- Chapter 10: List of publications written in the context of this dissertation
- Chapter 11: List of explanation tags
- Chapter 12: Publication bibliography

Figure 2 - Structure of the work

2. Architectural building design process

The architectural building design process is the main focus of this work. The principles of the design activity and process will thus be investigated and evaluated in greater depth in the following sections. This inquiry serves as this work's thematic foundation and allows a consistent understanding of the architectural design process. The goal is to explore the design's fundamental features and methods to determine the requirements for proper design decisions documentation, and support.

To do so, this chapter will delve into the intricate world of architectural design, exploring its terminology, characteristics, and the complex nature of design problems. The aim is to comprehensively understand the design process, highlighting the continuous dialogue and negotiation between problems and solutions. Additionally, the decision-making process in architectural design and the importance of the iterative cycle of analysis, synthesis, and evaluation will be examined. This chapter emphasizes the dynamic nature of design as a continuous dialogue and argumentation, whether with oneself or others. This chapter lays the groundwork for the subsequent discussions on machine-interpretable design communication and decision documentation by clarifying the architectural design concepts and exploring their nuances.

2.1. Planning and designing – a terminology clarification

A design is usually embedded in a broader planning process. However, a planning process can also be designed, and a design can be understood as planning if it is divided into further sub-designs (Reinhard König 2022).

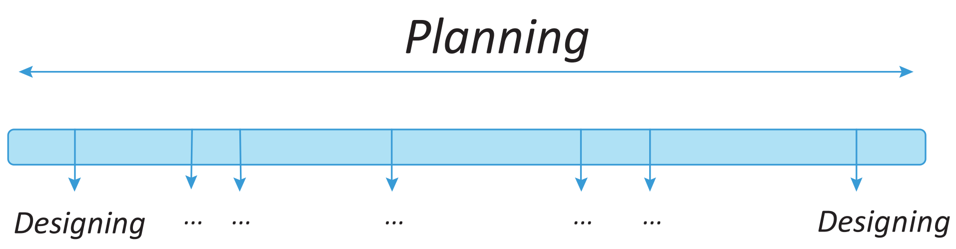

Figure 3 - Planning and Designing based on (Reinhard König 2022)

In other words, planning defines the search space for designs, while multiple planning and design search spaces can be nested (Reinhard König 2022). Can planning and designing be separated so easily? In terms of methodology, the planning process is a goal-driven procedure often based on a set of principles and is used to acquire information or practical outcomes (Sieverts and Vohlwahsen 1977). Design process, on the other hand, depends on heuristic approaches. Heuristics are cognitive fast-track methods of finding workable solutions based on experience-driven rules of thumb or know-how (Gigerenzer and Todd 1999). Although they do not guarantee a solution to a design task in every circumstance, they reduce the time necessary to accomplish the task on average.

2.2. The universe of design

The ability of humans to create a wide variety of tools and other objects for their specific needs is one of their most fundamental traits. Therefore, there are many things in the world, including tools, machinery, buildings, furniture, clothes, and many other items that humans either need or use to improve their lives. Anything that is not a straightforward, unaltered piece of nature has been designed by someone (Cross 2008, p. 3).

"People have always designed things" (Cross 2008, p. 3),

The scope of what gets designed is vast, and the knowledge used to design varies widely, touching all aspects of human experience (Rittel 1988, p. 1).

"Everyone designs at times … Design is not the monopoly of those who call themselves 'Designers'." (Rittel 1988, p. 1)

Planners, engineers, architects, business managers, legislators, and educators are sometimes designers. They are driven by the ambition to conceive a desirable state of the world, to play out various ways of bringing it about, and to examine the consequences of the actions they consider carefully.

But does the design process have a core model? Attempts to develop a universally valid structure for the activity of design have been undertaken in the past. For example, Hugh Dubberly's collection of over a hundred design theories (Hugh Dubberly 2022) demonstrates that design is difficult to describe and that it appears nearly impossible to compress the processes into a generally valid schema. Nevertheless, this chapter tries to review some essential theoretical background about design theories that are later relevant to the work and contributions of this dissertation.

2.3. Understanding the activity of design

Starting at the end and working backward from the point where designing is complete and making begins may be a helpful strategy for understanding design (Cross 2021, p. 5). At least the purpose of the design process is evident if production cannot begin before the design is done. The only leading conclusion is that it must include a detailed description of the intended object, including all its contained entities and the corresponding geometrical and semantical attributes. In a way, the detailed description is what the customer asks for when they ask the architect for a design. That end-point is the main focus of all design activities (Cross 2021, p. 5).

Furthermore, Rittel (Rittel 1988, p. 1) argues that to talk about design in general terms, despite the great diversity of the designed objects, one must first find some common ground or similarities between various activities in the design process. But what are these similarities? In some sense, all designers intend to intervene in the expected course of events by some sort of premeditated action. Furthermore, they all want to avoid mistakes caused by ignorance and spontaneity. They want to think first, then act (Rittel 1988, p. 1). Instead of trying to change their environment immediately by trial and error until it takes on the desired form, architects want to think up a possible course of action and examine it thoroughly before they decide to carry it out.

In addition, Cross argues that a few recurring themes appear when the architects are asked to describe their processes and capabilities. One is the significance of creativity and intuition in design activity, while another important theme is that design problems and solutions coexist and are closely interwoven (Cross 2021, p. 4). A third recurring feature is the need to express and articulate ideas through models, sketches, or drawings to investigate the design problem and its potential solutions jointly. This happens very much like a dialogue with oneself or other domain experts and stakeholders. In a recurring manner, this dialogue or conversation takes place when the architect evaluates and reflects on the ideas and concepts expressed using sketches or models (Cross 2021, p. 5).

One way to structure the design process is to break it down into manageable phases. Based on Rittel, the following phases are often referred to in the literature:

1. Understand the problem
2. Gather information
3. Analyze the information
4. Creative act
5. Synthesis
6. Execution and communication of results

The attempt to see a chronological sequence for the problem understanding, information gathering, and problem-solving is typical for the first-generation system design theories meant for military and space projects. However, as it will be discussed in more detail, designing in architecture cannot be described in chronologically consecutive design steps. The architect rather finds it difficult to move exclusively in the defined phase in each case.

> *“All of these occur all the time. A design problem keeps changing while it is treated, because the understanding of what ought to be accomplished, and how it might be accomplished is continually shifting. Learning what the problem is, IS the problem.” (Rittel 1988, p. 2)*

The architect starts out with a notion of the "complete" answer to his problem. Still, as one gains a better grasp of it, one’s perception of the solution shifts from vague to precise and back again, constantly being revised, adjusted, detailed, and modified. One continuously moves one’s attention between the main issue and little details, then back to the main issue. In other words, designing (in architecture) cannot be described with chronologically consecutive design steps. Thus, stage models are not suitable for establishing a better understanding of the architectural design process.

2.4. Design problems are wicked problems

Horst Rittel, representing the design methodology movement, described the conflict between intuition vs systematics and design as a system delicately as follows:

> *“On the one hand, there is the belief in the 'feasibility' or unlimited malleability of future destinies through the possibilities of the planning intellect - through reasoning, rational discourse, and cultivated forms of negotiation. At the same time, there are voices in favor of the 'feeling approach,' passionate commitment, and dramatic action, even a revival of mysticism, with the goal of defeating THE SYSTEM, which is seen as the evil source of all misery and suffering.” (Rittel 2013, p. 23)*

Rittel and Webber, in their famous article about ‘Dilemmas in the general theory of planning’ (Rittel and Webber 1973), claimed that because of the nature of social policy problems, the quest for finding a general theory of planning is doomed to failure. They identified that the central difficulties of such a quest lie at the intersection of goal formulation, problem definition, and actions identification. In other words, the main challenge is knowing what makes the difference between an observed and a desired state, figuring out where in the complex causal network the difficulty lies and identifying those actions that could effectively narrow the gap between what is and what should be.

They distinguished between the ‘wicked’ problems that architects and planners cope with, which in most cases contend with some sort of subjectiveness or social engagement and the ‘tame’ problems that scientists and engineers deal with, which are definable and separable and may have solutions that are findable (Rittel and Webber 1973).

“Planning problems are inherently wicked… we are calling them ‚wicked‘ not because these properties are themselves ethically deplorable. We use the term ‚wicked‘ in a meaning akin to that of ‚malignant‘ (in contrast to ‚benign‘) or ‚vicious‘ (like a circle) or ‚tricky‘ (like a leprechaun) or ‚aggressive‘ (like a lion, in contrast to the docility of a lamb).“ (Rittel and Webber 1973)

Rittel and Webber identified ten traits for wicked problems that very much apply to architectural design problems. The important ones are:

- A wicked problem cannot be defined precisely and comprehensively because the knowledge needed to grasp the problem relies upon one's notion for addressing it. That is to say, one must create a thorough inventory of every potential solution in advance in order to adequately characterize a wicked problem.
- The designer ends work on a wicked problem, not for reasons dependent on the "logic" of the problem, as there is no stopping rule for wicked problems. They stop because of external factors: they run out of time, money, or patience. That is good enough; this is the best we can accomplish given the constraints of the project; we like this solution, are their concluding words.
- Solutions to wicked problems are not true-or-false but good-or-bad. Evaluations and judgments regarding design solutions may involve many subjective aspects and are likely to differ by various involved parties as they may act differently based on their level of expertise, group or personal interest, or ideological preferences.
- There is no immediate and no ultimate test of a solution to a wicked problem: with architectural design problems, any given solution, when executed, may create waves of effects over a long, in fact, almost unbounded period of time.
- No measures can allow one to demonstrate that all potential solutions to an architectural design problem have been found and taken into account.
- Every design problem is (nearly) unique.

2.5. Architectural building design

Generally speaking, architecture is the art and science involved with the design and construction of buildings (Wilde 2018, p. 328). The profession of architecture and the notion of design were not separated from the construction process until the mid-16th century, during the Renaissance period, and in the run-up to the Industrial Revolution, when they were impacted by the cultural changes, and technological advancement, among other things (Heskett 1980, p. II). As building projects grew larger, more sophisticated, and more elaborate, new ways were necessary, and planning ahead was required. The logical change to separate the planning process from the construction act prompted this move. As Nigel Cross deliberately puts it:

> *"The whole point of having the process of design separated from the process of making is that proposals for new artifacts can be checked before they are put into production" (Cross 2021, p. 7).*

As already discussed before, what the design process sets to achieve is *"[…] to provide a description of the artifact that is to be made."* (Cross 2021, p. 5) Design objectives are thus found in the concrete description of an initially unknown entity, a future vision, moving from an abstract job to a concrete, three-dimensional model (Gänshirt 2012). The complexities and ironies of this task are well described in a quote from Richard MacCormac in Brian Lawson's book:

> *"This is not a sensible way of earning a living, it's completely insane, there has to be this big thing that you're confident, you're going to find, you don't know what it is you're looking for and you hang on." (Lawson 2006, p. 192)*

What makes it even more complex and challenging is that architectural design objectives and parameters, such as the space plan, costs, function, or construction, are often at odds with one another. Furthermore, challenges might vary during the design process, drifting away or resurfacing. These design-relevant characteristics do not exist in isolation. They are often linked, impact one another, and must be assessed against each other according to various criteria.

Even though, as mentioned before, one cannot design using a generally valid formula, the following sections will discuss some standards and structured procedures, as well as some relevant concepts and frameworks described in the literature from which this dissertation descends.

2.6. Structured design process and standards

Structured design processes are essential in the fields of architecture and engineering to ensure that projects are executed efficiently, safely, and according to specific standards and regulations. Various countries and professional organizations have established their own standards and guidelines for design processes. In this section, an overview of the structured design process based on three prominent sets of standards, HOAI[3] (Germany), RIBA[4] (United Kingdom), and AIA[5] (United States), will be provided.

2.6.1. HOAI (Honorarordnung für Architekten und Ingenieure - Fee Structure for Architects and Engineers - Germany)

In Germany, the structured design process is codified within the framework of Leistungsphasen (LPH), which stands for service phases. The HOAI is the official fee structure for architects and engineers in Germany. It defines various phases of architectural services, each with its own set of tasks and responsibilities.

- **LPH 1: Grundlagenermittlung (Preliminary Planning)**
  - Clarification of the task on the basis of the client's specifications or requirements planning
  - Define the project's basic parameters and goals.
  - Evaluate site conditions.
  - Examine legal and regulatory requirements.
- **LPH 2: Vorplanung (Conceptual Design)**
  - Develop conceptual design options.
  - Prepare rough sketches and layouts.
  - Estimate project costs.
  - Discuss design options according to the same requirements with the client.
- **LPH 3: Entwurfsplanung (Design Development)**
  - Refine the chosen design concept.
  - Develop detailed drawings and specifications.
  - Providing the results of the work as a basis for the other technical parties involved in the planning as well as coordinating and integrating their services.
  - Finalize cost estimates.
- **LPH 4: Genehmigungsplanung (Approval Planning)**
  - Prepare documents required for official approvals.
  - Coordinate with relevant authorities.
  - Address any comments or modifications.

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[3] - https://www.hoai.de/hoai/volltext/hoai-2021/

[4] - https://www.architecture.com/digital-practice-tools/riba-contracts/riba-standard-professional-services-contract

[5] - https://www.aia.org/resources/8066-aia-compensation-report

- **LPH 5: Ausführungsplanung (Execution Planning)**
  - Create detailed construction drawings.
  - Specify materials and construction techniques.
  - Providing the results of the work as a basis for the other specialists involved in the planning, coordinating and integrating their services.
- **LPH 6: Vorbereitung der Vergabe (Preparation of the Award)**
  - Preparation of an award schedule.
  - Assist in preparing tender documents and service descriptions with specifications according to various fields.
  - Assist in the tendering process for contractors.
- **LPH 7: Mitwirkung bei der Vergabe (Contract Award)**
  - Collaborate with the client during the contract award process.
  - Assist in contract negotiations.
  - Monitor compliance with contractual agreements.
- **LPH 8: Objektüberwachung (Site Supervision)**
  - Monitor construction progress.
  - Ensure compliance with design and quality standards.
  - Address and resolve on-site issues.
  - Document and report progress to the client.
- **LPH 9: Objektbetreuung (Object Care and maintenance)**
  - Professional assessment of defects identified within the limitation periods for warranty claims.
  - Inspection of the property to determine defects before the expiry of the limitation periods for claims for defects against the executing companies.
  - Participation in the release of security deposits.

Further details on the specific services that are expected as standard or extra for buildings and interiors on the basis of the individual LPH are described in Annex 10[6].

2.6.2. RIBA (Royal Institute of British Architects - United Kingdom)

The United Kingdom's RIBA standards outline stages for structured design.

[6] - https://www.hoai.de/hoai/volltext/hoai-2021/#P51

- **Stage 0 Inception, preparation and brief:** The project starts with defining the client's objectives and requirements. A project brief is developed, outlining the scope and purpose. Feasibility studies are conducted to assess the project's viability.
- **Stage 1 concept design:** Architects create initial design concepts and sketches, often focusing on spatial arrangements and aesthetics. Client feedback is crucial.
- **Stage 2 design development:** Detailed design work takes place, incorporating structural and technical considerations. Sustainability, materials, and cost are evaluated.
- **Stage 3 technical design:** Technical drawings and specifications are developed. Regulatory approvals are sought, and a construction strategy is formed.
- **Stage 4 construction:** Contractors are selected through competitive tendering or negotiation. Construction commences, and the design team administers the contract.
- **Stage 5 handover and closeout:** The completed project is handed over to the client. Final inspections, snagging (defect identification), and documentation are completed.

2.6.3. AIA (American Institute of Architects - United States)

In the United States, the American Institute of Architects (AIA) defines a structured design process consisting of six phases.

- **Predesign:** Project goals, scope, budget, and schedule are established. Feasibility studies and site analysis are conducted.
- **Schematic design:** Initial design concepts are created, often in the form of sketches and diagrams. Client input and approval are critical.
- **Design development:** The design is refined and developed, incorporating technical and structural details. Sustainability and materials are considered.
- **Construction documents:** Detailed construction drawings and specifications are prepared. Bidding or negotiation with contractors takes place.
- **Construction administration:** The design team oversees the construction process, addressing issues, ensuring quality, and maintaining the design intent.
- **Post-occupancy evaluation:** After the project is occupied, its performance is assessed, and any necessary improvements are identified and implemented.

These structured design processes, as outlined by HOAI, RIBA, and AIA, serve as valuable frameworks for professionals in the fields of architecture and engineering. They help ensure that projects are well-planned, executed efficiently, and meet the needs and expectations of clients while adhering to local regulations and industry best practices. These structured design processes and their respective standards, offer a roadmap for professionals to navigate complex projects successfully. However, it is important to note that specific project requirements may lead to variations in these processes.

This section has provided an overview of the structured planning process based on three well-known sets of standards: HOAI (Germany), RIBA (United Kingdom) and AIA (United States). A critical observation is that, using the HOAI as an example, standard negotiations and exchanges between architects and other specialist planners and domain experts predominantly only begin in LPH 3. In this phase, preliminary plans are submitted that form a basis for other specialist planners to facilitate the integration of their services. In LPH 4, templates for public-law approvals are then created, taking into account the findings of other domain experts. It is worth noting, however, that the refinement of technical details typically reaches maturity in LPH 5 during the development of comprehensive execution plans. Nevertheless, some intricate technical details are extensively addressed in LPH 6, 7 and even 8. These negotiations may involve multiple iterations and revisions to earlier design decisions, which can lead to additional costs and time.

This dissertation considers proactive measures, such as the feedback mechanism (discussed in more detail in section 7.1), to enhance this process. These proactive measures would enable a more collaborative and iterative approach, allowing expert opinions and suggestions to be incorporated with full detail at earlier stages, such as LPH 2 and 3, ultimately reducing the need for extensive revisions at later stages. This proactive approach not only streamlines the negotiation process but also minimizes the potential for extra costs and delays associated with repeated modifications.

In the context of this dissertation, it is crucial to recognize that the early design stages discussed herein specifically refer to LPH 2 & 3, as outlined in the (HOAI) (Wiesbaden 2013). Notably, the criteria set during LPH 1 can serve as benchmarks for evaluating and comparing design variations.

2.7. Problem-solving vs puzzle-making

Architects typically build their designs in a graphical, drawing-based manner (Zeiler et al. 2007). Two distinct design paradigms have evolved over the last decades, reflecting two fundamentally different approaches to interpreting the causal link between form and function. Design is a difficult task that has been referred to as ‘problem-solving’ or ‘puzzle-making' (Kalay 1999; Wilde 2018). Building design as a problem-solving process starts with the customer's demands, which are then converted into a design job. It is anticipated that the architect begins with the desired function or the system's desired behavior. This desired function is frequently expressed as a set of objectives and constraints. Using deductive search techniques, the architect then attempts to find a shape that will support the intended function (Kalay 1999). In the other paradigm for building design, known as puzzle-making, the architect starts with a set of forms, including materials and shapes, then modifies and adjusts them according to specific principles to fit the functional needs and requirements. This paradigm is based on inductive reasoning (Kalay 1999).

It is crucial to remember that building design is an iterative and creative process in which the architect chooses, over and over, from a pool of available components, materials, and control options to synthesize the solution under specified constraints. Design processes generally run iteratively (in different steps) and non-linearly (by jumping amongst the steps) between the problem description and the solution-finding. According to Rittel (Rittel 1992, 2013), the 'elementary activities' of design are the 'generation and reduction of variety', whereas Simon (Simon 1994) describes the process of designing as a 'Generate-Test Cycle'. Similar explanations with slight alterations may be found in the literature by other scholars; Schön (Schön 1992) describes it as a 'See-Move-See' dialogue, whereas Zeisel (Zeisel 2006) refers to it as a cycle of 'imaging-presenting-testing'.

However, in the beginning, the design task is abstract and vague. According to Harfield (Harfield 2007), requirements are not the same as defining the design problem, and the architect must interpret the requirements meaningfully. The design task and its potential solutions coexist and co-evolve as a result of arguing and reasoning about the to-be-designed building details. Furthermore, it is not only the client's wishes and demands that form a building design but also numerous regulations, constraints, and technical aspects. It is commonly acknowledged that today's architectural design process is a social activity in which a growing number of stakeholders participate and cooperate.

As the design progresses, more insight, information, and details will be obtained. Gaining insight into the true essence of the challenges involved with the design task also necessitates returning to formulating the design problem and recompiling requirements. Due to the new knowledge obtained, changes are needed to expand or sharpen the design task's original formulation. The downside to this process is that little knowledge is available during the early stages of design, even though almost all critical decisions must be taken during this period.

2.8. A negotiation between problem and solution through iterative analysis, synthesis, and evaluation

Many conditions must be met for a building to be designed. In most cases, a brief must be put together, the architect must research and comprehend the requirements, create one or more solutions, test them against some stated or implicit criteria, and convey the design to clients and builders. However, as mentioned before, it seems highly improbable that these activities occur in that order, or even the assumption that they are identifiable separate events, is very questionable. Instead, it appears more plausible that design is a process in which problem and resolution coexist and coevolve together.

> *"Often the problem may not even be fully understood without some acceptable solution to illustrate it. In fact, clients often find it easier to describe their problems by referring to existing solutions which they know of." (Lawson 2006, p. 47)*

Bryan Lawson sees the design problem and solution as a reflection of each other. He describes the design process as a negotiation between problem and solution by leveraging three activities of analysis, synthesis, and evaluation but without having any starting and finishing points or the direction of flow from one activity to another (as shown in Figure 4) (Lawson 2006, p. 48). Iteration and nonlinearity are typical design elements when going through the cycle of analysis, synthesis, and evaluation over and over again.

> *"In this kind of situation, it can be easy for the designer to become trapped in an iterative loop of decision-making, where improvements in one part of the design lead to adjustments in another part which lead to problems in yet another part. These problems may mean that the earlier 'improvement' is not feasible. This iteration is a common feature of designing." (Cross 2021, p. 8)*

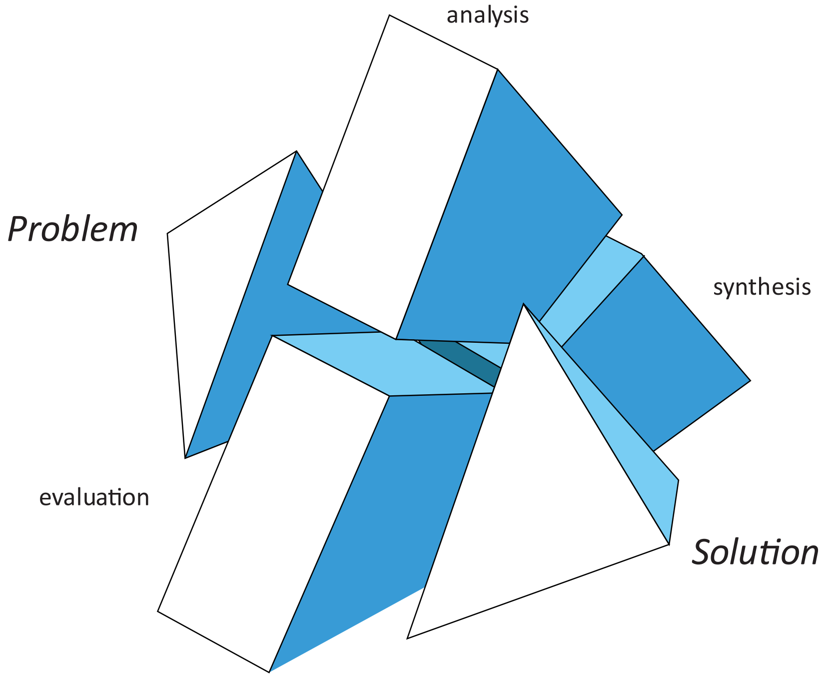

Figure 4 - Based on Lawson (Lawson 2006, p. 48), the design process is viewed as a negotiation between problem and solution through the iterative switching between analysis, synthesis, and evaluation.

In search of Microstructures for the design process, Rittel (Rittel 2013, p. 73) defines two elementary processes. These are ‘creating variants’ (having ideas) and ‘restricting variants’ (rejecting ideas). Hillier (Hillier 2007, p. 44) sees the architectural design as a cyclic process between these two and refers to developing variants as the 'creative phase' and then evaluating whether the variant meets the requirements as the 'predictive phase'. Paul Laseau (Laseau 1980, p. 91) uses the concept of the Design Funnel to explain how, as the design process advances, targeted decisions gradually restrict the number of explored ideas while the level of detail of pursued individual ideas rises accordingly (shown in Figure 5).

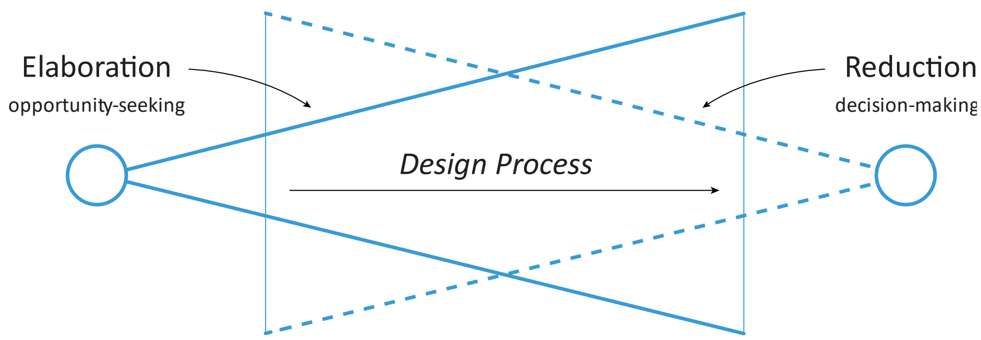

Figure 5 - The ‘Design Funnel’ based on Laseau (Laseau 1980, p. 91) shows the overlapping of elaboration (opportunity-seeking) and reduction (decision-making) in the design process.

2.9. Decision-making process in architectural design

In both engineering and architecture, design is a crucial activity. In construction science, design as decision-making is well-established (Wilde 2018). Four essential cognitive activities are frequently identified in design thinking: creation, exploration, comparison, and selection of design variants (Stempfle and Badke-Schaub 2002). The selection of variants, in this perspective, is unmistakably a design decision point. It's worth noting that there are opposing viewpoints on design selections (Wilde 2018). For example, Almendra and Christiaans (R Almendra and HHCM Christiaans 2011) refer to activities in the conceptual design stage simply as 'interactions' because various acts interact with one another, making it difficult to determine what is a real choice or decision (Wilde 2018, p. 334). In a research study by Zanni et al. (Zanni et al. 2017), case studies were investigated with design practitioners organized around identifying incidents, e.g. decision points, reflection, and justification, that impacted the building design in some way.

Some design factors may later be discovered to be dominating, and their adoption becomes a design driver; however, identification as a critical design decision may only be made with hindsight. Besides, design can be primarily about establishing geometry and form finding, particularly for those with an architectural background (Ercan and Elias-Ozkan 2015). Based on this point of view, variant generation, exploration, comparison, and selection often happen in real-time and fast, making it hard to identify decision points. Nonetheless, just like in many other domains, focusing on logical decision-making moments is a popular approach.

However, the critical question concerning this dissertation is: besides the logical decision-making moments, what else could the design decisions be made of, and how could they be recorded transparently and traceably? How about the decisions that contradict logic in one way or another? How about the design decisions that are open to interpretations based on various perspectives? How about the design decisions made based on some subjective (qualitative) criteria?

2.10. Design as continuous dialogue and argumentation with oneself or another

According to Rittel (Rittel 2013, p. 77), architectural design is a continuous process that involves forming an "image" of the problem and its solution. As the architect gains more knowledge and concretizes the design problem, the direction of the design solution becomes more apparent, and uncertainties are reduced.

In every design task, there are boundary conditions that the architect considers unchangeable and beyond their control, such as building regulations and financial constraints. These influencing variables are represented in the context model. Depending on the weighting and individual decisions, they affect the design problem as context variables. Additionally, design variables, which are values for certain architectural aspects (e.g., space allocation, proportion), have an impact. They are to be understood as *"the summary of well-defined partial solutions independent of each other"* (Rittel 2013, p. 77). The solution variants are then generated by the object model through combining the context and design variables. In the next step, these solution variants are fed into an evaluation system, the performance model, to select the presumably suitable solution (final judgment). The evaluation is done by the performance variables, which can be seen as functions of the context and design variables. The performance variables for the generated design variants could be estimated via various analyses or simulations done by different domain specialists.

It is important to note that the design process is dynamic, and the context, object, and performance models must be modified as the architect's understanding of the problem shifts. Rittel also introduces the concept of logical constraints (e.g. no timber construction, max. three stories, etc.), which might be better represented as subjective design decisions in the author's opinion. These constraints do not necessarily represent objective facts but are rather the product of the designer's subjective decisions.

Above all, Rittel described the design process as a series of argumentations of the architects with themselves or other involved parties. Ranulph Glanville expresses the same concept:

> *“I characterize design as a conversation, usually held via a medium such a paper and pencil, with an other (either an ‘actual’ other or one-self acting as an other) as the conversational partner” (Glanville 1999, p. 88)*

Based on Rittel’s definition, the elements for this chain of reasoning and argumentation are so-called ‘*issues*’, each of which will be answered with alternative ‘*positions*’, and they will be in turn associated with ‘*arguments*’ to support or object to a given position or another argument.

“The designer's reasoning appears as a process of argumentation. He debates with himself or with others; issues come up, competing positions are developed in response to them, and a search is made for their respective pros and cons; ultimately he makes up his mind in favor of some position, frequently after thorough modification of the positions. In this model of design as argumentation, the various issues are interconnected in intricate ways; usually several of them are 'open' simultaneously, others are ‘postponed' or ‘reopened’. He finds himself in a field of positions: with competing arguments which he must assess in order to assume his own position.” (Rittel 1988, p. 3)

This understanding has led Noble & Rittel (Noble and Rittel 1988) to introduce the concept of Issue-Based Information Systems (IBIS), intending to make the design decision-making process more explicit, understandable, and transparent. They argue for many advantages of such a system, for example, the architect’s ability to reconstruct or follow back the train of decisions once they reach a dead end with an idea. Architects may also use these documentations to defend or justify their choices. Rittel & Noble’s IBIS was among the first computerized attempts to document the chain of design decisions and argumentations. Noble & Rittel saw the opportunity to search and retrieve records of previous projects and their documentation as the future work in developing similar systems to IBIS.

3. Building information modeling (BIM)

3.1. Introduction

This chapter delves into the Building Information Modeling (BIM) methodology, recognizing its significance and transformative impact on the architectural design and construction industry. This chapter aims to provide a comprehensive understanding of BIM and its role in the design process, emphasizing its potential to enhance collaboration and digitalization.

The rapid development of digital technologies over the last 40 years has led to ever-new applications in architecture. Computer Aided Architectural Design (CAAD), rendering, animation, and Building Information Modeling (BIM) are becoming evermore recognized working tools in planning practice. The computer has found its way into most architectural offices. Still, most software systems are merely oriented towards classical established working methods and use digital tools as a presentation medium. These are used separately and sequentially. In the following, the current state of digitization in AEC industry is presented. This chapter's focus will be building information modeling (BIM) since it is the foundation and enabling platform for this dissertation’s proposed concepts and methods.

3.2. Why BIM

Let us begin with the primary question that frames this chapter: why BIM? To demonstrate the need for modernization via BIM, let us start with some facts about the enormous environmental footprint of the AEC industry on our planet earth. Statistics[7] show that of the yearly worldwide CO_2 emissions, 40% are caused by the built environment. Building operations account for 27% of those total emissions annually, while construction of buildings and infrastructure and the related materials (often referred to as ‘embodied carbon’) accounts for another 13%. With that in mind, it is predicted that over the next 40 years, the world's building stock will increase by 230 billion m^2 of extra floor space to handle the most significant wave of urban expansion in human history. To put that in perspective, imagine it would be the same as adding an entire New York City to the planet each month for 40 years. Despite this tremendous environmental impact, considering the built environment as the end product, the AEC industry is still way less modernized or digitalized compared to other stationary manufacturing industries. In the past decades,

[7] Why The Building Sector? – Architecture 2030 2022.

digitization has taken hold of large areas of the economy and brought about an immense increase in productivity in a wide range of industrial sectors. One may reasonably ask why the AEC industry, with such great importance, is so underdeveloped and still lagging behind in terms of digitalization. The answer lies in the AEC industry's unique boundary conditions that make it more challenging to meet the aim of digitalization compared to other advanced stationary industrial applications such as automobile manufacturing. Borrmann et al. (Borrmann et al. 2018a, p. 83) describe these special conditions as follows:

- The design and construction of a building consist of several phases and involve many different specialist planners, which are, in many cases, performed or represented by various independent companies.
- There are a lot of small and medium-sized businesses in this sector, which is highly fragmented. According to statistics for Europe, 93% of AEC firms employ fewer than ten people.
- In the building and construction industry, ad-hoc partnerships for the period of one project, as opposed to long-term working relationships with transparent processes and duties, are more common in cross-company collaborations.

Although digital tools are also used in the AEC industry for the planning, construction and operation of buildings, the degree of reuse of digital information that has been created lags far behind that of other sectors (Borrmann et al. 2018b). Valuable information is often lost due to the predominant transfer of information via printed construction plans or digital formats that can only be reused to a limited extent. Such information breaks occur over the entire life cycle of a structure, from the planning phase through execution and the long phase of management to the modification or deconstruction of the built facility.

3.3. Why is CAD, not enough?

After the first geometric computer formalizations in the 1950s and drawing approaches in the 1960s, between 1985 and 2005, CAD (Computer Aided Design) entered the design practice of buildings. Digital tools were mainly used for representation and storing, similar to how analog information was drawn and archived with an ink pen before. As mentioned earlier, designing and constructing buildings and other facilities is a complicated process involving diverse players with varying levels of competence. A constant reconciliation and extensive flow of information among various parties are required for a successful building project. Nowadays, to a vast extent, this usually entails the handover of technical drawings, such as horizontal and vertical sections, views, and detail drawings. These line drawings were created using CAD software that mimicked the centuries-old method of working on a drawing board. Computers, on the other hand, cannot wholly understand line drawings. Computational techniques can only comprehend and process a small portion of the information these line drawings contain. The information on the building design cannot be directly used by downstream applications for any analysis, calculation, or simulation since the information depth of technical drawings is limited. Instead, it must be re-entered manually, which adds to the work and presents additional errors. After the construction is completed, the information is handed over to the building owner. In the same way, a lot of time and effort has to be put in to extract the needed information from the drawings and documentation and feed it into a facilities management system. Data previously available in digital form is lost at each of these information exchange points and must be recreated painstakingly.

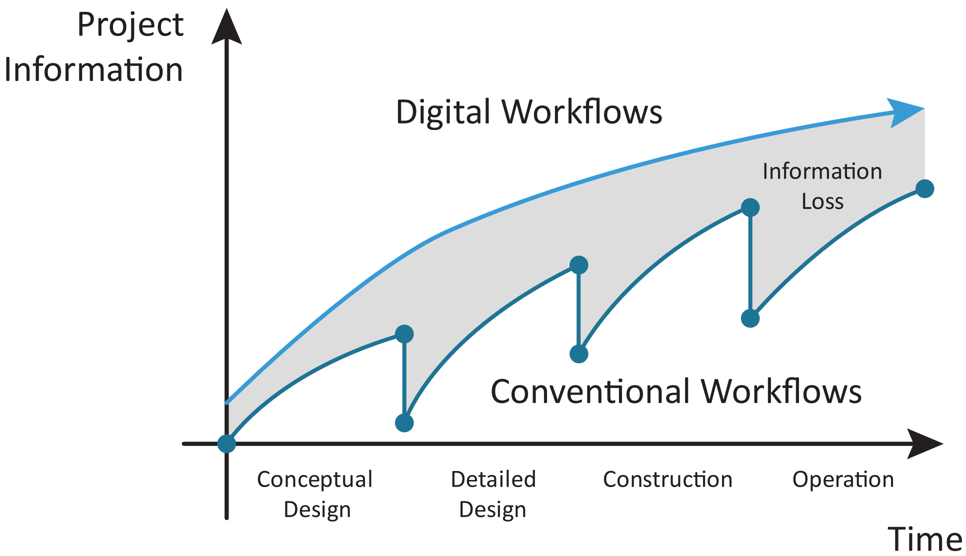

Figure 6 - Loss of information caused by disruptions in the digital information flow, based on (Borrmann et al. 2018b, p. 3)

Verifying technical drawings is a laborious manual process, posing a significant challenge. Given that drawings are created by specialists from different design disciplines and firms, this increases the likelihood of errors and inconsistencies. (Borrmann et al. 2018b, p. 2).

This is exactly where the idea of Building Information Modeling (BIM) comes in. BIM offers a more advanced approach to computer support in building planning, construction, and operation. Rather than storing building information in drawings, BIM forms a comprehensive digital building model created, maintained, and shared among stakeholders. This eliminates the need for manual verification of technical drawings and allows for more efficient collaboration across various design disciplines and firms. (Borrmann et al. 2018b).

3.4. What is BIM

Building Information Modeling (BIM) has gained significant recognition in recent years as a methodology that revolutionizes the construction industry. BIM can be seen as the second digital revolution in the construction industry, following the introduction of Computer Aided Design (CAD). The shift from 2D CAD to modeling objects (such as walls and rooms) marks the start of the construction industry's digitalization process in 2005. BIM is a potential breakthrough in the architecture, engineering, and construction (AEC) industry. There are many definitions and explanations for BIM in the literature. According to Eastman et al. (Eastman et al. 2011), BIM is a collaborative method for storing, sharing, exchanging, and managing interdisciplinary information across the lifecycle of a facility, including planning, design, construction, operation, maintenance, and end-of-life phase. Similarly, the US National Building Information Modeling Standard (NIBS) defines BIM as:

> *„a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder."*[8]

The key to BIM is the uniform formalization of construction information in digital semantic models. BIM distinguishes itself from traditional paper-based workflows by using complete digital representations called building information models to store, maintain, and share data. A building information model is a comprehensive digital model of a built facility that includes both physical and non-physical components, such as spaces and rooms, component types, technical properties, materials, costs, and relationships between them. The process of creating, modifying, and managing such a digital building model with the help of appropriate software tools is called Building Information Modeling (Borrmann et al. 2018b). BIM methodology increases the information flow between stakeholders at all stages of a built facility's life cycle, increasing efficiency by minimizing the time-consuming and error-prone manual data re-entry (Borrmann et al. 2018b, p. 3).

BIM methodology enhances the coordination of design operations, simulation integration, construction process setup and control, and the transfer of building information to the client. A complete BIM model serves as a digital twin of a facility's physical and functional

[8] Frequently Asked Questions About the National BIM Standard-United States™ | National BIM Standard - United States 2022.

characteristics and a trustworthy basis for decision-making throughout the facility's life cycle. BIM is a valuable tool that brings digitalization to the construction industry, streamlining processes, reducing errors, and increasing stakeholder collaboration. As depicted in Figure 7, along with various use cases for BIM (Borrmann et al. 2018b, p. 4).

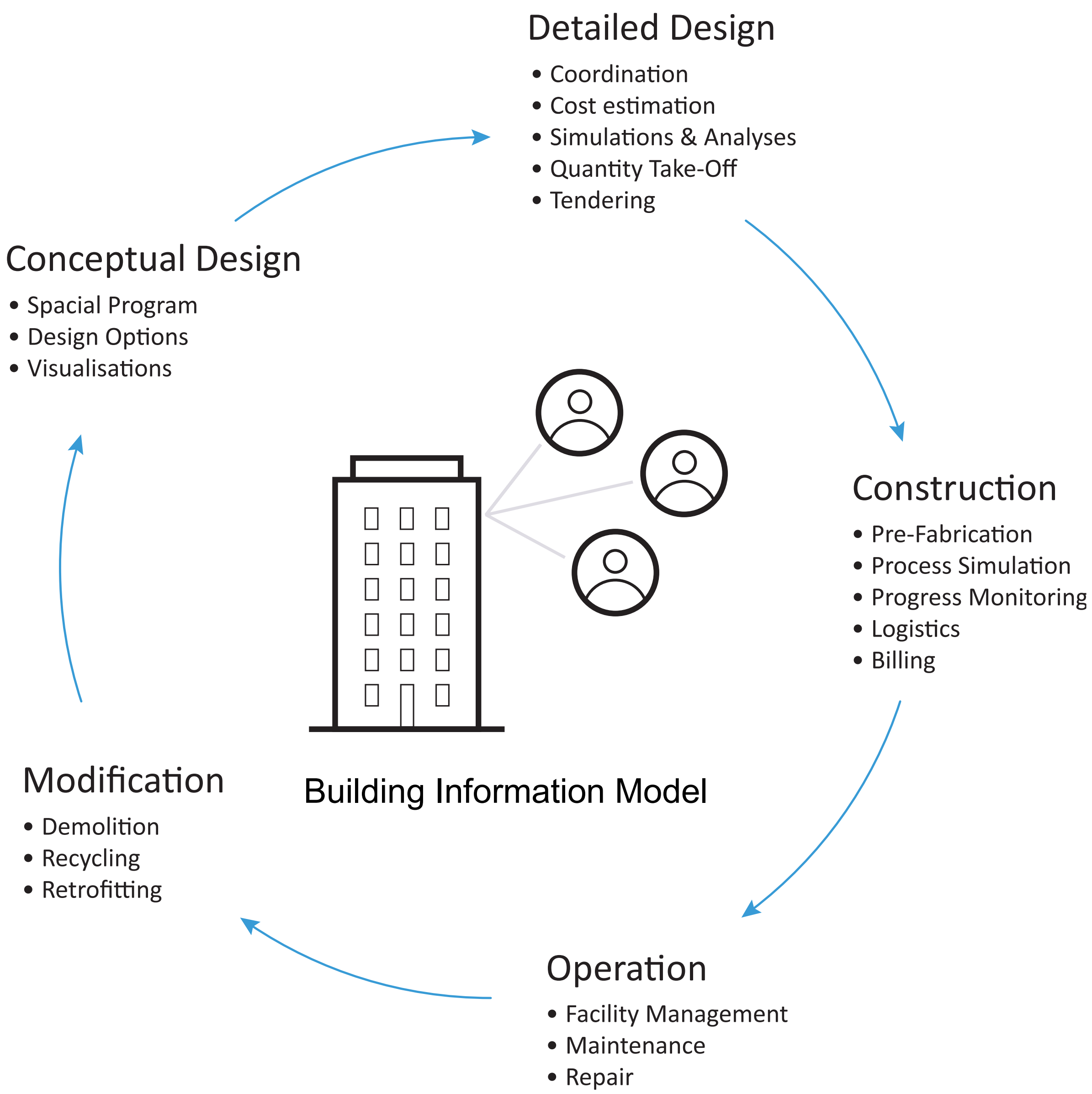

Figure 7 - Continuous use and low-loss handover of digital information throughout the entire lifecycle of a built facility (based on (Borrmann et al. 2018b, p. 5))

BIM is already being used in many building projects worldwide due to its numerous benefits. However, the fragmentation of the construction industry prevents BIM from becoming ultimately adopted and widely used. Even though BIM is potentially altering how architects, engineers and contractors conduct their work and daily jobs, it is still early in its implementation, so there is much to improve.

3.5. BIM in the design process

While BIM offers several benefits during the design phase, such as generating technical drawings, visualizing in 3D, detecting clashes, estimating costs, and coordinating disciplines, its application necessitates a shift of focus to the earlier conceptual design stages. Figure 8 illustrates this shift in design efforts. However, this poses challenges as the conceptual design phases are characterized by vagueness and uncertainty regarding design details. Architects typically rely on incomplete and imprecise conceptual sketches and schematics at this early stage. Yet, the decisions made during these phases have far-reaching consequences for the final design solution. Modifying or changing them later on can be time-consuming, costly, and demanding.

The dilemma lies in the limited availability of information during the initial design phases, despite the necessity to make crucial decisions during this time. Ullmann (Ullman 2003, p. 19) explains the relationship between knowledge about the design problem and the freedom to make decisions as follows: as the design process progresses, more knowledge about the problem and potential solutions becomes accessible, but the freedom to make design decisions within the solution space diminishes. The challenge with applying the BIM methodology, using existing software solutions and authoring tools, is that architects find it difficult and sometimes overwhelming to make numerous design decisions early on with limited information. Although these decisions may seem precise and certain at this stage, they are not, thereby narrowing their creative solution space.

Once the burden of design decisions is overcome and uncertainties are managed in the BIM-based planning process, it becomes possible to evaluate the impact of design decisions more thoroughly. The early identification and resolution of conflicts through detailed coordination planning and utilizing computational analyses in the initial design phases are all advantages of using BIM from the outset. This significantly reduces the efforts required in later phases and enhances the overall design quality.

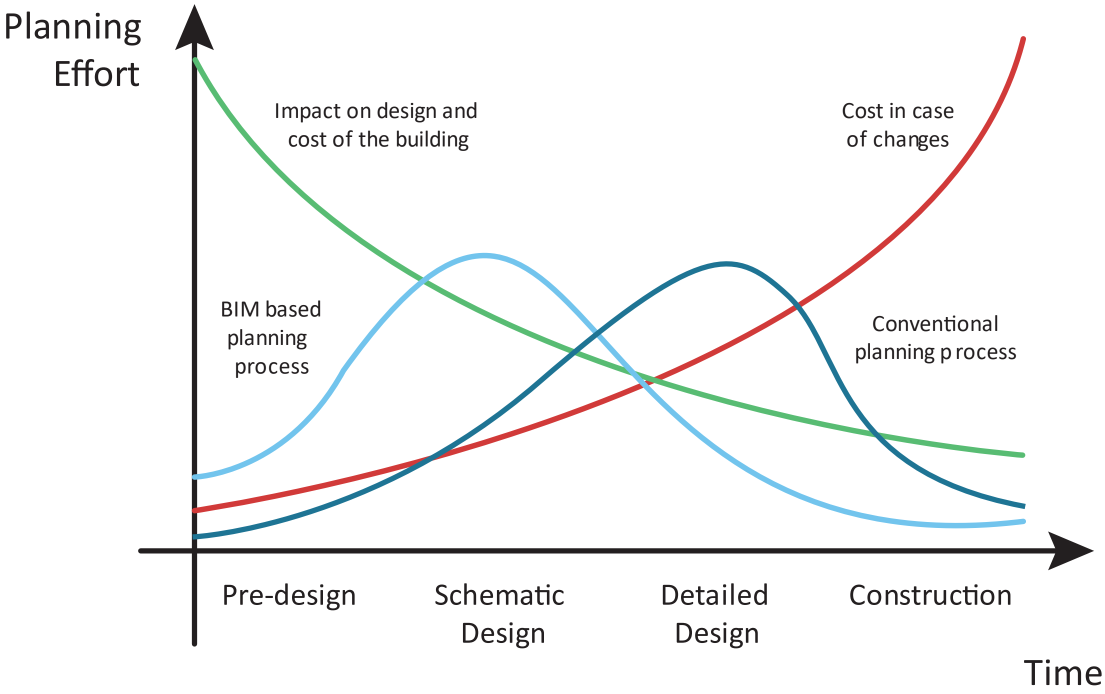

Figure 8 - By utilizing Building Information Modeling, the planning process and design choices are shifted toward the earlier stages, allowing for an opportunity to impact the design, functionality, and expenses of the final structure prior to the implementation of costly design modifications (Borrmann et al. 2018b) based on (MacLeamy 2004).

3.6. CDE (common data environment)

In the context of Building Information Modeling (BIM), CDE stands for "Common Data Environment." It refers to a centralized digital platform or repository where project stakeholders can collaboratively store, access, and manage all project-related data and information throughout the various stages of a construction project's lifecycle. The Common Data Environment is a fundamental component in BIM implementation as it serves as a single source of truth for all project data. All project-related data, including 3D BIM models, 2D drawings, specifications, schedules, documents, and communication records, are stored in a central location accessible to authorized stakeholders. It ensures that all team members, including architects, engineers, contractors, and owners, are working with the most up-to-date information, reducing the risk of errors, miscommunications, and conflicts during the design and construction phases. Furthermore, The CDE allows administrators to define user roles and permissions, ensuring that data is accessed only by authorized personnel.

3.7. IFC (industry foundation classes)

As mentioned, the AEC industry is highly fragmented, with multiple distinct and independent companies and actors. This indicates that a variety of software tools are employed. To avoid vendor lock-in, both public and private clients should avoid becoming overly reliant on any one software developer. Furthermore, governmental and public bodies must also be vendor-impartial, which means they cannot stipulate the usage of certain software products when soliciting bids for new projects. As a result, the IFC is introduced by Buildingsmart[9] as an open standard and vendor-neutral file format for data exchange between different BIM software and for various data exchange scenarios.

The IFC[10] schema is a standardized object-oriented data model that codifies the objects (both physical, like windows or beams and non-physical such as spaces and rooms), their identity, and semantics (e.g. name, machine-readable unique identifier, object type, or function), their characteristics or attributes (such as material, color, and thermal properties), their relationships (including the locations, connections, and ownership), as well as the abstract concepts (e.g. performance, costing), and the processes (like installation, operations) and people (such as owners, architects, contractors, suppliers, etc.).

3.8. BCF (BIM collaboration format)

BCF[11], short for BIM Collaboration Format, introduced by Buildingsmart as an open standard, is a pivotal component of the Building Information Modeling (BIM) ecosystem. BCF serves as the communication standard within the BIM ecosystem, enabling collaboration among multidisciplinary teams. At its core, BCF allows architects to annotate, comment, and mark up 3D models and 2D drawings, fostering effective communication. In recent versions, the BCF format went beyond simple notations, incorporating vital metadata to provide context, enhancing issue tracking and aiming to make discussions more machine-readable. It encompasses essential components like header information, topics, comments or annotations on BIM models, status and priority categorization, author details, time stamps, visual references, and customizable extensions. BCF is compatible with various BIM software applications, ensuring that professionals can communicate regardless of their BIM authoring software. Architects, engineers, contractors, and project managers can rely on BCF to streamline their collaboration efforts, minimize errors, and keep projects on track. A more detailed discussion about BCF and its capabilities and limitations will follow in section 5.2.

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[9] https://www.buildingsmart.org/

[10] https://technical.buildingsmart.org/standards/ifc/

[11] https://www.buildingsmart.org/standards/bsi-standards/bim-collaboration-format-bcf/

3.9. Integrated design process (IDP)

Integrated Design is a collaborative process that aims to achieve optimal building performance by considering various aspects and involving different disciplines (Wilde 2018, p. 339). A building's final performance is influenced by numerous factors and systems, as well as their relationships and interactions. Therefore, many efforts to enhance building performance prioritize collaboration and coordination among various disciplines. The Integrated Design approach, also known as Integral Design (also referred to as integral planning or 'Integrale Planung') or Integrated Design Process (IDP), is the associated term for this type of performance-based design. Other disciplines use similar terms, such as Integrated Project Delivery (IPD) or Integrated Product Teams (IPTs), or associate integration with optimization as Multidisciplinary Design Optimization. By using collaborative techniques and tools, the integrated design approach fosters and enables experts in multiple fields to collaborate and co-create an integrated design (Tichkiewitch and Brissaud 2013). Comprehensive integral planning[12] may include the following areas of integration:

- Professional integration (covering all disciplines such as architecture, engineering, and construction),
- Chronological integration (taking into account the entire lifecycle of the building, including the conceptual and detailed design, construction, operation, refurbishment, modification, and demolition),
- Perspective integration (equal and simultaneous consideration of the critical aspects, including investment and running costs, user comfort and health, and environmental and ecological footprints of the building)

[12] https://www.integrale-planung.net/nutzen-der-integralen-planung_1592?p=1

4. Knowledge management in architecture

This chapter delves into the field of knowledge management in architecture, recognizing its critical role in leveraging the expertise and insights accumulated within this industry. Knowledge management provides a systematic approach to capturing, organizing, and utilizing architectural design knowledge, empowering practitioners to make informed decisions and drive innovation. This chapter aims to explore various aspects of knowledge management, including the nature of architectural design knowledge and the possible techniques and tools employed for its representation and retrieval.

4.1. About knowledge

Knowledge appears to be a multifaceted notion with various meanings throughout the literature. This section starts with defining knowledge in general and then further describes what knowledge is within the context of architectural design.

Information, data, knowledge, and wisdom, however different, are sometimes used as interchangeable terms. The Data–Information–Knowledge–Wisdom (DIKW) Hierarchy, also known as 'Knowledge Hierarchy,' 'Information Hierarchy,' or 'Knowledge Pyramid,' among other names, is one of the most fundamental and generally recognized frameworks in the information and knowledge literature. The hierarchy is used to position data, information, knowledge, and occasionally wisdom in context with one another, as well as to identify and describe the processes involved in the transformation of a lower-level entity (e.g. data) into a higher-level entity (e.g. information) (Rowley 2007). The underlying premise is that data can be used to generate information, and information can be used to produce knowledge, which can then be used to create wisdom. According to Ackoff (Ackoff 1989), whose study is frequently referenced when the DIKW hierarchy is discussed, each of the higher categories in the hierarchy includes the ones that fall below it.

Attempting to enhance knowledge exchange in architecture, one must first ask: what is knowledge? Knowledge emerges in the literature as a term with numerous aspects and complex meanings. Rather than defining exact definitions, knowledge is usually treated by drawing various differences between different forms of knowledge, such as declarative and procedural knowledge (Ryle 2009) or explicit and tacit knowledge (Polanyi 2009).

One way to categorize knowledge is into explicit and implicit (or tacit) types. Explicit knowledge is knowledge that can be easily articulated and codified, such as facts, concepts, and procedures written down or recorded in some way. Implicit knowledge, on the other hand, is knowledge that is difficult to articulate or express in words and is often embedded in skills, habits, and values.

Another common classification scheme divides knowledge into three main categories: factual, conceptual, and procedural. Factual knowledge refers to knowledge of specific facts, such as dates, definitions, or lists of things. Conceptual knowledge refers to understanding concepts or abstract ideas, such as principles, theories, or frameworks. Procedural knowledge refers to knowledge of how to do something, such as skills or processes.

An additional classification scheme divides knowledge into four main categories: declarative, procedural, conditional, and situational. Declarative knowledge refers to knowledge of facts or information. Procedural knowledge refers to knowledge of how to do something. Conditional knowledge refers to knowledge of when or why to do something. Situational knowledge refers to knowledge of the context or situation in which something is done.

In architectural building design, things like different materials' properties or building codes and regulations, based on different knowledge categorizations, might be considered; explicit knowledge, or factual knowledge, or declarative knowledge. Likewise, in this context, implicit and tacit knowledge might include things like design intuition, problem-solving skills, and the ability to understand and respond to clients' needs. Similarly, conceptual knowledge might include understanding design principles or theories, and procedural knowledge might include skills in using design software or creating construction documents. Conditional knowledge might include understanding when specific design approaches are appropriate or when certain materials should be used, and situational knowledge might include awareness of the context in which the building will be constructed, such as the local climate or the users' needs.

Another way to categorize knowledge is into different domains or areas of expertise. In architectural building design, this might include categories such as structural engineering, mechanical engineering, electrical engineering, and so on.

As mentioned, unlike formal, codified, or explicit knowledge, tacit or implicit knowledge is more difficult to articulate or extract, making it even more challenging to communicate verbally or in writing to others. Personal knowledge, experience, insight, and intuition fall under this category. In other words, individually acquired knowledge and experiences are referred to as tacit knowledge, and it manifests itself in human activities as judgments, attitudes, and points of view, among other things. Tactic knowledge is often difficult to communicate directly in words. Hence, almost the only way to do so is through metaphors, drawings, or other non-verbal representation techniques. On a practical level, many experts struggle to express what they know and can do, as well as how they make judgments and reach conclusions.

In the professional setting, a difference is established between the ‘knowledge base,’ or the formal and codified domain expertise claimed by a profession (Habraken 1997), and the practitioner’s ‘knowing-in-practice,’ which is mainly implicit and learned by doing, as Schön (Schön 1987) explains it. Medical physicians, for example, must have a basic understanding of the human body, but this knowledge alone will not be sufficient to diagnose and treat a patient’s disease. Similarly, if attorneys are to apply the law successfully in actual circumstances, they must know more than the law.

4.2. Architectural design knowledge

Architecture is a broad term that refers to the art and science of building design and construction (Wilde 2018). After gaining a general understanding of the many forms of knowledge, the next question to be addressed is: what, if anything, is unique to architectural knowledge? To put it another way, why might one believe architectural knowledge is special and requires particular treatment? A first indication, according to Lawson (Lawson 2018), is that design education differs from most of what is taught in other educational institutions across the world. When visiting a design school, you will see a pattern based on the classic master-apprentice model: the students are taught by working on small but realistic design projects while being mentored by more experienced architects. The studio setting provides students with a transitional phase (Winnicott 1991), where they learn by doing (Schön 1983, 1985).

CB de Souza argues that the knowledge associated with the architectural design of buildings is mainly *constructivist*; it is a sort of knowledge that comes from experience (Souza 2012). Indeed, this unique implementation of knowing-in-practice (or Knowing-by-doing) may lead to the architectures’ reluctance to claim a shared knowledge base. The issue, according to Habraken (Habraken 1997), is not that architecture does not codify its knowledge base formally, as other professions such as law or medicine do. Given the implicitness, there should be some proof that architects communicate their knowledge and information because it is only through sharing that a professional knowledge base can be taught and learned (Habraken 1997). The architectural knowledge base appears to be mainly implicit and embedded within the architects' reasoning and creativity. And this is where the difficulty lies: not only does the architectural profession have a reputation for secrecy, but it also ignores knowledge management concepts and techniques that have achieved universal acceptance in other areas. Even the basics of having a shared lexicon are not satisfied. Moreover, architects have a worrisome proclivity for inventing their own vocabulary, coining new terms, and renaming things all the time (Heylighen et al. 2007). A key challenge here is that the professional language of architecture is not easy to define, as it can undoubtedly be seen on the one hand as a technical language, the language of civil engineers, and on the other hand as the artists' specialized language (Kuznecova and Löschmann 2008).

Another exciting indication can be found in the innovation concepts where a distinction is established between components and architectural knowledge (Henderson and Clark 1990). Architectural knowledge in the framework of innovation literature is referred to as how elements are merged and connected together to form a unified entity. This connection to architecture appears to stem from the fact that the many challenges that architects must address demand the constant acquisition and integration of ideas from several other disciplines to assist in the design process (Heylighen et al. 2007).

4.3. Objective/quantitative vs subjective/qualitative design decisions

As described in Chapter 2, the entire architectural design process is characterized by first generating and then reducing variants. Assessment and evaluation are the means to distinguishing variants concerning the fulfillment of specific criteria (requirements) to make well-founded design decisions on how to proceed. This assessment and evaluation of variants can be done based on objective (quantitative) or subjective (qualitative) criteria. The main challenge lies in agreeing on a formal definition and evaluation scale for the subjective criteria; as per the definition, a subjective judgment occurs within one's mind and is affected by individual bias[13]. The closest to achieving such formalizations could be seen in the architectural design competition procedures, which, due to public demand for transparency and fairness, the design evaluation criteria, both objective and subjective, should be formally defined with related evaluation scales and elaborated through example scenarios for each outcome. For example, for planning competitions of the public sector in Germany, in the context of design sustainability criteria, a handbook or recommendation for action called " Systematik für Nachhaltigkeitsanforderungen in Planungswettbewerben - SNAP" (Fuchs et al. 2013) was developed by the Federal Ministry of Transport and Digital

[13] WordNet 3.1 © 2011 by Princeton University

Infrastructure. Based on SNAP guidelines, the topic "sustainable development" is divided into different dimensions and then into categories (or themes) to which criteria (or aspects) are assigned. These aspects are later recorded and measured by corresponding indicators. A distinction is made between criteria and indicators: a criterion (or aspect) defines a characteristic or key distinguishing feature of the issue under consideration that is relevant to a decision. Criteria are not measurable and require specific indicators. On the other hand, an indicator is used to assess characteristics whose degree cannot be determined directly. Indicators are, therefore, (substitute) facts that make selective statements about addressed phenomena.

4.4. Formal knowledge representation techniques

Formal knowledge representation, knowledge graphs, the semantic web, and ontology are all related concepts used to represent and organize information in a way that computers can understand and use. Formal knowledge representation is the practice of representing knowledge in a way computers can process. It includes using formal languages and logical frameworks to convey information in a structured and unambiguous manner. Knowledge graphs are a specific type of formal knowledge representation that uses a graph-based data model to represent entities and their relationships. They are used to organize and make sense of large amounts of information, enabling more intelligent and accurate decision-making, especially when the relationships between entities are complex.

The semantic web is a vision for the future of the internet, where information is represented in a way that computers can understand. It aims to make the web more machine-readable by using formal knowledge representation techniques, such as Resource Description Framework (RDF) and Web Ontology Language (OWL), to represent information in a structured and unambiguous way. Ontology is a branch of formal knowledge representation that deals with representing knowledge about a specific domain, such as biology or engineering. It involves using standard languages and logical frameworks to illustrate concepts, classes, and relationships within a particular domain, which can be used to create knowledge graphs that the semantic web can use to make the web more machine-readable.

Graph databases are designed to work with graph-based data models, while relational databases are designed to work with tabular data. One of the main benefits of using a graph database is for searching since it is optimized for querying and traversing relationships between entities. In a graph database, relationships are first-class citizens, meaning they can be queried, indexed, and traversed just like entities. This allows for more efficient and accurate data querying, especially when the relationship between entities is complex or hierarchical. Another benefit of using a graph database for searching is that it allows for more flexible and expressive querying. With a graph database, you can use graph traversal languages, such as Cypher (Neo4j Graph Data Platform 2023), Gremlin (Apache TinkerPop: Gremlin 2023) or SPARQL (SPARQL Query Language for RDF 2018), to express complex queries that involve multiple entities and relationships.

Additionally, graph databases are suitable for handling large volumes of data and can scale horizontally, allowing for efficient querying of huge datasets. On the other hand, relational databases are designed to work with tabular data and are optimized for querying data based on its structure rather than its relationships. They also have a more rigid data model that can make it challenging to represent certain types of relationships, such as hierarchical relationships.

4.5. Graph representations

Graph structures have been widely used in the Architecture, Engineering, and Construction (AEC) industry for decades for various purposes, such as path planning (Hamieh et al. 2020), retrieving similar designs (Langenhan et al. 2013), integrating heterogeneous building models (Hor et al. 2016), and encoding engineering knowledge (Vilgertshofer and Borrmann 2017). The popularity of graph structures in the AEC industry is due to their ability to represent complex relationships, which is particularly useful in the Building Information Modeling (BIM) domain (Isaac et al. 2013). In BIM, nodes represent building elements, and edges represent their relationships (Khalili and Chua 2015; Denis et al. 2017; Donato 2017; Ismail et al. 2018). Depending on the use case, graphs can be simple or attributed (also referred to as property graphs), where nodes and edges hold key-value pairs (Robinson et al. 2015). The current state of research concerning the existing graph representations in the BIM domain will be discussed in more detail in the discussion of the related work (section 0) with a categorization of these efforts.

The primary benefit of using graph structures in BIM is the ability to handle large amounts of data and scale horizontally (Kolbeck et al. 2022). Graph databases optimized for querying and traversing relationships are well-suited for BIM applications that require efficient querying of large and complex datasets. Additionally, graph structures in BIM can be used to support knowledge discovery and data integration. They can connect data from multiple sources, making it more accessible and valuable, and also help identify patterns and relationships that would be difficult to discover using other methods.

In summary, graph structures are widely used in the AEC industry, particularly in the BIM domain, due to their ability to represent complex relationships and handle large amounts of data (Kolbeck et al. 2022). Graph databases are well-suited for BIM applications that require efficient querying of large and complex datasets and allow for more flexible and expressive querying. Graph structures in BIM can also support knowledge discovery and data integration.

4.6. Case-based design (CBD)

A general methodology in problem-solving called Case-Based Reasoning (CBR), is carried out by using past experiences to solve new problems (Watson 1999). Basically, four stages make up the CBR cycle (Aamodt and Plaza 1994). After describing the new problem, the following steps take place in a cycle:

- *Retrieve*: find and fetch the most similar case to the new problem from the database containing all the cases.
- *Reuse*: the information and knowledge contained in this case to solve the problem.
- *Revise*: modify or adapt the proposed solution.
- *Retain*: the new experience to be used as a possible solution for future problems.

Likewise, learning from previous design cases and using them as inspirations for solving at-hand problems or using similar details and information from other building designs is an established and well-researched methodology in architecture. The building design lends itself nicely to case-based reasoning since architects incorporate elements of earlier design solutions while creating new ones. During the building design process, architects use earlier (partial or complete) designs as inspiration or for reasoning and argumentation when developing new ideas. Significant design thoughts may be remembered during such recalls and used to inform the present design solution. 'Precedent-based' (Oxman 1990; Oxman 1994; Oxman and Oxman 1993) design is another name for utilizing prior design precedents or instances. The application of case-based reasoning to the design practice is called Case-Based Design (CBD);

> *"The process of creating a new design solution by combining and/or adapting previous design solutions" (Watson and Perera 1997).*

Watson and Perera (Watson and Perera 1997) use the design methodology of Propose-Critique-Modify (PCM) by Chandrasekaran (Chandrasekaran 1990) to illustrate the suitability of CBR for design tasks. The PCM method includes the subtasks of suggesting (proposing) whole or partial design solutions, validating suggested solutions, evaluating proposals by identifying potential sources of failure, and revising proposals to meet design objectives.

4.7. Natural language processing (NLP)

Natural Language Processing (NLP) is a branch of artificial intelligence (AI) that deals with the interaction between computers and human languages. NLP techniques can be used to analyze and understand text, speech, and other forms of natural language. They can be applied in various industries, including the architecture, engineering, and construction (AEC) industry. Some of the basic steps and techniques involved in NLP and how they work together to allow machines to understand and process natural language data are as follows (Wilbur and Sirotkin 1992):

1. **Text Preprocessing**: The first step in NLP is to preprocess the text data to prepare it for further analysis. It typically involves tasks such as tokenization, which breaks the text into individual words or phrases and stemming or lemmatization, which reduces words to their base form. Other preprocessing steps include removing stop words, special characters, punctuations, converting the text to lowercase, etc.

2. **Part-of-Speech (POS) Tagging**: The next step is to identify the parts of speech of the words in the text, such as nouns, verbs, adjectives, etc. It can be done using POS tagging algorithms, which use a set of rules or a pre-trained model to assign POS tags to the words in the text.

3. **Named Entity Recognition (NER)**: Once the POS tags have been assigned, the next step is identifying named entities, such as proper nouns, organizations, locations, and other specific entities, such as room, wall, or door in the AEC industry. NER algorithms use a set of rules or a pre-trained model to identify named entities in the text and assign them to specific categories such as Room, Wall, or Door.

4. **Chunking/Shallow Parsing**: After identifying named entities, the next step is to group the words in the text into meaningful chunks or phrases. It can be done using chunking algorithms, which group words together based on their POS tags or syntactic relationships.

5. **Dependency Parsing**: Dependency parsing aims at identifying the syntactic relationships between words in a sentence. It can be done using dependency

parsing algorithms, which analyze the sentence's grammatical structure and create a tree-like representation that shows the relationship between the words.

6. **Coreference Resolution**: Coreference resolution is identifying when two or more mentions in the text refer to the same real-world entity. For example, it might determine that "the room" and "it" both refer to the same room.

These are the basic steps and techniques commonly used in NLP, but different models or strategies might be used depending on the specific task and the data (Chen 2020). Additionally, after performing these steps, the extracted information can be stored in a structured format, such as a database or a knowledge graph, which could be used for various purposes.

5. Discussion of the related work

This chapter critically analyses and synthesizes relevant research connected to the research question/problem. This involves a review of previous studies, research, and theories in the field, highlighting their strengths and limitations, identifying gaps in these works, and presenting arguments for the significance of this research in the broader context of the field. The related work discussion is used to provide a framework for the next chapter, which is the deficit analysis followed by research methodology and concepts, demonstrating the scholarly background of this research and positioning this work in relation to previous scientific work in this field.

5.1. The EarlyBIM research group

The early stages of building design entail considering and evaluating many design choices regarding various performance criteria, such as energy or structural performance. The specialists from many disciplines participating in the design process often share and exchange building information models in order to develop a final design that meets the needs and goals of the project. Different variants are formed during this creative iterative design process, and the building design evolves throughout multiple refinement stages until one final design or multiple design alternatives are reached. As already discussed, incomplete information about the design problem and its solution, coupled with uncertainty regarding design decisions, are two major issues that arise during the early conceptual phases of building design. In the meantime, in most cases, more information and details, which are only available later in the design process, are necessary to seek expert advice on various design features (through analysis or simulations). Furthermore, most design features are still regarded as uncertain throughout these early stages, even if they appear to be precise and exactly chosen while modeling in BIM-based tools (Abualdenien and Borrmann 2019). Collaborations involving many domain experts have also been shown to be critical to developing a sound and optimum solution (Zahedi et al. 2019; Wilde 2018).

To address these challenges, the researchers in the EarlyBIM research group propose the concept of adaptive detailing strategies. Based on this concept, expert opinion could be provided to the architect to make better-informed design decisions in the early conceptual phases. Even when some details in the design model essential for analysis or simulation are missing, options to fulfill these details will be suggested based on best practice examples and in relation to the corresponding analysis results.

The EarlyBIM research group is funded by the German Research Foundation (DFG -- Deutsche Forschungsgemeinschaft) (DFG last updated: 2021) under project ID FOR 2363 (DFG - FOR 2363: Evaluation of building design variants in early phases on the basis of adaptive detailing strategies 2017). The main objective of the research group is to develop new methods to demonstrate the enormous potential of model-supported and simulation-based design planning and the possibilities for its technical implementation. Several fundamental concepts were introduced during the first funding phase of this research project (Abualdenien et al. 2020); for example, Abualdenien and Borrmann developed a multi-LOD meta-model for formal specification of maturity levels of building information models while allowing the explicit expression of potential information vagueness during the early design phases (Abualdenien and Borrmann 2019). Abualdenien and Borrmann also provided several methods and concepts for visualizing ambiguity and uncertainty in building models at various design phases (Abualdenien and Borrmann 2020b) and concepts for formally evaluating and classifying the geometric details of building parts (Abualdenien and Borrmann 2020). Matern and König proposed a method for handling numerous design variants in a consistent digital building model throughout several planning phases (Mattern and König 2018). Zahedi and Petzold introduced a machine-interpretable communication protocol based on BIM that can support various projects and requirements (Zahedi and Petzold 2019a), which can also couple with the multi-LOD meta-model from Abualdenien and Borrmann to define the exchange requirements for various analysis and simulation methods in different Building Development Levels (BDL) (Zahedi et al. 2019). Zahedi & Petzold also tried out and demonstrated various visualization methods (Zahedi and Petzold 2019b) for the assessment and comparison of design variants to support decision-making (Jaskula et al. 2021) as well as the feedback from domain specialists (Meng et al. 2020). In contrast to the dynamic simulation technique, Geyer and Singaravel showed that engineering surrogate models based on components and machine learning (ML) can forecast energy consumption with the needed accuracy (Geyer and Singaravel 2018) and with a minimal prediction gap (Singh et al. 2020).

In its second funding phase, the EarlyBIM research group focuses on capturing, reusing, and optimizing knowledge for creating and evaluating building design variants. In this phase, various scientific questions are addressed in the individual sub-projects. How can detailing processes between different design variants be transferred as automatically and comprehensibly as possible? And how can experience gained in the creation of variants from similar projects be easily integrated into the current design? In response to these questions, Zahedi et al. (Zahedi et al. 2022) introduced an extension to the multi-LOD model to include design knowledge and constraints and to enable the BIM-based design decisions documentation. Furthermore, Zahedi and Petzold also implemented an add-on for Autodesk Revit to capture the tacit design knowledge and support its reuse by exporting it to a graph database (Zahedi and Petzold 2022). In another paper, Napps et al. coupled design variants management with the above-mentioned BIM-based plugin for design knowledge documentation (Napps et al. 2022). To capture the detailing patterns in building models and enable their transfer to other models, Abualdenien and Borrmann introduced a parametric building graph (PBG) (Abualdenien and Borrmann 2021). Another scientific question is how the potentials for improving building designs can be better recognized, and planners be supported in a more targeted manner. To show design potentials and tendencies as a link between the early stages of design and prospective future outcomes, Staudt et al. (Johannes Staudt et al. 2022) used the life-cycle assessment (LCA) of a real-world case study to demonstrate the process of designing and detailing with guidance from potentials and improvement opportunities.

5.1.1. Extensions to multi-LOD meta-model

Explicitly defining design requirements and constraints can facilitate the documentation of design intentions and decisions, particularly in the early stages of the design process. Furthermore, such conditions can be checked to ensure that design decisions are consistent and adhered to throughout the design process. As a result, the meta-model (Abualdenien and Borrmann 2019) design has been expanded to include documentation of design decisions and constraints (Zahedi et al. 2022). Specifically, the data-model level has been extended to enable the definition of design knowledge in three forms: explanation tags (which will be discussed in more detail in Section 7.2), design requirements (which can include RFP requirements or building code provisions), and design episodes (which will be discussed in more detail in Section 7.3). At the instance level, ETs, requirements, and DEs can be assigned to describe components, property values, and constraints. This documentation records the rationale behind using a specific property value or constraint.

While constraints are primarily used to maintain design decisions throughout the design process, explanation tags and design episodes are used to document and explain design decisions in more detail. To draw an analogy from software design, constraints in this concept serve as frameworks and blueprints that keep the further detailing and development of design decisions in line with previously established fundamental choices. While ETs are akin to commenting on the code while programming to ensure its comprehensibility later on, DEs are like code snippets that can be used later in other projects to address similar tasks or challenges.

5.2. Model-based issue management, communication and collaboration

Throughout a project, the design team and many other technical specialists must discuss various details and objects in the design model. Doing so over the phone or via email carries inconsistencies and ambiguity and is inefficient for collaboration and communication. As a result, model-based issue-management, communication, and collaboration via leveraging Building Information Modeling (BIM) is a promising area of research with still some challenges. However, there are various BIM software with different file formats.

One of the long-standing goals in the architectural design and construction sector is to achieve full semantic interoperability. Thus, a vendor-neutral standard data model such as IFC is needed for exchanging information between various BIM software. The BIM Collaboration Format (BCF) was created to allow multiple project participants to exchange concerns in a BIM model while utilizing various software programs. Buildingsmart, an international organization that aims to provide open standards and exchange formats, such as the IFC file format, created BCF to enhance the flow of information between various BIM applications. BCF enables model-based communication of various issues between project participants by leveraging IFC data that is shared among them. Bypassing proprietary formats and workflows, BCF was developed to improve IFC-based processes and facilitate open communication so that BIM software tools may more easily discover and communicate model-based concerns. The issues can be created and assigned to other planners. Given the issues, the planner might then remark on them or allocate them to someone else. So that these Issues may be monitored in the BIM process, the status of an Issue in a BCF can be altered.

BCF can be used in one of two ways: as a web service or file-based exchange. A BCF file (.bcfzip) is sent from user to user, changed, and then returned in the file-based exchange procedure. Contrary to the recommended IFC file procedures, BCF files can be "roundtripped" as long as everyone upholds the shared BCF file's integrity and no further copies are distributed. A web service RESTful API option for BCF may be used as an alternative to the file-based process. This entails setting up a BCF server, which might also function as a BIM server, to store all the BCF data and let team members coordinate the creation, modification, and maintenance of BCF topics on a centralized CMD (common data environment).

Despite being well suited for its initial purpose, the BCF format is limited and not flexible enough to retrieve or change the information in combination with the BIM models (Schulz et al. 2021). Even though the BCF issues are linked to model elements and their geometrical position, they are only loosely connected to the actual BIM model and its information. To tackle this problem, Schulz et al. introduced the BIM Collaboration Format Ontology (bcfOWL), which translates the format to the Semantic Web and allows for extended relationships between a BIM model and BCF information (Schulz et al. 2021). The authors claim that the ontology enables integration into the Linked Building Data environment and facilitates access to synergies between heterogeneous building data without losing compatibility with existing implementations and workflows.

The use of semantic web technologies in architecture, engineering, and construction has significantly risen in recent years. These technologies are considered to enhance BIM software. Among the main reasons to adopt these technologies in the AEC domain are: (1) to address the lack of compatibility among software tools used in different disciplines or, at the very least, to streamline information exchange processes and (2) to connect with various application domains that have potential to uncover valuable resources connected to information already available in the AEC domain (Pauwels et al. 2017). Thus, the use of these technologies in the AEC domains is driven by two goals: (1) a desire to solve the problem of software tool interoperability across diverse disciplines, or at least improve information exchange processes, and (2) a desire to connect to various application domains that have opportunities to identify underutilized valuable resources closely linked to the information already obtained in the AEC domains. Pauwels et al. (Pauwels et al. 2017) presented a review of semantic web technologies in the AEC, including the interoperability category. The ifcOWL ontology was created by the BuildingSMART Linked Data Working Group, which may be used as a domain ontology for the AEC sector. Pauwels and Terkaj (Pauwels and Terkaj 2016) provide one of the most thorough studies of the transition from IFC schema to OWL ontology for the construction sector (ifcOWL).

Recently, there has been a growing interest in using cloud technologies and linked data techniques to improve the delivery and exchange of project files such as BIM models, drawings, images, etc. One example is the micro-service approach developed by Senthilvel et al. for delivering project files following the ISO 21597 standard for information containers (Senthilvel et al. 2021). Additionally, Karlapudi et al. have studied the features of ISO 21597 and conducted a case study to evaluate the use of SPARQL queries in information containers (Karlapudi et al. 2021). To make it easier to trace design changes and reduce the overhead of sharing information in BIM projects among team members, Esser et al. suggest using an event-driven system architecture, commonly used in modern communication systems, in combination with the publish-subscribe design pattern, patch-based update mechanisms for BIM models, and asynchronous, decentralized collaboration (Esser et al. 2022a).

5.3. Tacit design knowledge acquisition

Identification of the knowledge categories that companies hold and should maintain is an integral part of knowledge capture (Wang and Leite 2016b). Finding where new knowledge is formed and who has the appropriate expertise is also essential (Yu and Yang 2018). Due to delays in time, significant personnel turnover, and reassignments, knowledge loss is widespread in the construction industry (Kamara et al. 2003). Particular attention should be paid to tacit design knowledge (Jia et al. 2022). Various knowledge-capturing approaches, such as expert interviews, weekly site meetings, lessons learned meetings during a project, training, and post-project evaluations, are suggested by Song et al. (Song et al. 2016), Jia et al. (Jia et al. 2022), Tan et al. (Tan et al. 2007) as well as Wang and Meng (Wang and Meng 2021) to be used in construction projects. Expert interviews are the most commonly utilized technique for extracting knowledge (Song et al. 2016). By way of an interview, professionals communicate their underlying expertise by directly responding to a series of unstructured, semi-structured, or structured questions (Song et al. 2016).

However, many of these approaches have some limitations. One such example is the use of post-project reviews, which typically take place at the end of a project to gather lessons learned. However, there is often not enough time to conduct an adequate review because relevant personnel may have already moved on to the next project (Udeaja et al. 2008). As a result, even in the case of a successful post-project review, the current project team cannot utilize the gathered knowledge because the project is nearly finished (Tan et al. 2012). The practice of gathering knowledge through post-project reviews has been criticized for resulting in the loss of valuable lessons learned during the project. To overcome this, Kamara, Anumba, and Carrillo (Kamara et al. 2003) proposed the idea of capturing knowledge in real-time during the project. Several studies (Tan et al. 2007; Udeaja et al. 2008; Tan et al. 2012) have developed information technology-based systems to implement this real-time capturing of knowledge concept. However, these systems do not account for the varying knowledge needs of different project participants, which can result in excessive or duplicated information being captured (Wang and Meng

2021). Furthermore, these studies do not consider the context in which the knowledge was acquired (Wang and Meng 2021).

Other frequently employed knowledge acquisition techniques include data mining (Chen and Rao 2008), fuzzy mathematics (Azadeh et al. 2010; Castro-Schez et al. 2013), and manual extraction (Liu et al. 2014). Data mining methods used to gather knowledge include neural networks, Bayesian networks, regression, key graph algorithms, and rule-based data mining. Data mining tools can help automate the process of knowledge acquisition, which can be facilitated by fuzzy math to connect numerical data and knowledge ideas. However, the knowledge sources often contain inconsistencies and redundancies and are highly dimensional, which may require manual labor in the acquisition process. For example, in their research, Song and colleagues (Song et al. 2016) suggested a context-aware approach for acquiring experiential knowledge (EK), utilizing Q&A to facilitate experimental knowledge acquisition, combined with machine learning techniques to classify sentences into appropriate Q&A elements.

Different methods have been proposed for acquiring knowledge, but there is a gap in getting Tacit Design Knowledge (TDK). Sometimes, knowledge engineers process TDK instead of the experts, so it does not match the personal nature of the knowledge. It is also hard to get TDK directly only through interviews or conversations when it is not connected to actual design elements and models. Additionally, experts may not want to share their TDK. This knowledge acquisition bottleneck is a significant issue for design firms. Data mining might be a way to get TDK indirectly, but there is no reliable method yet.

5.4. Design knowledge capture in semantic models

Previous research has identified the difficulty in establishing a formalized schema for capturing the complex knowledge present in construction projects (Motawa and Almarshad 2013). However, Building Information Modeling (BIM) has been identified as a helpful tool for improving knowledge capture due to its object-oriented nature, parameter-driven approach, and lifecycle management philosophy (Wang and Meng 2019). Various studies have suggested that BIM can be used for capturing process knowledge representation (Wang and Leite 2016a), failure-cause-effect knowledge (Pärn et al. 2017), risk-related knowledge (Okudan et al. 2021), and knowledge generated by different project parties during collaboration (Aragao and El-Diraby 2021). BIM's lifecycle management philosophy enables design knowledge to be captured and retained, at the very least in its final solution version, in semantic models to help avert knowledge loss due to staff turnover. One approach some researchers use to capture knowledge related to specific objects or projects is to create customized objects or parameters in the BIM model. An example of this approach is the work done by Deshpande et al. (Deshpande et al. 2014), which added custom parameters about problems, solutions, and expert contacts to the BIM model. Another way is to use an application programming interface (API) provided by BIM software vendors to implement the parameters in BIM models through addons and plugins or external applications. Researchers such as (Wang and Leite 2016b; Lin 2014; Ho et al. 2013), have applied this approach; including this dissertation; more details will be discussed in sections 8.1 & 8.2. The last way is to capture knowledge by integrating BIM with other external tools or systems, such as facility management systems, using techniques like linked data and ontologies to improve data interoperability in a BIM environment (Ding et al. 2016). In another example, Fruchter et al. (Fruchter et al. 2009) introduced and incorporated two knowledge capture systems named RECALL and TalkingPaper into BIM models to capture knowledge in conversations and audio-sketch objects.

Furthermore, BIM-based collaborative platforms bring together resources from diverse disciplinary teams, facilitating the capture of knowledge generated by different project parties during the collaboration process. For example, Aragao and El-Diraby (Aragao and El-Diraby 2021) have created a BIM-based interaction platform that simplifies communication between project shareholders and offers a new source of knowledge capture. Some other studies, such as (Okudan et al. 2021), (del Amo et al. 2022), have combined CBR with BIM to capture knowledge during construction projects.

However, some studies highlight that it is crucial to avoid knowledge redundancy when using this federated BIM-based knowledge capture (Suresh et al. 2019; Pärn et al. 2017). In the author’s opinion, it is also equally important not to neglect the capture of design rationale during BIM-based knowledge acquisition. Finally, it has been suggested that integrating employer information requirements and BIM-based knowledge management can be an effective mechanism for capturing the required knowledge (Wang and Meng 2021).

5.5. References and knowledge extraction from semantic models

Using references in architecture is considered a recognized method (Gänshirt 2012) for supporting design, testing ideas, clarifying design parameters, or showing new ways and possibilities. In other words, using best-practice projects as references is a well-established architectural method to support decision-making. The built and planned design models serve as a knowledge base that includes spatial configurations and solutions for specific architectural expressions. Using analogies in references is an efficient method for documentation, both in design and downstream activities. A retrieval system is a prerequisite for effectively managing and using these models as possible references.

The process of identifying and retrieving text-based information in document collections has been widely studied in two main categories; statistical vs semantic techniques (Zou et al. 2017). On the one hand, are statistical approaches that often rely on keyword matching without considering the meanings of terms and semantic relationships. Some example studies in this category are (Marzouk and Enaba 2019) to find crucial phrases in a project contract that needed to be actively watched (Caldas and Soibelman 2006) to classify and retrieve documents in a model-based information system (Kovacevic et al. 2008) to gather relevant answers from websites to assist in decision-making, (Fan and Li 2013) to find alternate dispute remedies in construction accidents, (Shen et al. 2017) combining text mining with CBR to find relevant knowledge cases when designing green buildings.

On the other hand, semantic approaches, which rely on term meanings rather than literal strings, are applied in natural language processing (NLP) systems. Ontology was used to facilitate semantic search and define concepts in a specific domain, which characterizes semantics. For instance, Park et al. (Park et al. 2013) developed an ontology-based system that suggested related search words to users, while Wu et al. (Wu et al. 2021a) used ontology to automate knowledge retrieval in concrete bridge rehabilitation. Xu et al. (Xu et al. 2019) presented highway construction knowledge to support retrieval during the inspection process, and Yuan et al. (Yuan et al. 2018) developed an ontology to represent residual-value risk factors and vulnerabilities, enabling retrieval of specific limitations through query functions. Relevant studies have identified several shortcomings of ontologies, including the high costs involved in their creation (Jain and Singh 2013), their limited ability to represent concepts and relationships only within a specific domain (Wang and Meng 2019), and their inability to handle a large number of diverse terms (Jain and Singh 2013). Recently, some studies, such as (Zangeneh and McCabe 2020; Wagner et al. 2022; Soman et al. 2020), have integrated linked data into ontology-based systems to enable uniform knowledge retrieval across multiple domains.

Due to the growing acceptance of BIM methodology, BIM models are increasingly being stored in cloud repositories. Most commercial BIM retrieval approaches use text-based and keyword-based search strategies that rely on metadata (e.g. keywords, tags, descriptions). Gao et al. (Gao et al. 2015) presented a concept for a text-based semantic search engine and its prototypical implementation, “BIMSeek”, to make online BIM resources accessible. Based on the IFC data model, this approach built a domain ontology to encode BIM-specific knowledge in the search engine (Gao et al. 2015). In this approach, by combining ontology and local context analysis techniques, an automatic search-enhancement method was integrated to improve search performance (Gao et al. 2015). In addition to the textual search, a graphical search is also a viable solution; examples of which are presented by Inanc (Inanc 2000) with a 2D graphical search as well as Funkhouser et al. (Funkhouser et al. 2003) with a 3D graphical search. Whereas, Demian et al. (Demian et al. 2016) presented a combination of graphical and topological searches.

Using graphs in the BIM context for analyzing and extracting information and knowledge has been the focus of various national and international research projects. Langenhan et al. introduced the concept of the semantic fingerprint of buildings to formalize architectural spatial situations and computer-aided similarity determination (Langenhan et al. 2013). Furthermore, Eisenstadtet al. designed an extension assistance system based on the distributed AI-based methodology FLEA (Find, Learn, Explain, Adapt) to inform architects and offer solution suggestions on how the current floor plan solution tends to evolve during the design process (Eisenstadt et al. 2018; Eisenstadt et al. 2019). Further detailed investigation of the state of the art regarding various graph representations in the AEC will be discussed in section 5.6.

5.6. Various graph representations in the AEC

Researchers in the AEC sector have been using graph structure for a variety of use cases, such as path planning (Rüppel et al. 2010; Kneidl et al. 2012), retrieval of related designs (Langenhan et al. 2013), combining GIS and BIM models (Hor et al. 2016), BIM variants and version management (Mattern and König 2018; Esser et al. 2022b), engineering knowledge (Vilgertshofer and Borrmann 2017) or structural aspects of construction (Vestartas 2021) so on. Due to their capacity to depict complicated interactions, like those seen in BIM (Isaac et al. 2013), graph structures are common in various fields. Most of the graphs created in the BIM field have nodes that represent building elements and, in some cases, their attributes as well, and edges that stand in for the connections and relationships between those elements (Ismail et al. 2018; Khalili and Chua 2015). Such graphs can vary in complexity from basic nodes and edges to attributed graphs, where nodes and edges contain characteristics depending on the use-case (key-value pairs).

Space layouts and floor plans are essential aspects of architectural building design, and thus, a significant category for graph representations in the context of AEC is space connectivity graphs. In these graphs, Spaces are represented as nodes, and edges represent either (or both) the accessibility or (and) adjacency between the different spaces. Possible use cases for these space connectivity graphs in the literature include evaluating the similarity between designs (He et al. 2018) or in the form of so-called fingerprints (Langenhan et al. 2013), evaluating design quality (Donato 2017), reasoning about disability mobility (Strug and Ślusarczyk 2017), emergency path planning (Rüppel et al. 2010; Ismail et al. 2018), and security analysis (Porter et al. 2014). Another similar category of applying graph representation in AEC is for Navigation. These graphs are used, for example, for simulating pedestrians' behavior or navigating robots and drones, where just a space graph is not sufficient. They include additional special nodes representing visibility points, such as the work done by (Kneidl et al. 2012) or navigation tasks and interaction with the environment as presented by (Dubey et al. 2020).

Another major category of graph representations in AEC focuses on different ways of translating and representing IFC model graphs, examples of which are the work done by (Khalili and Chua 2015) for topological queries on building elements or the work done by (Ismail et al. 2018) for building knowledge extraction or with the focus on design variants management as the research done by (Mattern and König 2018) and (Exner et al. 2019). In these graphs, the resultant nodes represent building elements, their geometric representations, material layers, and more. Additionally, graph transformations can be used to describe changes to a BIM model and facilitate version control by transmitting modifications as graph transformation rules. For example, Esser et al. presented a method for object-based version control in Building Information Modeling (BIM) by first representing the object networks of BIM models as formal property graph structures and then describing changes to the model using graph transformations (Esser et al. 2022b).

One more key category of graph representations addressed by many researchers focuses on knowledge representation graphs, examples of which are for formalizing infrastructure construction knowledge as done by (Vilgertshofer and Borrmann 2017) or for BIM-based rules and requirement analysis done by (Solihin and Eastman 2016) and linking heterogeneous data models. These graphs either use a customized graph representation or a combination of multiple graph structures. Ontology approaches have also been used to provide machine-interpretable building representations to seamlessly exchange BIM models through web services such as the Building Topology Ontology (BOT) done by (Rasmussen et al. 2021).

5.7. Application of NLP in AEC

The AEC sector experiences challenges with requirements management and traceability that can negatively impact the entire construction process (Arayici et al. 2006).

Requirements serve as every construction project's origin, defining stakeholder and user needs and criteria for the final built facility. Effective requirement management is critical for planning, risk management, information exchange, and control of design modifications, as noted by (Hull et al. 2005), playing a vital role in the preliminary design phase and throughout the design and construction process (Yu et al. 2010). Therefore, proper identification and management of requirements are essential for project success. Information contained in the client's needs (request for proposal-RFP) or knowledge from building codes and regulations represented in plaintext must be extracted and used during the design process. A key stream of research aims to utilize Natural Language Processing (NLP) techniques to provide a machine-interpretable representation of these text sources and automatically extract valuable information from them. Researcher studies used NLP to serve a variety of use cases in the AEC sector. To automatically categorize the various case studies of building projects according to their use of BIM, Jung and Lee developed and leveraged a system based on NLP and unsupervised learning (Jung and Lee 2019). Furthermore, Salama and El-Gohary (Salama and El-Gohary 2016) integrated supervised learning algorithms with NLP to aid in executing an automated compliance assessment. Also, Song et al. (Song et al. 2018) leveraged NLP for semantic analysis of regulatory sentences and its utilization for automated rule checking.

Additionally, Lin et al. (Lin et al. 2016) presented a method for data retrieval from cloud-hosted BIM models, while Wu et al. (Wu et al. 2019) offered an NLP-based retrieval engine for BIM object databases using a domain ontology. A study by Amer et al. (Amer et al. 2022) utilized deep learning in natural language processing (NLP) to learn construction-scheduling domain knowledge from existing records automatically. Another study by Feng and Chen (Feng and Chen 2021) highlighted the importance of training feature extractors on large amounts of data. It proposed a strategy to train them on small samples without compromising performance. Jallan and Ashuri (Jallan and Ashuri 2020) applied deep learning in their NLP model to retrieve risk information from textual disclosures, while Wu et al. (Wu et al. 2021b) used deep learning-based NLP to recognize communication-oriented entities within patent documents.

Additionally, Fang et al. (Fang et al. 2020) employed deep learning neural networks to automatically classify near-miss information in safety reports, which helps site managers better understand the nature of near-misses. However, relying solely on text to extract information and knowledge may overlook the role of project attributes, potentially affecting the applicability of information and expertise in construction projects (Wang et al. 2022). In summary, in the context of BIM, NLP techniques are used by many researchers to improve the domain knowledge management and semantic modeling of requirements definition (Di Giuda et al. 2020). Using NLP techniques to model the semantic data in text documents at the early stage might prevent or decrease mistakes when finding and translating textual needs into semi-formal or formal requirements (Di Giuda et al. 2020).

5.8. Application of CBR in AEC

Several studies have applied Case-Based Reasoning (CBR) in AEC, particularly in construction project management. For instance, several studies used some combination of CBR to estimate project cost, such as An et al. (An et al. 2007), Ahn et al. (Ahn et al. 2020), Hyung et al. (Hyung et al. 2020), Jung et al. (Jung et al. 2020), Le´sniak and Zima (Leśniak and Zima 2018), and Ji et al. (Ji et al. 2018). Further research studies have used CBR techniques in other various areas of construction project management. These include estimating project duration (Jin et al. 2016), mining and retrieving experiences for dispute settlement (Liu et al. 2019), safety control (Jiang et al. 2020; Pereira et al. 2018a; Pereira et al. 2018b; Goh and Guo 2018), construction planning (Ryu et al. 2007), contractor selection (Juan 2009), risk identification (Somi et al. 2021), and construction noise prediction (Kwon et al. 2017).

The application of CBR in design, as discussed in section 4.6, is called Case-Base Design (CBD). Based on two review papers by Heylighen et al. and Richter et al. (Heylighen and Neuckermans 2001; Richter et al. 2007), some example case-based design (CBD) tools and studies include Archie-II (Domeshek and Kolodner 1992; Domeshek and Kolodner 1993), CADRE (Hua et al. 1996; Hua and Faltings 1993), FABEL (Voss 1997; Schmidt-Belz and Hovestadt 1996), IDIOM (Smith et al. 1995; Smith et al. 1996), PRECEDENTS (Oxman 1994), SEED-Layout (Flemming et al. 2003), SL-CB (Lee et al. 2002), TRACE (Mubarak 2004), CaseBook (Inanc 2000), MONEO (Taha et al. 2007) and Case Base for Architecture-CBA (LIN and CHIU 2003).

5.9. Key findings and implications for this work

One of the key challenging areas for further research based on the above literature review is developing a system or framework that facilitates the model-based and machine-interpretable communication and exchange of information between stakeholders within the AEC industry. This gap will be addressed in this dissertation via the Feedback mechanism.

In addition, while the significance of Tacit Design Knowledge has been well-established in architectural design, its unarticulated nature poses a challenge in capturing, representing, and reusing it effectively. This difficulty has been a longstanding issue in managing and reusing architectural firms' designs and intellectual property, as well as glitches with expert employees leaving the company. Furthermore, the ability to break down complex design problems into reusable fragments, which can then be synthesized into a cohesive solution, is perhaps the most significant and yet missing in the above-mentioned valuable contributions. This gap will be addressed via Design episodes and Explanation tags.

Furthermore, this literature review shows that NLP techniques applied to BIM models can potentially improve the semantic modeling of requirements definition and domain knowledge management. Using NLP methods to model semantic information found in text documents during the preliminary phase or while documenting design decisions, design errors or deviations that may occur during later stages could be avoided or minimized. Besides, valuable lessons could be learned from documented design decisions, which can be used in the future as a source of inspiration and to avoid redoing the work or making the same mistakes again. Methods for partially reusing design knowledge based on NLP techniques are presented in section 8.3.1. Moreover, graph models provide a powerful and flexible representation of architectural design knowledge and have the potential to support its reuse. Proposals on how to utilize graph models to capture and reuse architectural design knowledge are presented in section 7.4. Further research is required on Human-Computer-Interaction, which primarily relates to design knowledge documentation and case representation. Related implementations and demonstrations are presented in sections 8.2 & 8.3.

6. Deficit analysis

The building design process is complex and multi-faceted, involving a wide range of actors with various knowledge and expertise. First and foremost, at the center of this process are the architects as the lead designers in the team. They must have a strong foundation in design principles and a sound understanding of materials, construction methods, building codes, and regulations. They may require expert opinions about many technical topics to create functional, safe, and aesthetically pleasing buildings. In addition, architects must also comprehend clients' needs and preferences, the site's constraints, and the social, cultural, and environmental context in which the building will be constructed. What makes it even more challenging is that designing a building involves a process of continuous learning and coevolving of the design task and final solution. Effective communication and collaboration are essential for ensuring that the knowledge and expertise of individual architects and other domain specialists are shared and leveraged within the team and the organization. As such, architectural building design knowledge is constantly evolving and expanding. Thus, managing and preserving architectural design knowledge is essential for creating successful and meaningful building projects. It involves various technical and creative skills that must be carefully balanced to produce functional, efficient, and sustainable buildings. Figure 9 portrays an exemplary architectural building design process.

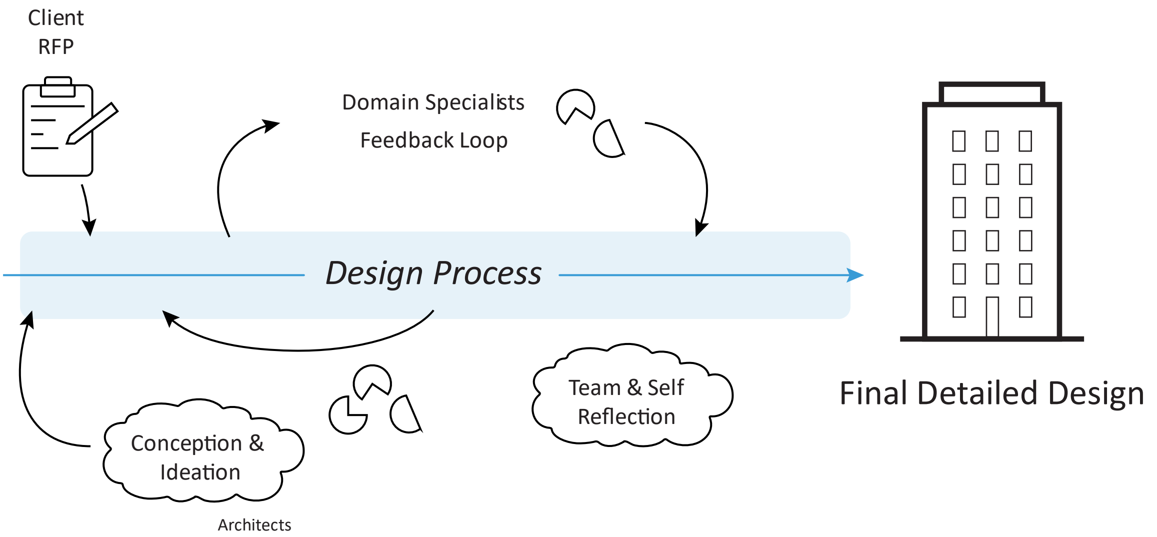


Figure 9 - Architectural Building Design Process

As already discussed in the previous chapters, in today's architectural design practice, digital models, if any exist, are only created for the final design and not for the intermediary stages and phases. Design decisions are hardly ever documented or explained.

Furthermore, communication between many stakeholders, especially between the architects and other domain specialists, is rarely done through model-based frameworks. If so, the contents of the exchanged feedback are neither machine-interpretable nor minimized. It makes all this valuable feedback and expert suggestions incomprehensible to computers and, therefore, unintelligible to future analysis and learning.

Furthermore, using HOAI for illustration, a crucial observation emerges that the standard negotiations and exchanges between architects and other domain experts mainly commence in LPH 3, with rare initiation in LPH 2. In this phase, preliminary plans are presented, laying the groundwork for other domain experts to integrate their services. Subsequently, in LPH 4, the creation of templates for regulatory standards approvals unfolds, incorporating insights from other domain experts. Notably, the refinement of technical details typically reaches maturity in LPH 5 during the development of comprehensive execution plans. However, some complicated technicalities are still negotiated and addressed in LPH 6, 7, and even 8. These negotiations may involve multiple iterations and corrections of previous design decisions, potentially resulting in additional costs and time.

The AEC industry's fragmented nature has led to many working methods and software solutions, resulting in the need to transfer digital information across various interfaces. Even in advanced companies that employ BIM authoring tools for design, most communications between architects and engineers still occur outside these BIM platforms, typically through emails and telephone calls. While some closed BIM solutions and platforms offer model-based communication and collaboration features, most interactions remain human-interpretable. They heavily rely on screenshots, annotations, and comments that lack comprehensibility for computers and automated processes.

Besides the closed BIM solutions, one potential solution that has emerged is using the BIM Collaboration Format (BCF) as an open standard for communication and issue tracking. However, it is essential to note that the machine-interpretable features and capabilities of BCF are not yet fully functional in practice and face limitations in their current state, such as the fact that all fields for the description are plain text. This presents an opportunity for improvement by incorporating our novel concepts and methods. It would allow for better machine interpretability and automated processing of design issues and communications, reducing the reliance on human interpretation and enabling smoother collaboration between actors within the AEC industry.

Numerous vital decisions are made throughout the design of a built facility, either based on feedback from other domain experts or based on self-reflection, which are often not documented explicitly or communicated clearly to other stakeholders, even when using BIM methodology and semantical digital models. As a result, the reasoning behind the decisions is lost, and the design knowledge is only shared verbally, if at all. Furthermore, in reality, these design decisions are not separate artifacts and need to be linked to individual design model elements or even their specific attributes. These valuable and vital design decisions, together with their related design model elements and the rationale and argumentation behind them, if captured properly, can be reused as a valuable chunk of architectural knowledge. Figure 10 demonstrates this deficit and compares the undocumented design process versus the machine-interpretable documented version of it, which is intended as the goal of this work to address this deficiency.

In this illustration, special attention should be drawn to the small boxes to depict valuable design knowledge and details within the large boxes that gradually and incrementally form the final design solution. In the top half of this illustration (undocumented design process), all of these cubes are greyed out and, in other words, unknown or lost due to a lack of machine-interpretable communication and decision documentation. In contrast, in the bottom half of the image (machine-interpretable documented design process), they are colored and, in other words, captured and externalized for future learning and use.

Some methodologies, such as BIM or Integrated Design, as partial solutions, already tackle the deficiencies in the architectural building design process where intermediary models and decisions are not documented, leading to untransparent and untraceable decisions. Furthermore, even with the advancements with BCF, the challenge remains for minimized machine-interpretable model-based design communications and workflow. Despite these efforts, no ultimate solution exists for minimized model-based machine-interpretable design communications and externalizing architectural tacit design knowledge in digital semantical models.

This dissertation aims to find approaches and propose proactive concepts and methods to overcome this challenge and document design decisions in a detailed and machine-interpretable manner, thus making the design decisions more transparent and partially reusable. Furthermore, these proactive measures facilitate a more collaborative and iterative approach, enabling the incorporation of expert opinions and suggestions at earlier stages. This approach ultimately diminishes the necessity for extensive revisions in later phases. It not only streamlines the negotiation process but also minimizes the potential for additional costs and delays linked to repeated modifications. Various important design decisions throughout the design process, once captured and documented in a machine-interpretable format, depicted as numerous colored chunks in the lower part of Figure 10, portray valuable and possibly reusable pieces of design knowledge.

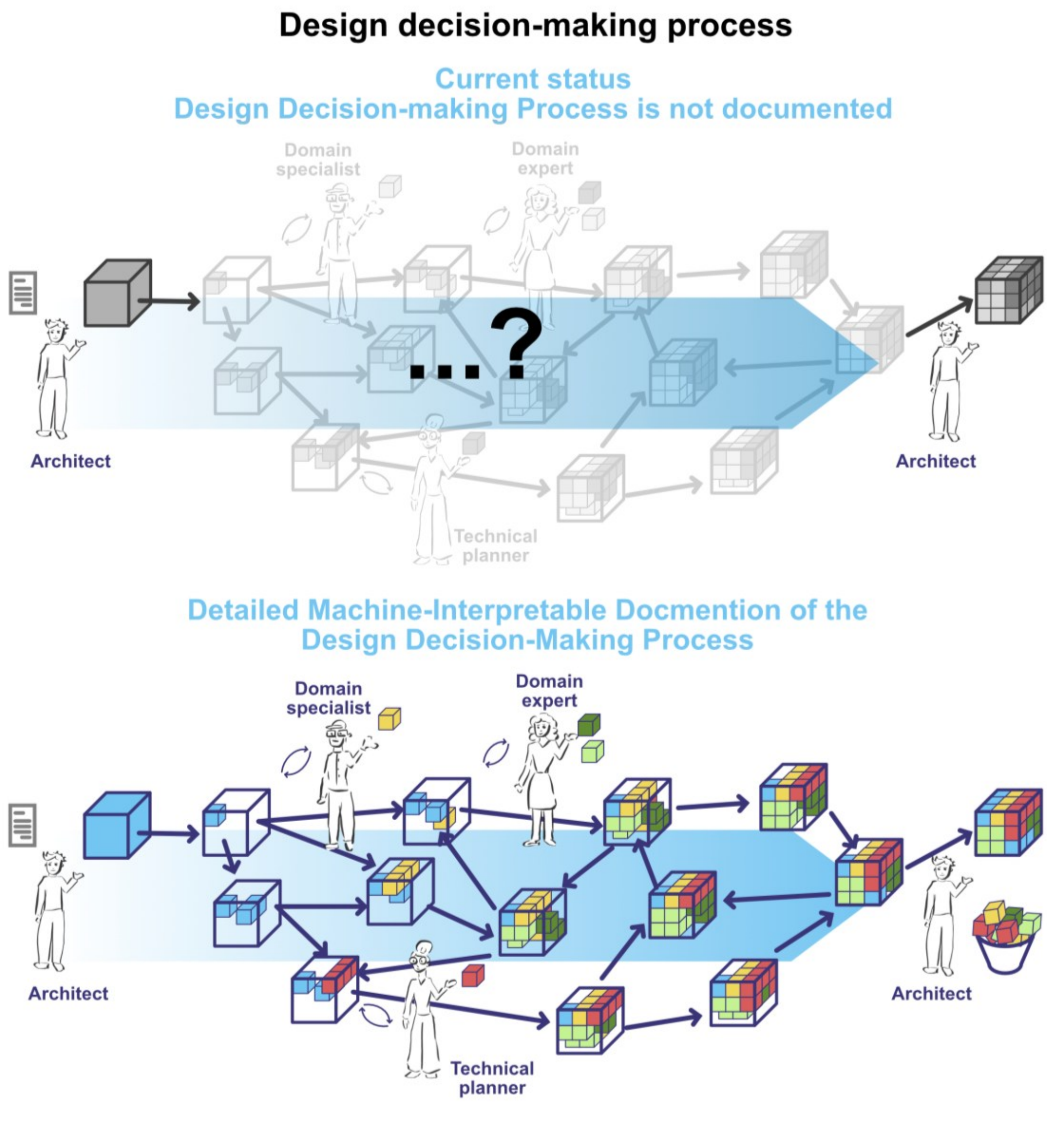


Figure 10 – Current status vs. Documented Design Process

In the following chapters, this dissertation will introduce novel concepts and provide relevant prototypical implementations to serve as proof of concept for addressing this deficiency and providing a comprehensive solution. Shortly after, in chapter 7, the proposed methodology and novel concepts will be discussed in more detail. Subsequently, in Chapter 8, the corresponding prototypical implementations will be covered in more depth.

7. Proposed methods and concepts

This chapter presents an in-depth exploration of the novel concepts introduced to enhance the design process. This chapter holds immense significance within the dissertation as it outlines the innovative ideas and methods that serve as the building blocks for subsequent chapters. By delving into these proposed methods and concepts, this chapter sets the stage for a deeper exploration of their implementations and ramifications in the following sections.

However, first and foremost, it should be stressed that this work has no intention of replacing or impeding architects' existing working methods with any new digital technology. This dissertation’s primary objective is to improve and directly integrate the established design tools that use the BIM methodology with innovative ideas. This should not significantly change or harm but rather enrich architects' design process, giving them more abilities rather than introducing more complexities.

With that in mind, the first objective is to establish a minimized, machine-interpretable communication protocol based on the BIM framework, enabling seamless design collaboration through the feedback mechanism. Additionally, this work delves into digital design knowledge documentation by incorporating explanation tags and design episodes. Furthermore, the chapter discusses the proposed graph representation concepts for design episodes, offering a structured approach to capture design knowledge. To provide practical insight, a range of demonstrative examples are showcased.

7.1. Feedback mechanism

Partial results of the presented work in this chapter have been published in:

Zahedi, Ata; Petzold, Frank (2019): Adaptive Minimized Communication Protocol based on BIM. In: 2019 European Conference on Computing in Construction. 2019 EC³. Chania, Crete, Greece, 10-12 July 2019.

Zahedi, Ata; Abualdenien, Jimmy; Petzold, Frank; Borrmann, André (2019): Minimized Communication Protocol Based on a Multi-LOD Meta-Model for Adaptive Detailing of BIM Models. In: 26th International Workshop on Intelligent Computing in Engineering. EG-ICE 2019. Leuven, Belgium, June 30 to July 3, 2019.

Abualdenien, Jimmy; Schneider-Marin, Patricia; Zahedi, Ata; Harter, Hannes; Exner, Hannah; Steiner, Daniel et al. (2020): Consistent management and evaluation of building models in the early design stages. In ITcon 25, pp. 212–232.

Given that the design of a building requires several specialists from various fields to collaborate and communicate with each other, a vigorous interchange of information amongst the experts is necessary during the design process. One of the main advantages of BIM is the exchange and sharing of semantically rich 3D models among various design disciplines. This capability promotes the early engagement of various domain specialists and technical planners, thus improving the design process's proficiency and quality.

During the early design phases, the BIM model is still in its early development and is thus immature and unsuitable for most numerical analyses and performance evaluations. Each domain specialist has specific requirements for exchanging BIM models in various design phases. In other words, in every design phase, certain information is needed in the design model to perform certain analyses, such as a life cycle assessment (LCA). Utilizing a Common Data Environment (CDE) for sharing BIM models, architects and domain experts can engage in negotiations and collaborative efforts through early proactive measures such as the concept of adaptive detailing (Zahedi and Petzold 2018). This allows architects to communicate with consultants and other experts, seeking their suggestions and input for design decisions, and assistance. Figure 11 demonstrates these negotiations using the feedback mechanism for LCA as an example.

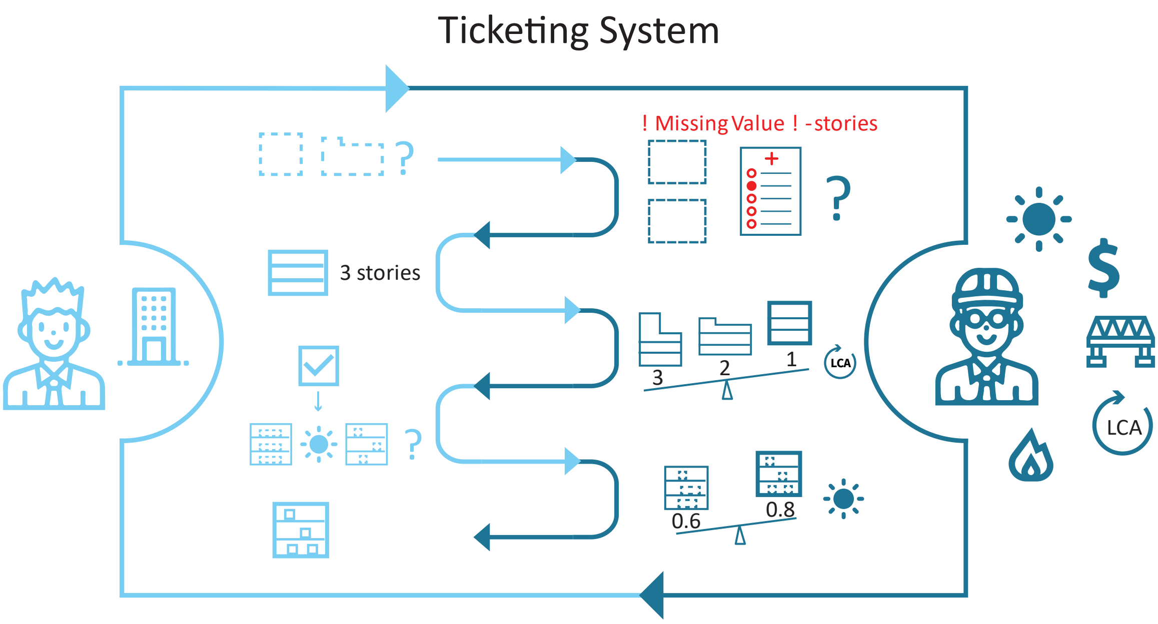


Figure 11 – Negotiating with experts and adaptive detailing of the design using the feedback mechanism, and LCA as an example (Zahedi and Petzold 2018, 2019b)

To clarify, it is important to note that during these exchanges and negotiations, a distinction is made between *variants* and *options*. Variants refer to the design models developed by the architect, while options comprise the feedback and partial design proposals from the specialist planners and domain experts. Options are meant to serve the architect as a suggestion, proposal, or possible solution by a specialist planner in order to take this into account or reject it in the further development of variants.

A ticketing system within the feedback mechanism ensures the traceability and transparency of these communications. It contains information on what type of analysis or simulation is requested, by whom it is requested, and who is responsible for it. Furthermore, the current status of the design model is stored in order to document the traceability of further developments and editing. The second part of the concept contains the feedback from the domain experts. In order to support schema-based, machine-interpretable and model-based communication between the project participants, the requirements for the exchange of information were defined as adaptive templates for various analyses and simulations.

The communication process is triggered by sending requests for analysis through a ticket, and subsequently, experts' responses are incorporated into the feedback mechanism using the feedback method function. With this system, the architect has the ability to prioritize each ticket, allocate responsibilities to relevant experts, and monitor responses from domain experts. Furthermore, this mechanism facilitates machine-readable communications for adaptive design detailing and the assessment of potential design variants. Typically, three different sorts of feedback are given:

- Missing details in the design model which are critical for analysis
- Options that have been proposed to address the missing information in the design model and conform to the design requirements
- Related results of simulations or analysis

The feedback function is set up with several arguments to accommodate the many demands that may arise in various scenarios. More details on how this method function works are described below:

Feedback (actionType, optionGroupID, GUID, schemaX, objecTypetID, propertyTypeID, value)

The first argument as *actionType* represents a use case for the feedback function. The possible value ranges are *missingObject*, *missingObjectProperty*, *createNewObject*, *deleteObject*, and *updateObjectProperty*. Naturally, *missingObject* handles the general use case where some building components are (supposedly) missing from the engineers' point of view, such as missing opening(s) on the side of the living room near the balcony - which hinders or impacts the analysis result of energy consumption. The *missingObjectProperty* refers to the incomplete properties or semantic information that need to be filled out by the architect(s) – a typical example is the strength (class) of the building material. Alternatively, *createNewObject* refers to a newly created building component (possibly as part of options) by a domain expert (consultant), depending on the architect's acceptance or objection. The newly created element has a unique GUID that will be used to reference the object. Along with the newly created ones, some existing objects might be deleted. Respectively, *DeleteObject* could also be assigned when engineers think some objects hinder the desired performance or have significant side effects that are hard to deal with. Lastly, *UpdateObjectProperty* refers to the suggested property value(s) as an option(s) to meet the architect’s design requirement.

The following argument, *optionGroupID,* makes it easier to group multiple suggestions and is optional, i.e., advised details can be individually treated or grouped together as batch information. It provides effectiveness and efficiency in accepting or rejecting the modifications in a package. This feature will also help keep the BIM model's consistency when properly arranged since building components are topologically and functionally interdependent. The following argument is GUID which holds the global identification IDs of the building components that rest over the CDE and refers to them – that is, if the building components cease to exist, their GUID parameters also vanish. If the *actionType* in the feedback function is *missingObject*, this argument (GUID) will be the unique ID of the hosting (building-) component. As to the example where the openings are absent, this GUID might belong to the wall adjacent to the balcony that is supposed to host the missing opening(s). Comparably, for *missingObjectProperty and updateObjectProperty*, the GUID applies to the existing building component, which lacks specific object properties. At the same time, the *createNewObject* action sets a GUID on the temporary newly created object advised by the domain expert to the architect. Finally, when *actionType* is *deleteObject*, this GUID refers to the (building) component the domain expert suggests for deleting.

For each type of analysis, there is a list of required information that has to be provided. For example, Life-Cycle-Assessment (LCA) requires the input value of the window-to-wall ratio (WWR), u-value, wall thickness, etc., which are classified as properties (represented with *propertyTypeIDs*) for different types of building components (represented with *objectTypeIDs*). The *schemaX* argument then functions as a dictionary or lookup table for required information exchange regarding various analyses. The schema, also called aLODx in previous works of Zahedi et al. (Zahedi and Petzold 2019a; Zahedi et al. 2019), is based on a more relaxed interpretation of multi-LOD meta-model introduced by Abualdenien & Borrmann (Abualdenien and Borrmann 2019) and may be modified for different design phased and various analysis.

7.2. Explanation tags

Partial results of the presented work in this chapter have been published in:

Zahedi, Ata; Abualdenien, Jimmy; Petzold, Frank; Borrmann, André (2022): Documenting Design Decisions using Design Episodes, Explanation Tags, and Constraints. Journal of Information Technology in Construction.

The benefits of explaining and documenting the reasoning and argumentation behind various design decisions have already been discussed in section 1.7 and chapter 6. But what are the expectations of architects willing to record and explain their design choices while planning and designing? How could this (extra) step be smoothed into the already established working methods when using BIM authoring tools? Reciting Nigel Cross from 'Designerly Ways of Thinking' (Cross 1982), the architects' cognitive process, way of thinking and expressing ideas is mainly spatial and graphical. They work through, in, and with sketches, drawings and plans, but also with 'numeracy' (the 'language' of science) and 'literacy' (the 'language' of humanities). They create a dialogue utilizing drawings, plans, models, figures, and sometimes words and other components comparable to all other visual artists (Cross 1982).

The main objective is to clarify and document the rationale behind design decisions and variant selections while interfering with the design process as minimally as possible. When working with BIM authoring tools, a great deal of semantic and geometrical information associated with various design decisions is already contained and stored in the design model. Besides all these quantitative information and objective reasons contained in BIM models, what is still missing to justify various design decisions and clarify their rationale? How can one explain the more qualitative criteria and subjective intentions behind his/her design decisions? Not everyone agrees on a formal definition for and has the same understanding of these subjective issues. To overcome this challenge, a collection of '*Explanation Tags'* is provided inside a BIM authoring tool, enabling the architects to elaborate and clarify the motivations behind their design decisions by assigning these tags to various details of the design model. These details may include several building components, spatial objects, and their individual properties. In other words, while designing within a BIM authoring tool and deciding on various details of the design model, users can apply a collection of explanation tags that cover most of the design aspects, allowing them to argue and explain their design decisions by attaching these tags to building components, spaces, or their attributes. Inspired by key architectural academic books and empirical standards, this extendable open-end collection of tags offers a graphical codification of architectural terminology and vocabulary.

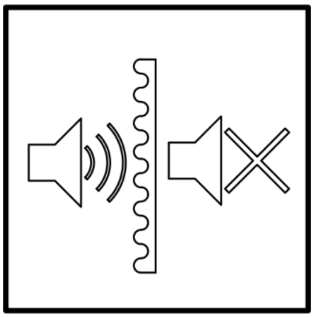
For example, an architect may have different reasons for choosing a high ceiling for a room, e.g. it could be its function or purpose as a chemical laboratory, or to keep the room cool in summer and provide comfort for its users, or to create the feeling of openness for its inhabitants. The architect can elaborate and describe his/her rationale by assigning the appropriate tags, such as functionality, or comfort, or openness to the height (attribute) of the room (space) in the BIM authoring tool. Another example may be a specific layout and design of the facade to make it accessible and usable by a maintenance and cleaning robot that climbs the facade. Then again, the architect can clarify and document this specific design and its features by assigning the tag for robot-oriented design. These explanation tags may include both subjective (qualitative) and objective (quantitative) aspects of architectural design.

Each explanation tag is represented as an icon and saved with an ID, name, written description, and graphical explanatory examples. Photos, Plans and Sections, 3D models, and even partial BIM models could be saved with an explanation tag. The explanation tags are also cross-connected using meta-data markers (in the back-end of the system) through a series of overlapping meanings such as synonyms, antonyms, and complementary, related, or associated definitions, which will be leveraged to offer suggestions to users when they are searching for similar terms, utilizing Natural Language Processing (NLP) techniques and domain-expert knowledge.

Moreover, these explanation tags also serve as labels to catalog design cases, allowing the architects to tag design examples and later find and use similar instances when searching for inspirations and solutions to design problems. This way, architectural expressions and characteristics can be communicated using explanation tags. For example, an explanation tag can relate to an open-ended grid for the structure or a plan-libre (as defined by Le Corbusier as non-structural divisions arranged in a free layout based on functional convenience) for the spatial configuration. Another explanation tag can relate to a building's purpose, such as a hospital, or a formal feature, such as symmetry in space layout.

Based on the related work and architectural literature, together with the SNAP (Fuchs et al. 2013) recommendations for sustainability, and with consultation with other domain experts in the Early-BIM research group, a set of explanation tags are prepared and presented in this work that could be found in chapter 11. Both subjective (qualitative) and objective (quantitative) design aspects and criteria exist in this collection of explanation tags. The subjective icons are framed in a circle to distinguish between these two groups, while the objective ones are placed in a box. Table 1 shows some of these explanation tags. More explanations and demonstrative examples on how to use explanation tags will be provided in section 7.5.2, and the complete list of available explanation tags until now will be presented in chapter 11.

Table 1: Two of the Explanation Tags related to subjective and objective criteria

Topic	***Explanation Tag***	***Description***
Comfort		A sense of physical contentedness, which comes from many physically measurable conditions, such as light intensity, atmospheric humidity, temperature, air exchange, and noise intensity. Alongside the physical measures, a spatial situation also interferes with comfortableness, including room size, spatial proportions, and gestures.
Sound insulation		Unwanted noise and acoustic conditions affect well-being and can affect health. By appropriate conceptual and structural measures, pleasant acoustic conditions are to be established. This applies equally to the structural sound insulation against external noise and noise pollution between different rooms. **Excellence rating:** favourable orientation of vulnerable areas; favourable orientation of private open spaces; structural noise protection measures considered; no conflicts of use.

7.3. Design episodes

Partial results of the presented work in this chapter have been published in:

Zahedi, Ata; Abualdenien, Jimmy; Petzold, Frank; Borrmann, André (2022): Documenting Design Decisions using Design Episodes, Explanation Tags, and Constraints. Journal of Information Technology in Construction.

After establishing the groundwork to explain and clarify the rationale behind various design decisions via explanation tags and through the BIM authoring tools, now it is time to ask the next important question; does a final design model with all its content concerning numerous details and design decisions a flexible enough and helpful answer to all design questions? Does one always need and can easily find answers in a big entire design model? Or would it be better and more efficient to divide the final detailed model into smaller, more precise, and better manageable pieces and episodes of design? Even if it succeeded, how can one store and share something as complex and dynamic as architectural designs? What method will be suited to express and convey the difficulties and delicacies of design? The solution to these questions is the concept of *'Design Episodes'* by harnessing the power of storytelling to unlock and explore the wealth of architectural designs.

In everyday life, people can remember, share and manage complicated events. They appear to achieve this naturally by exchanging stories with one another. In his book 'The Springboard' (Denning 2012), Denning explains how presenting a tale may effectively convey knowledge, not so much by communicating a lot of information, but rather by facilitating comprehension. In addition to its many advantages, storytelling is non-hierarchical and non-confrontational. As a result, it offers a chance to break through the defense mechanisms often common in the world of creative activity, such as architecture, where concepts and results have significant implications and value regarding ownership and recognition (Heylighen et al. 2007). Storytelling can be used to enhance our understanding of a phenomenon by introducing alternative viewpoints and perspectives. In other words, via narrative, one can discuss various complex issues related to architectural design altogether and simultaneously. As such, stories are clear, simple to read, and amusing; they also preserve the complex relationships between things in a way that makes them simple to recall in the future. As a result, the narrative structure offers a rich, condensed method of handling and communicating complexity in a brief amount of information and time. By relating the event being presented to the reader's own experiences, their results provide the reader meaningful applicability for his/her use cases. The conclusion is not just about the facts but also the concepts, methods, choices, and consequences of the relationships implanted within the narrative (Heylighen et al. 2007). With assistance from some of the top architectural firms in the San Francisco Bay Area, Berkeley University in California created and managed the "Building Stories" project (Martin et al. 2003), successfully demonstrating the potential of storytelling for documenting and preserving tacit architectural design knowledge. Several teams made and edited narratives about various architectural projects that were being developed or had already been built throughout this project. These teams included architecture students, interns, and professionals.

Architectural design variants are discarded, selected, and further detailed using both objective (quantitative) and subjective (qualitative) criteria. More importantly, a complete and detailed design model does not always need to be addressed in its entirety. Instead, it could also be accessed and re-used in its divided form of various design episodes, each addressing specific design challenges and tasks more specifically.

Later on, using some illustrative examples and use cases, we will explore in further depth how these ideas and concepts for documenting design decisions work. In a nutshell, the step-by-step process works as follows:

- Architects can assign various *'Explanation Tags'* to design objects or their properties to mark and clarify their reasoning and rationale for certain design decisions.
- Architects may use *'Design Episodes'* to encapsulate and explain their motives and intents through textual explanations for various design chapters (episodes) when addressing specific tasks or challenges.
- Architects can also export these design episodes and the attached explanation tags to a graph database that could be used further for inquiries in search of similar design ideas and examples.

7.4. Graph representations of architectural knowledge

To better query the captured and stored knowledge and information contained in the BIM models, this work represents two different novel graph representations to extract and convey the information and knowledge contained in BIM design models. The first graph representation, followed by a detailed discussion in section 7.4.1, translates the IFC file format into a knowledge graph. In addition to transforming IFC models into knowledge graphs, special attention is given to design episodes in this work and how to express them in knowledge graphs, which will be discussed in section 7.4.2.

7.4.1. A simplified graph representation of IFC models

Partial results and implementations of the presented work in this chapter have been published in:

Master's Thesis in Data Engineering and Analytics, by Wing Sheung Leung, titled "Sub-graph Isomorphism for Finding Similarities in Building Models".

Considering the importance of the IFC file format as an open standard for the exchange of BIM models, one of the main goals of this work is to handle BIM models in IFC4 format and convert them into knowledge graphs. The first step is identifying the IFC entities essential for forming building design patterns. The main three categories in the IFC schema are; IfcObjectDefinition, which is the supertype for any physical or virtual objects, IfcPropertyDefinition that is the supertype for all property-related entities and IfcRelationship, which is the supertype for all types of relationships between any entities. At first, a collection of the most important entities in the IFC4 schema, essential for searching similar building design patterns, including the important ones from IFC- object, relationship, and property entities is selected. For example, from the collection of IFC object entities, spatial elements (such as story or space) or physical elements like wall, door, or window are selected, whereas possible edges such as "a wall *has* a window" or "a wall *is next to* another wall" or "a room (space) *has* a virtual boundary with another space" could be formed based on selected IFC relationship entities. Finally, properties such as name, material layers, height or net floor area, etc., can be extracted by leveraging the IFC property entities. Since the generation of knowledge graphs is model-based, for each IFC model, a knowledge graph is generated and stored in a Neo4j graph database. The model name identifies every knowledge graph node belonging to the same model.

Figure 12 shows the collection of selected IFC Object entities. The knowledge graph contains the highlighted IFC elements as nodes. Almost every element essential to the building's construction is represented in this selected list of entities. Additionally, the IfcLocalPlacement entry that contains each object's geometrical coordinates is retained in the knowledge graph as one of the node characteristics.

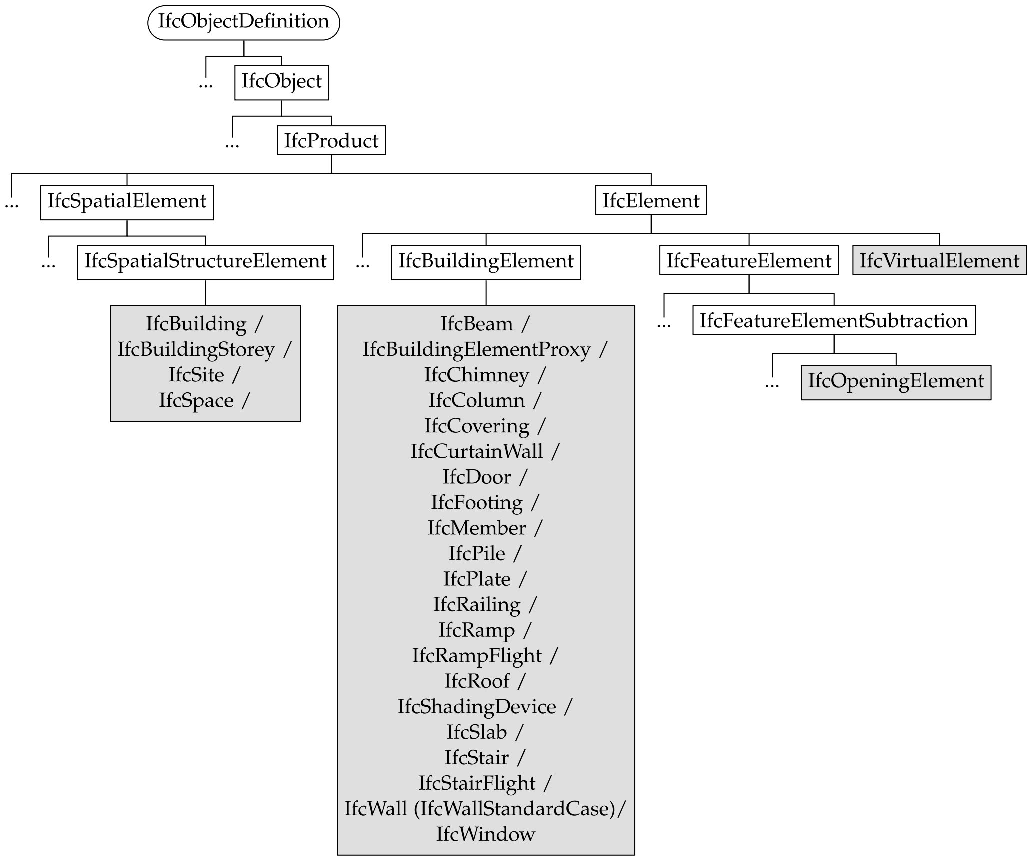


Figure 12 - The selection of IFC Object Elements

Figure 13 & Figure 14 show the selected list of IFC properties and relationships represented in the knowledge graph. The highlighted entities in Figure 13 are included in the knowledge graph as node properties. In contrast, the highlighted IFC relationships in Figure 14 are formed as edges in the knowledge graph, except for material-related items, which are regarded as node characteristics. To determine which material entities are allocated to which IFC object entities, IfcRelAssociatesMaterial is used. A similar relationship item, IfcRelDefinesByProperties, determines which IFC object entity is associated with the attributes detailed in the IFC property entities mentioned in Figure 13.

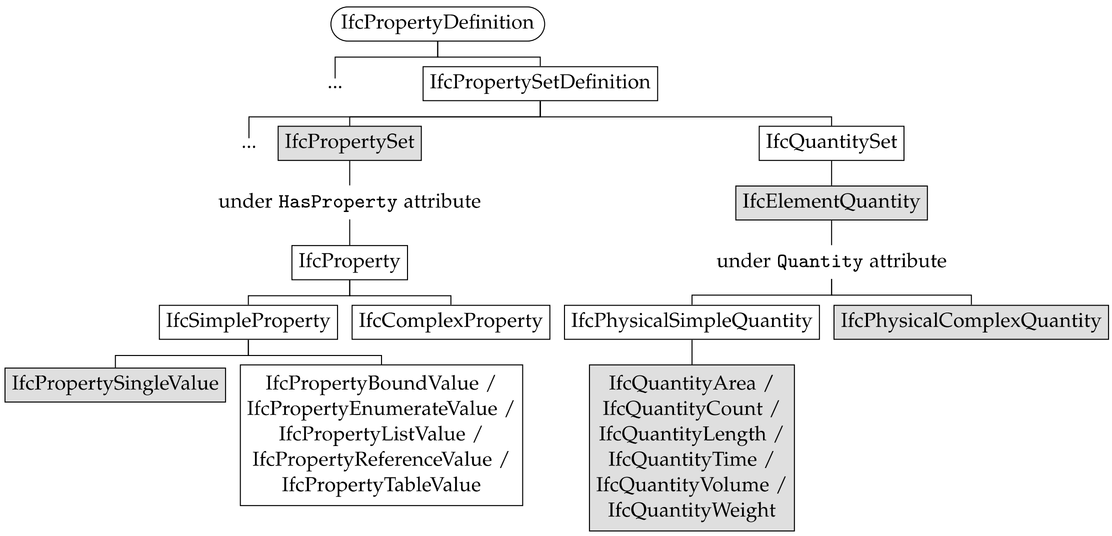


Figure 13 - The selected IFC Property related entities

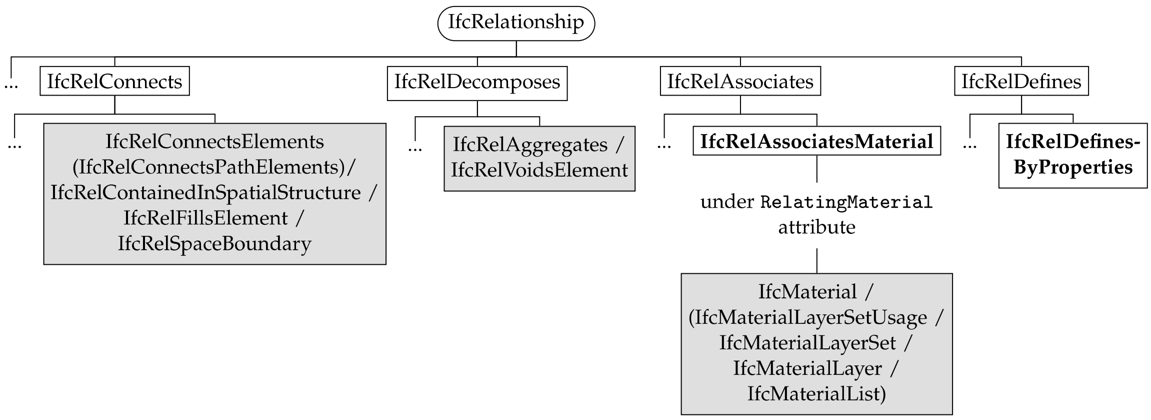


Figure 14 - the selected IFC relationship entities

In summary, the step-by-step process of creating the knowledge graphs from IFC files could be summarized as follows:

1. Identifying essential IFC entities
2. Creating nodes and relationships from the selected IFC entities
3. Assigning related properties and materials to the existing nodes
4. Renaming labels of nodes and edges, as well as simplifying specific paths; e.g. from *(:IfcWallStandardCase)-[:has]->(:IfcOpeningElement)-[:has]->(:IfcWindow)* to *(:Wall)-[:has]->(:Opening)-[:has]->(:Window)* then to *(:Wall)-[:has]->(:Window)*
5. Loading the final graph in the Neo4j database

In addition, the implemented Python program for creating this knowledge graph is flexible and generic enough to convert additional IFC object- and relationship entities to nodes and edges. For other property entities, some fine tweaking may be required. The existing list of node labels and edge types from converting IFC files is as follows;

- **Node Labels**: *Beam, Building, Column, Door, Member, Opening, Railing, Site, Slab, Space, Stair, Storey, Wall, Window*
- **Relationship Types**: *has, isNextTo, connectsWithVirtualBoundary*

7.4.2. Graph representation of design episodes

Partial results of the presented work in this chapter have been published in:

Zahedi, A.; Petzold, F. (2022): Revit Add-In for Documenting Design Decisions and Rationale. In: CAADRIA 2022. Post Carbon. Syndey.

Besides converting IFC files into knowledge graphs, special attention is given to design episodes and how to transform and represent them in knowledge graphs. Within the scope of this work, a design episode is formed by a selection of design elements that express a specific chapter or piece of design while giving it a name and explaining the story behind this chunk of design utilizing storytelling techniques. In terms of data modeling, a design episode is an object with a name, description, BIM model identifier, and a list of elements from the BIM model that represent it. The design episodes are model-bound, meaning they are stored within and can be passed on together with the BIM model.

As stated previously, to assure cross-project collaboration, the graph typology offered in this work for the export of design episodes is designed to be compatible with Abualdenien & Borrmann's Parametric Building Graph for capturing and preserving precise patterns (Abualdenien & Borrmann, 2021). There are two main types of nodes: the Element node is an exported episode element and the Design Episode node, as the name suggests, is an exported design episode. There are also several edges in this graph topology. The *EpsiodeElement* edge denotes that an element is part of a design episode. The nodes can be connected via four different edges: *Has*, *ContainedIn*, *IsAdjacent*, and *IsConnected. ContainedIn* is used when an element is physically or spatially contained in another element, while IsConnected denotes a physical connection between two nodes. An *isAdjacent* edge between two nodes implies adjacency between two spatial elements. In contrast, the *Has* edge represents a simplified parental relationship between two nodes, such as a wall that *Has* a window. Figure 15 shows the list of node types with their corresponding properties, and Figure 16 shows the list of edges for the knowledge graph representation of design episodes.

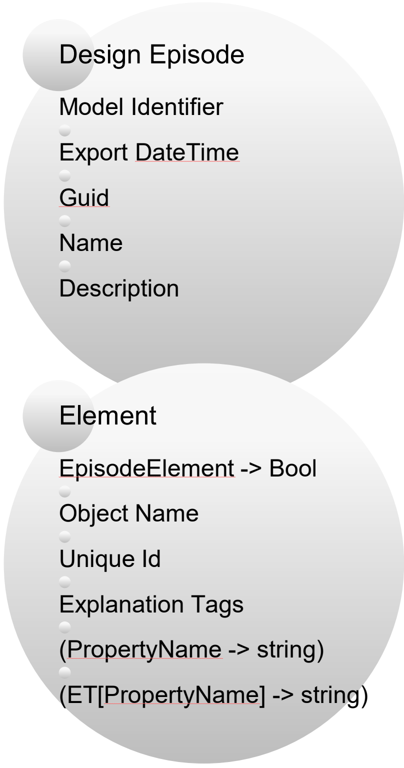


Figure 15 - Node types and their properties in the knowledge graph representation of design episodes

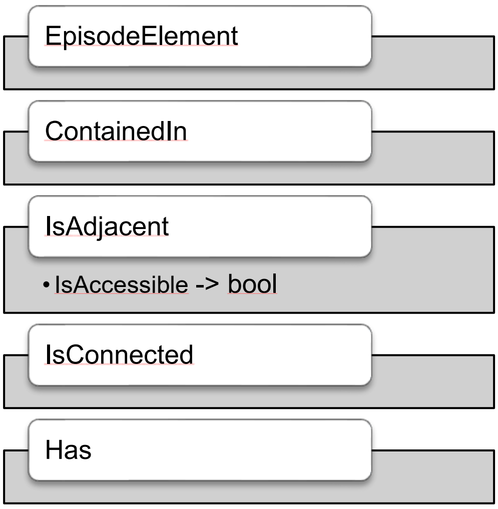


Figure 16 - Edge (relationship) types in the knowledge graph representation of the design episodes

7.5. Demonstrative examples

This section explains applying the concepts mentioned above using two real-world building projects.

One is in Regensburg, Bavaria, Germany, and belongs to and is operated by the Ferd. Tausendpfund-Gruppe as their main office building. The Ferdinand Tausendpfund building in Regensburg is an office building erected at the end of 2016. The building consists of three different exterior wall constructions. The building has a first and two upper floors with a gross volume of 3950 m^3 and a gross area of 1290.5 m^2. The overall window-to-wall ratio of the building is 25%. The building does not have a basement, so the floor slab, the exterior walls, and the roof form the thermal building envelope. All zones in the building are considered to be heated to normal temperatures (Vollmer et al. 2019).

Figure 17 - Ferdinand Tausendpfund GmbH & Co. KG office building in Regensburg, Germany, built in 2017. © Bauer | bauerwerner.com courtesy of F. Tausendpfund GmbH

The Lang Hugger Rampp Architekten GmbH office in Munich designed the other project called the Building Lab. The building is in Rudolf Vogt Str., Regensburg, next to two universities. It is part of the future 'TechCampus', which is aimed to be the hub for innovative High Tech companies such as start-ups in digitalization, economy, and research. The development plan of the Tech Campus is designed mainly for office use, as well as some public places and housing in mixed-use buildings. The site of the Building Lab, as part of the mixed-use buildings, is approximately 1650 m^2. The design of Building Lab started as a student competition, which followed into a detailed and final design stage based on the selected best student plan called 'Cubes'. The main ideas behind the concept of the cubes were;

- a modular system, which consists of several ´cubes´
- engaging the public by placing cubes around the building that provide information about sustainable buildings and offer activities for visitors
- high recyclability, dismantlability, or use of secondary building materials
- creating synergies between users, companies, and inhabitants of the Tech Campus
- flexible reusability of the building
- spacious atrium used for heating and cooling of the building as well as natural lighting
- two stories high workshop on the west side of the building

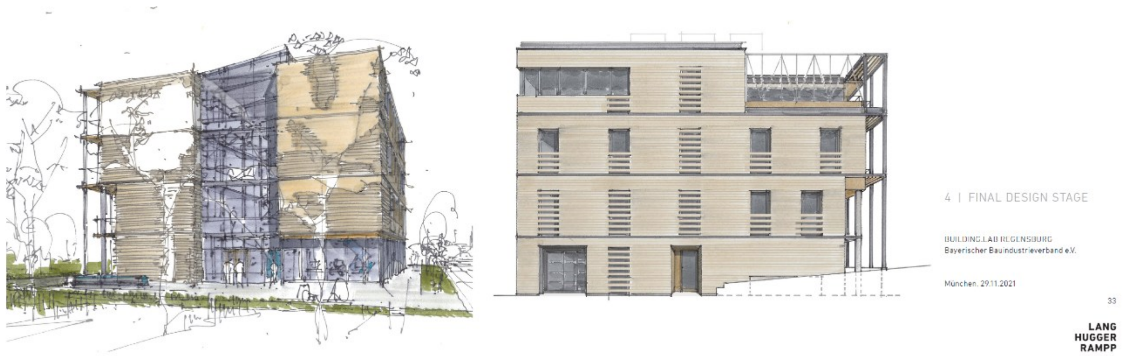


Figure 18 - Building Lab Elevation East & West (Second Sketch) @LangHuggerRampp

7.5.1. Feedback mechanism - demonstrative case study

The proposed feedback mechanism was applied to specify exchange requirements and support the decision-making process during the early design stages of a real-world construction project, as depicted in Figure 17. Two scenarios are discussed in detail: namely, evaluating and suggesting multiple structural systems and selecting different primary materials for the exterior walls

The structural system of the building significantly impacts the adaptability and effectiveness of the design solution. Making informed architectural decisions is easier when structural engineering knowledge is incorporated early. The exchange requirements are specified and assigned to component types using the multi-LOD meta-model (Abualdenien and Borrmann 2019). A collection of components and associated LOD definitions, including vagueness information, are defined for each design stage. The various simulations may be run in the early phases by estimating the parameters with a vagueness percentage. In this manner, the influence of each parameter on the computation's outcomes may be evaluated. It enables better decisions to meet the design objectives and enhance the building's performance during its lifecycle. (Hopfe and Hensen 2011).

The first scenario, as depicted in Figure 19, demonstrates how structural expertise was incorporated early in the design process. The architect initially sends a ticket to the structural engineer outlining the scope of the desired analysis after deciding on the height of the building and the number of stories. The structural engineer verifies the model against the specifications stated in the meta-model to find any missing information. Either the architect will estimate and choose or ask the structural engineer for suggestions regarding the missing information. The structural engineer uses intelligent substitution models to create preliminary structural designs based on the information presented and his/her technical expertise. The proposed structural options comprise a variety of structural element types and formations. Here, the structural engineer offers some choices with various horizontal and vertical load-bearing structures.

Figure 19 - Feedback Mechanism demonstration for Scenario I

The structural engineer also presents these options with assessments based on how well they will perform structurally. Meanwhile, the architect may also consider other factors while making design choices, such as the flexibility of the spatial arrangement or the preferred window-to-wall ratio.

In this scenario, the Feedback function is used in two main categories and multiple forms and instances. First, to report the missing details in the model, *missingObjectProperty* and *missingObject* as *actionType* are used in multiple cases. The *schemaX* argument is represented by *SchemaTP5,* which refers to the structural analysis specialist in our research group. The *missingObjectProperty* is used regarding the main material group and the slab type for the floor slabs. The *missingObject* is used to report the missing structural elements such as columns, slabs, and walls. In the next step, the structural expert will present options, each represented by an optionGroupID and using the *createNewObject* as *actionType*. All new (proposed) objects within an option group will share the same *optionGroupID*, but each will be referred to using their unique GUID. The feedback function is demonstrated in Figure 20 using the scenario mentioned above.

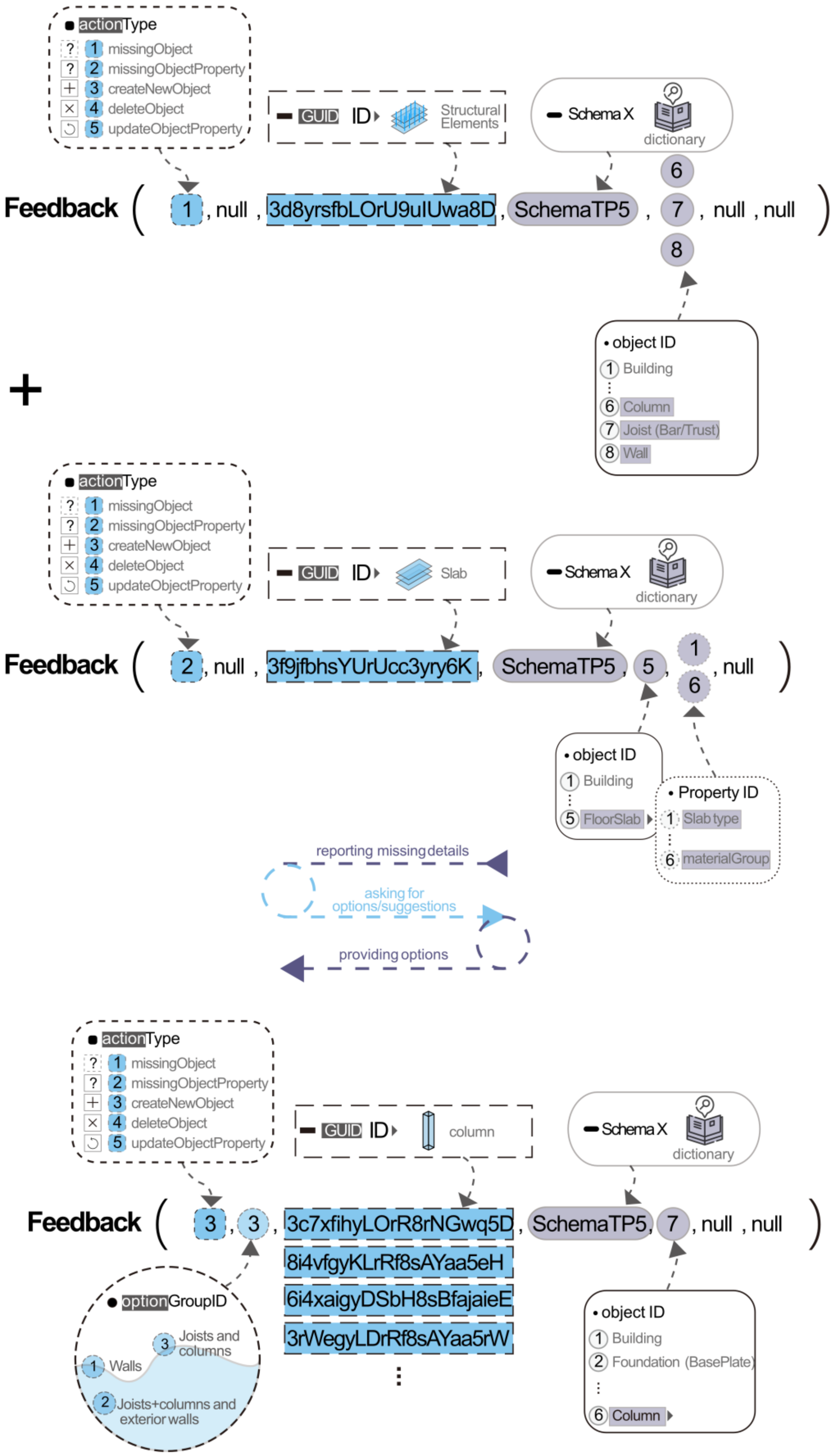


Figure 20 - Feedback Function demonstration for Scenario I

In the second scenario (Figure 21), an energy specialist is incorporated into the design process to assess the effects of choosing the primary material for the outer walls on the building's performance. The communication procedure begins when the architect requests an energy simulation by sending the energy specialist a ticket outlining the scope. The ticket, which includes a link to the digital model, is delivered to the domain expert, who then verifies the quality of the model to ensure it complies with the simulation exchange requirements. As a result, a report describing the missing details is delivered back to the architect and suitably visualized to highlight the deficiencies in the model. In this simplified example, the building's overall window-to-wall ratio, the exterior walls' thickness and main material are missing. With some fuzziness, the architect predicts that the wall thickness will be about 40 cm and the window-to-wall ratio will be 0.4.

The exterior walls' main material, which has a significant influence on the performance of the building, is still up for debate. As a result, the architect consults the domain expert for advice and the appropriate assessment. The expert generates four potential material options—steel, bricks, wood, and concrete—and sends the developed options and their corresponding evaluation results to the architect. The architect can also send these options to additional experts for further analysis. In our example, the structural engineer offers more insight, such as recommending that an outside wood wall should not be load-bearing. In this manner, the architect may make an informed choice on the best alternative in light of the assessment findings, and the system will automatically add the features (such as the material for the exterior walls) to the swapped model.

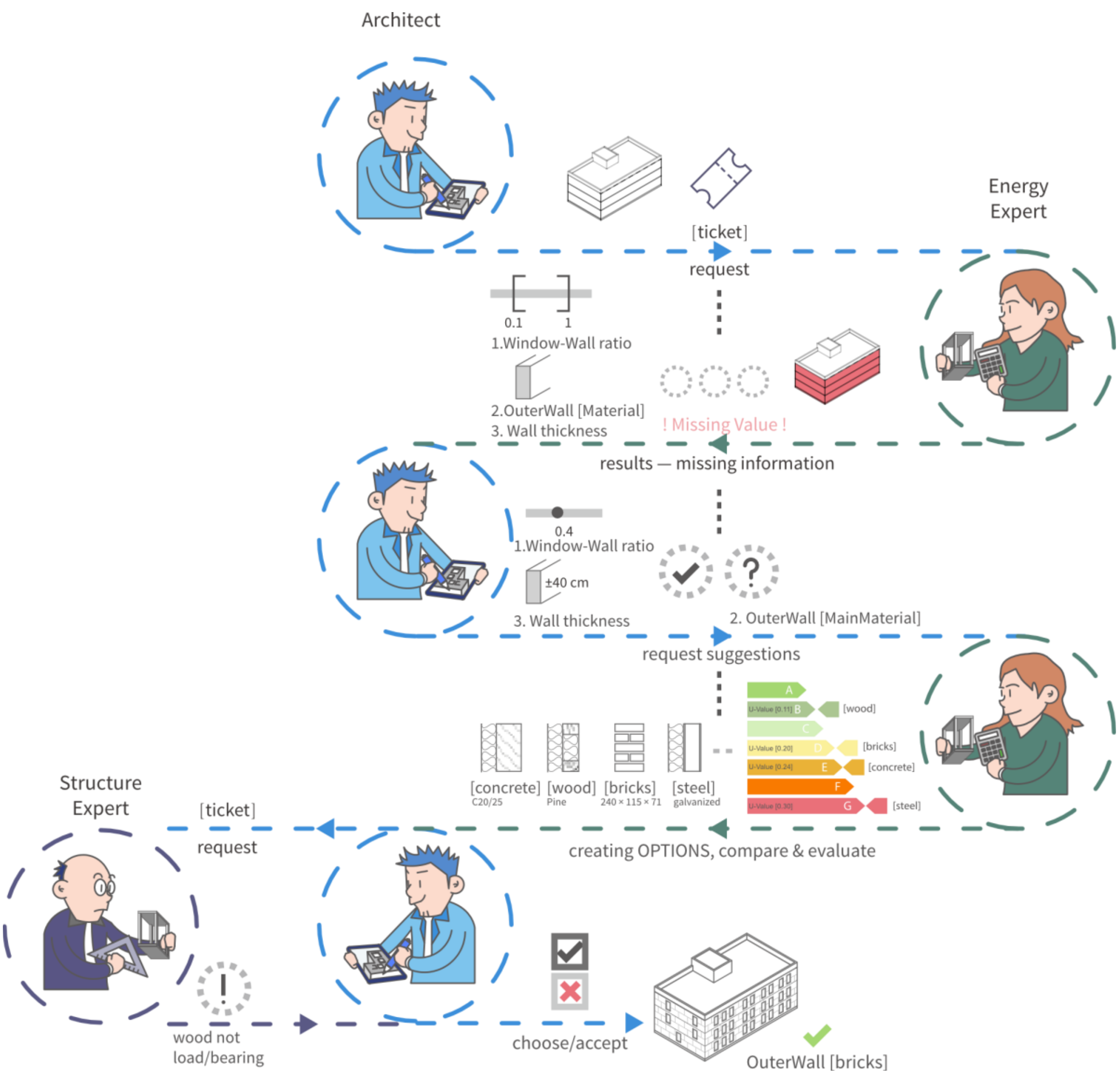


Figure 21 - Feedback Mechanism demonstration for Scenario II

Accordingly, the feedback function is applied in two main steps (Figure 22). In the first step, it is utilized via the *missingObjectProperty* for *actionType* to convey the design model's missing information. In this example, the Window-to-Wall-Ratio, main material group, and thickness of the outer walls will be reported using *SchemaX*, *objectID* and *propertyID* arguments. In this example, the *schemaX* is represented by *SchemaTP4* for the LCA specialists in our research group. The architect estimates that the wall thickness will be around 40 cm and the window-to-wall ratio will be 0.4. Leveraging the *updateObjectProperty* as *actionType* provides options for the material group, and the four proposed material groups, namely steel, bricks, wood, and concrete, will each have a separate *optionGroupID*.

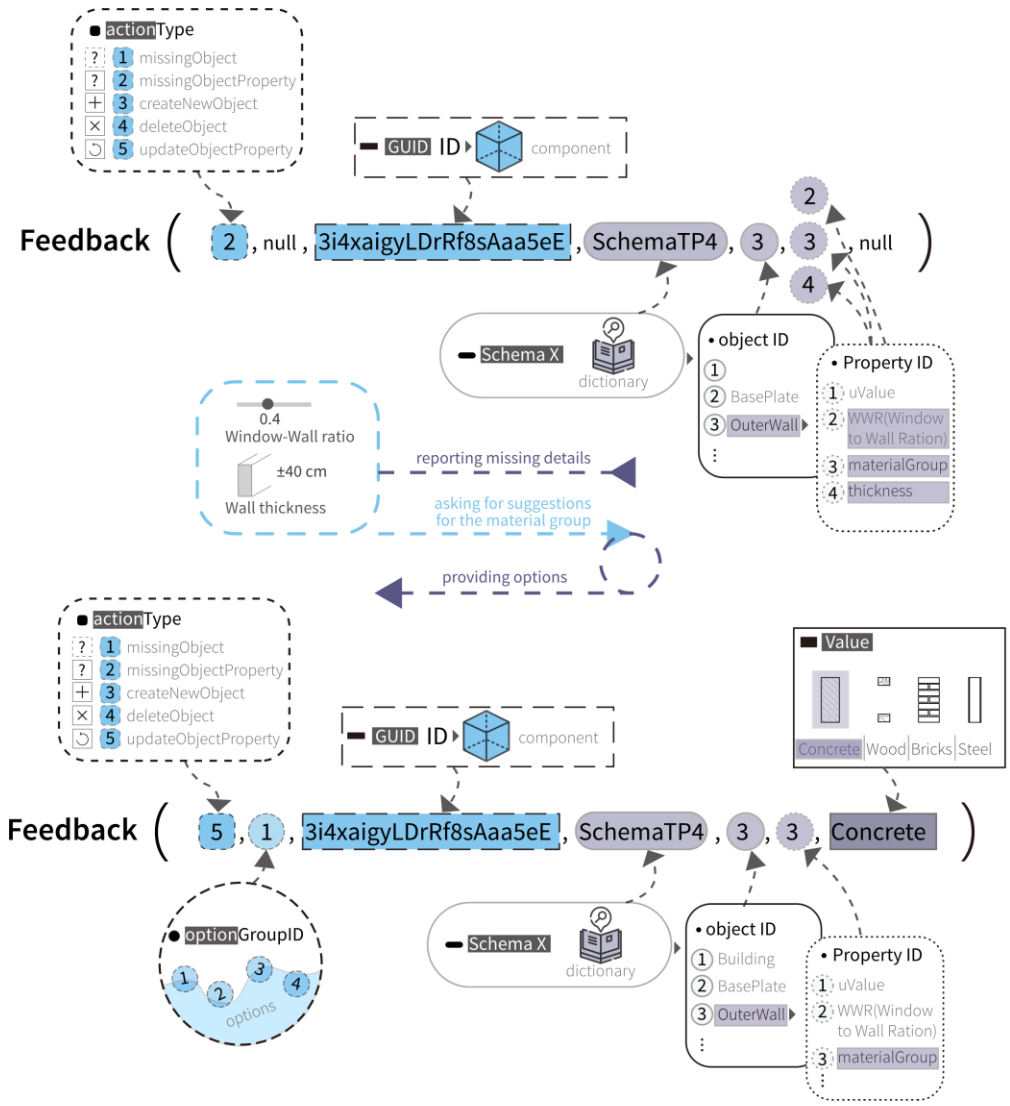


Figure 22 - Feedback Function demonstration for Scenario II

7.5.2. Explanation tags and design episodes – demonstrative examples

The first example regarding the use of explanation tags and design episodes is based on the Tausendfund building in Regensburg. The application of explanation tags is shown in Figure 23, whereas the following describes this design episode accordingly:

> *"In this design, structural elements are mostly put in the outer walls or in the core with vertical circulation and services in the center. Only a few columns are left elsewhere, creating spatial efficiency. This was done according to the owner's requirements for making it possible to flexibly use the building design for both occupancy usages, as an office or residential building. This building is also thoughtfully designed considering criteria such as accessibility and barrier-free access, external space quality and spaces for social integration, etc."*

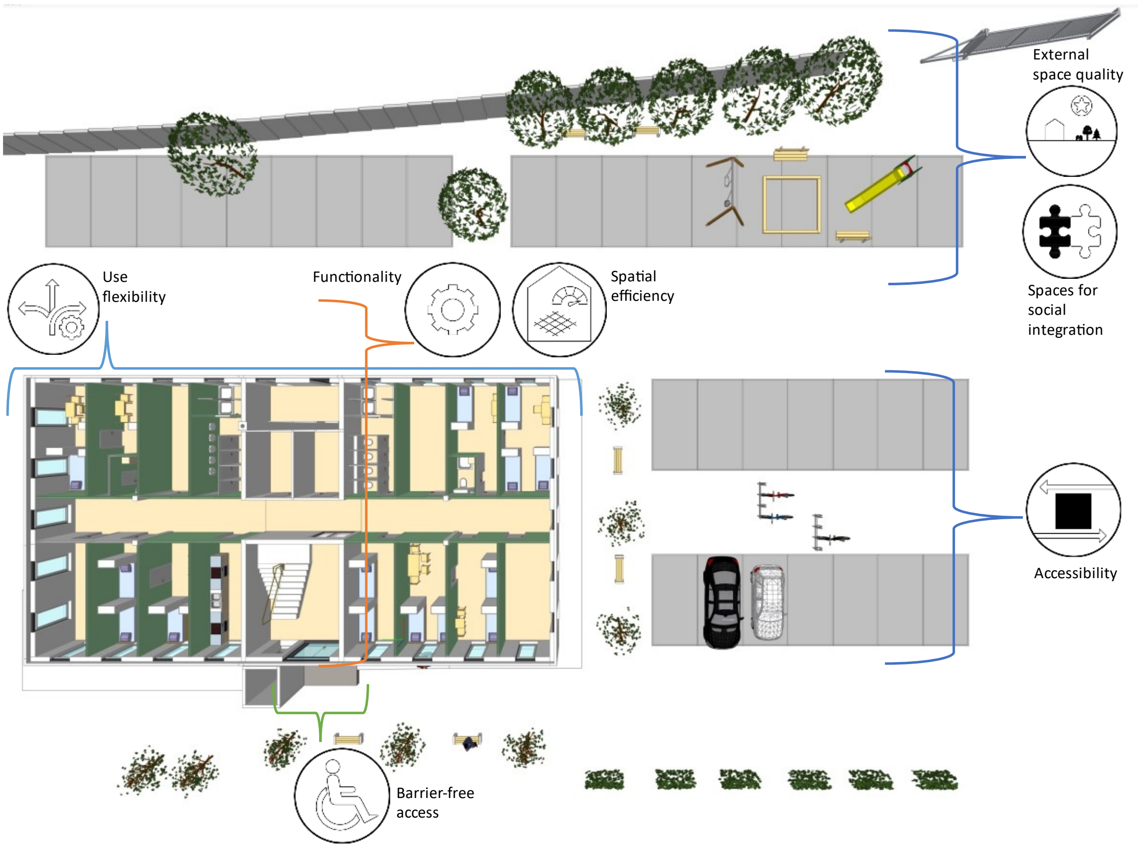


Figure 23 - Demonstrating the design ideas for the Tausendpfund project in the form of a design episode and by using explanation tags

The exterior walls of this building are built floor by floor using three different solid construction methods. The load-bearing material is reinforced concrete on the ground floor, thermal insulation bricks on the first floor, and sand-lime bricks on the second floor. In addition, a composite thermal insulation system is used as external insulation for the outer walls. The three exterior wall constructions each have approximately the same heat transfer coefficient (U-value) of 0.18 to meet the *Effizienzhaus KfW55* standard (Vollmer et al. 2019). The floor slabs, the load-bearing interior walls, and the roof slab are constructed of reinforced concrete. Designing according to this kind of requirement demands careful consideration of the various aspects that influence energy performance and embedded concepts. Accordingly, documenting which requirements were fulfilled using which design concepts is essential for communicating the final solution to the owner or to different domain experts involved in the project. As demonstrated in Figure 23, by utilizing explanation tags, one can describe the designed concepts and help the owners and domain experts understand the reasoning behind various design decisions. That is to say, e.g. *Use-flexibility* tag for the arrangement of the structural elements, *Functionality* and *Spatial efficiency* tags for the wrapping and centralization of the core with vertical circulation and services, together with some constraints for material and position of these elements, some other tags include *Accessibility* for parking spots, the *Barrier-free access* for the ramp on the entrance door, *External space quality* and *Spaces for social integration* for the green space outside the main building.

Further examples of the application of design episodes and explanation tags are presented in this work based on the Building Lab project in Regensburg. The first design episode is about the measures taken regarding the passive solar effects of this building.

> *"The building is terraced on the south side and has passive shading, so the steep summer sun is effectively excluded. Such passive measures can effectively protect the building from overheating and increase comfort. The lower-angle winter sun, on the other hand, can continue to enter the living areas through the south-facing window openings and contributes solar gains. The south side has a punched façade with generous glazed doors. The seminar rooms, which have high requirements for lighting, are oriented to the north. The north facade is largely glazed to gain as much daylight as possible, reducing the energy demand. Due to the north orientation, there is no danger of overheating. The curtain wall facade in the east provides light to the central atrium. When the atrium heats up, the heat can vent through openings in the roof without mechanical ventilation. In this design episode, one can see that the orientation has a decisive influence on the concept and the interior climate."*

Figure 24 shows a cross-section of the building lab and the assigned explanation tags in this design episode.

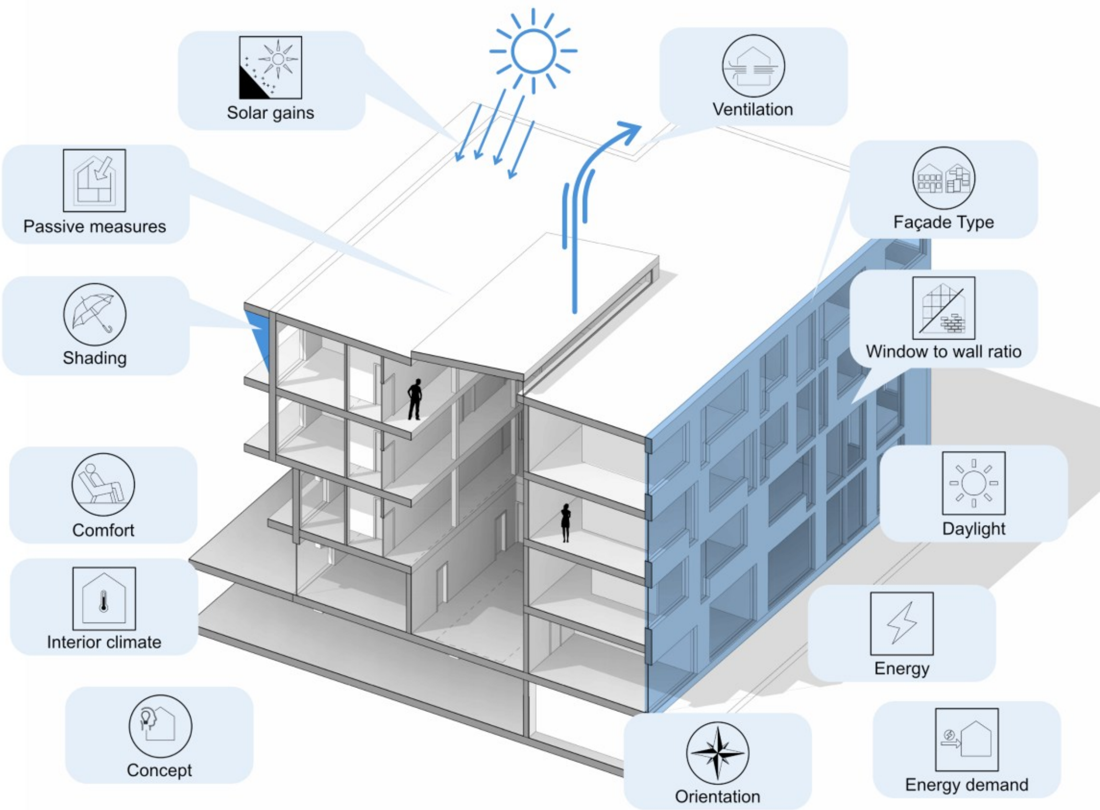


Figure 24 - Building Lab Design Episode Passive Solar Effects

Another design episode regarding the Building Lap project is about the Room and Ceiling Height in this building. This design episode and the related assigned explanation tags are depicted in Figure 25. This design episode's description is as follows:

> *"Despite its different uses (residential and seminar rooms), the Building.LAB building has the same room height throughout. The room height is adapted to the use for seminars and is thus above average for residential use. The* ***tall spaces*** *allow great* ***use flexibility*** *in the basic structure of the building and are suitable for a variety of future alternative uses, allowing the building to adapt to foreseeable and unforeseeable changes in requirements. The increased room height represents a* ***design quality****, which thus significantly influences the* ***functionality*** *of the building according to the concept of* ***Plan Libre****. The height of the space allows for higher window openings, which provide more daylight and a better* ***view****, allowing for* ***deeper spaces*** *and, thus, more* ***comfort*** *overall. Higher rooms, as shown by historical buildings, enjoy high popularity and offer a high quality of space and stay. Because of the high rooms, the floor slabs must be as slim as possible, not to exceed the permissible building height.* ***Slim building parts*** *are becoming increasingly essential, especially in urban areas where building sites are expensive and living space is rare. In this case, the height of the building was the main problem and could be reduced by using prestressed concrete."*

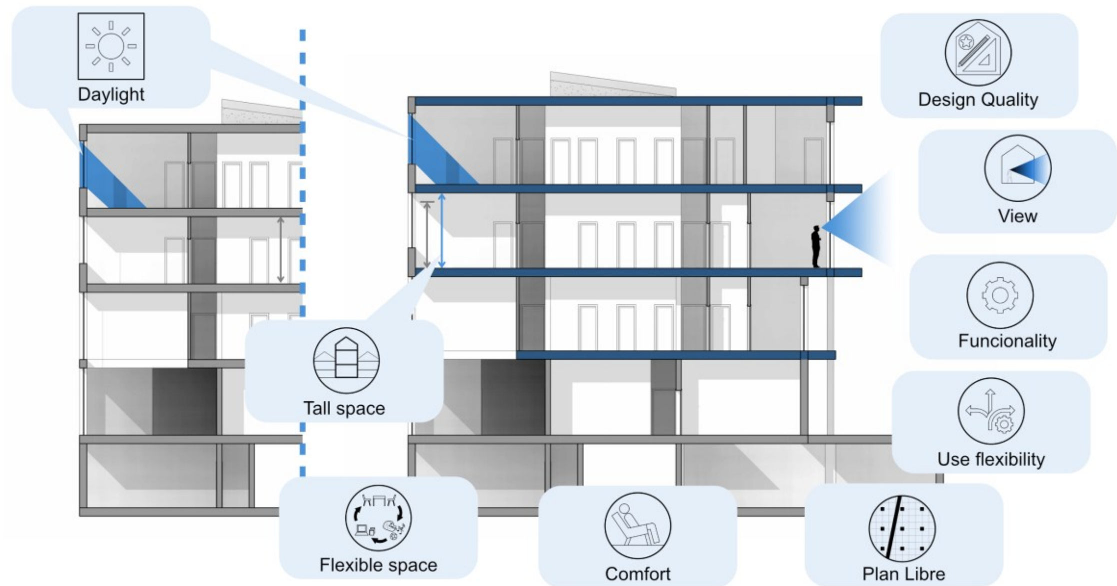


Figure 25 - Building Lab Design Episode Room & Ceiling Height

The final design episode regarding the building lab project is about the grid and construction type. Figure 26 shows this design episode and the associated explanation tags. The description for this design episode is as follows:

> *"The construction grid of this building results from the planned use, the supporting structure, the development, and the façade division and exhibits great* ***design quality****. In practice, the dimensions of the* ***underground parking*** *garage often determine the grid. In the case of the Building-LAB, the staircases were decisive since it was originally planned without an underground garage. The basic decision to use a skeleton construction method was made regardless of the materiality of the supporting structure. Skeleton constructions per se show a high* ***use***

flexibility *due to the separation of* ***structural elements*** *and space-forming elements. When used correctly, such structures not only exhibit extreme* ***structural efficiency****, but are also* ***functional****, save* ***resources****, and due to their* ***simplicity*** *and high prefabrication potential, they also make* ***economic*** *sense. According to the principle of* ***Plan Libre****, such floor plans are very* ***adaptable*** *and can be very well converted or deconstructed. The* ***circularity*** *potential of building materials and components can be fully exploited. This can significantly extend the life of a building and reduce* ***embodied emissions****, resulting in increased overall* ***sustainability****. The decision to use a concrete support structure was a* ***client's wish****. From a sustainability point of view, a timber frame structure would have been advantageous. Construction grids are a suitable and proven tool for structuring complex building tasks from design to execution. The well-chosen grid in this project allows achieving good* ***proportions*** *of the façade design and room divisions and permits a harmonious* ***composition*** *of all building elements."*

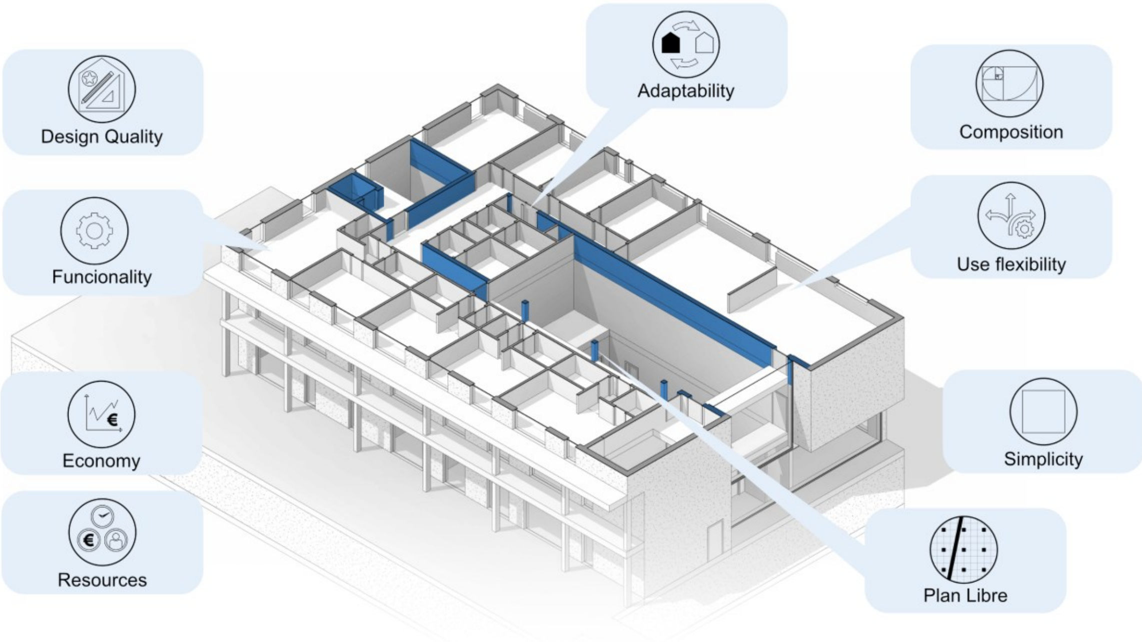


Figure 26 - Building Lab Design Episode Grid & Construction Type

8. Implementations as proof-of-concept

This chapter presents the implementations related to the proposed methods and concepts introduced in the previous chapter. The primary objective is to demonstrate these concepts' practical application and feasibility, establishing them as proof of concept. This chapter illustrates how these innovative ideas can be effectively integrated into the design process by showcasing real-world examples.

Throughout this chapter, detailed descriptions of the implemented solutions are provided. These implementations highlight the minimized machine-interpretable BIM-based communication protocol, the utilization of explanation tags and design episodes for digital design knowledge documentation, and the graph representation concepts for design episodes. By examining these implementations, readers can gain a deeper understanding of these novel concepts' practical implications and benefits.

Furthermore, this chapter aims to illustrate the outcomes and lessons learned from the implementations, offering insights into the challenges faced and the solutions devised. It means showcasing these concepts' potential impact in enhancing collaboration, transparency, and efficiency in architectural design.

Overall, this chapter serves as a crucial step in validating the proposed methods and concepts, providing tangible evidence of their efficacy and value. This chapter contributes to the broader understanding and acceptance of these innovative approaches in actual practice by presenting concrete implementations as proof of concept.

On a side note, it should be noted that in this work and similarly by Autodesk, the terms "plug-in" and "add-in" can be used interchangeably.

8.1. Revit plugin for feedback mechanism

Partial results and implementations of the presented work in this chapter have been published in:

Master's Thesis in Informatics at TUM, by Marija Rakic, titled "Lean BIM-based communication and workflow during design phases", supervisors: F. Petzold & A. Zahedi

The Feedback mechanism, as explained in section 7.1, is implemented and tested as a Revit plugin. The implemented plugin for Revit is designed to realize the proposed communication system, which is responsible for the feedback mechanism and consists of two parts. One part would be an issue tracking system or a so-called ticketing system. As with any other ticketing system, requests and responses are managed, and their progress is monitored. Priorities can be set for each ticket, and the person responding can also be traced. Multiple custom fields can be assigned to tickets, making coordination and communication seamless and transparently traceable. The other part stores the essence of the feedback from various consultants and domain experts using the feedback method function. Figure 27 illustrates this combination.

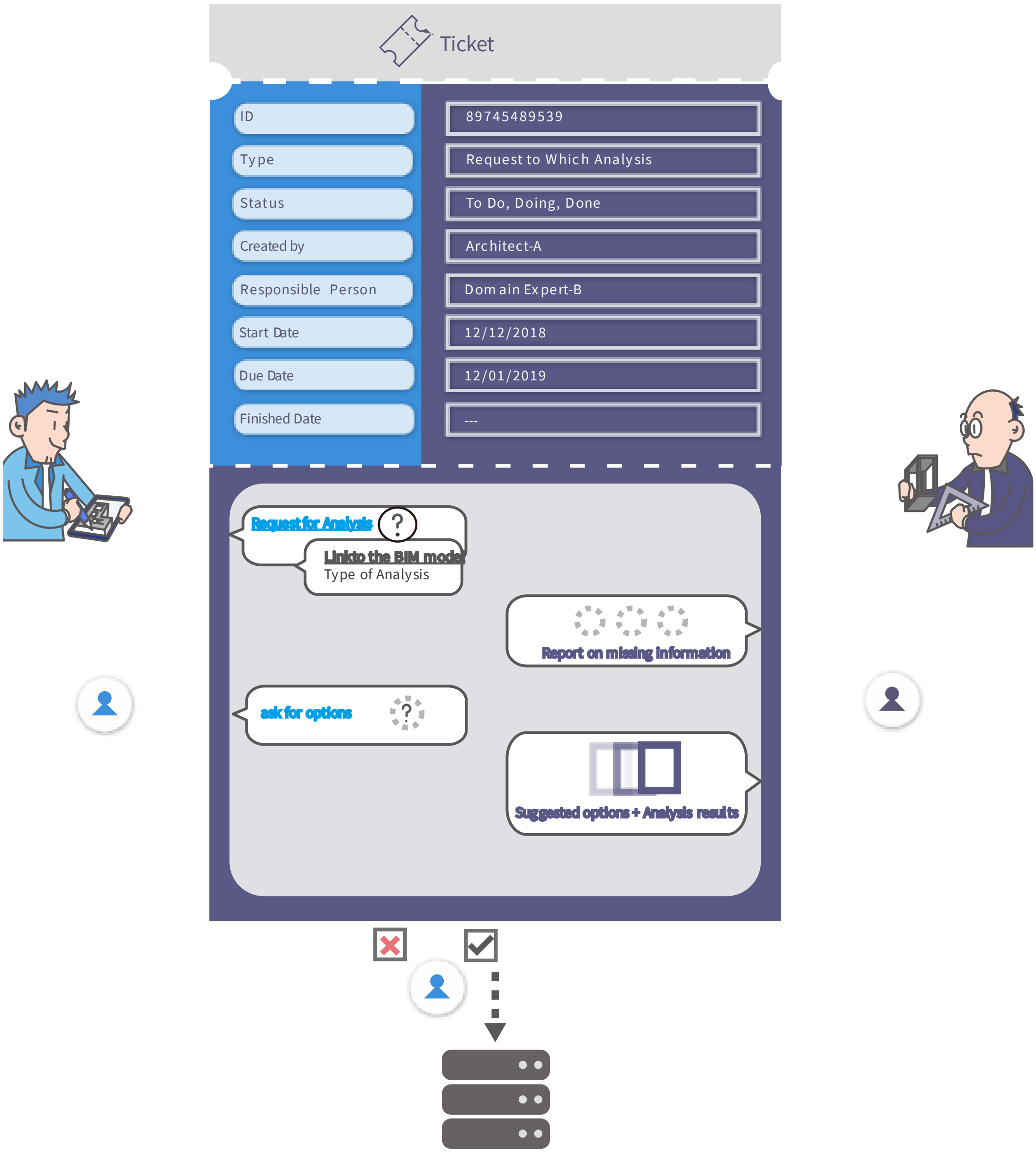


Figure 27 - Structure of Feedback Mechanism implemented as Revit Plugin

Different users can log in with their roles via the plugin, follow up, and respond to their tasks or forward them to other users. In an example scenario where the plugin is used, the architect requests a specific type of analysis and sends it to the responsible expert. This request is represented as a ticket that contains the requested type and scope of analysis. In the next step, the domain specialist reviews the content of the submitted BIM model by following the link to the CDE and creates a feedback report for the architect. This feedback report can include the missing building components and attributes required for the analysis. In response to this report, the architect may fill in some missing details, and since s/he does not know exactly what to choose for the other missing information, s/he will ask the domain expert for suggestions or so-called options. The domain expert would provide the architect with some best practice suggestions and options for completing the missing details in the design model and the ensuing analysis results if these suggested details are chosen. In this way, the architect can be informed of the consequences of his/her decisions resulting from each option and choose them wisely. At each step, the back-and-forth communication is performed using the feedback adaptive method function and will be stored in a communication history server.

8.2. Revit plugin for design decisions documentation

Partial results and implementations of the presented work in this chapter have been published in:

Zahedi, Ata; Petzold, Frank (2022): Revit Add-In for Documenting Design Decisions and Rationale. In: CAADRIA 2022. Post Carbon. Syndey.

A plugin for Autodesk Revit is implemented to enable design decisions documentation based on the concepts of explanation tags and design episodes. Generally speaking, the plugin adds a tool to Revit's toolbox accessible via the Revit ribbon. The code-behind and backend of the add-in were written in C#, while the user interface (UI) was created using XAML. With the help of the plugin, users may interact with the Revit environment and, consequently, read and write to any open Revit models. After installation, the plugin may be accessed via the Revit toolbar's Design Documentation tab.

This plugin has two primary uses, each highlighted by a separate main tab of the tool. The first is to give users access to the functionalities of explanation tags. Specifically to enable the searching and assigning of explanation tags inside the BIM model. Users can stage the desired tags and elements. They can then assign the tags either to the elements or their attributes. In other words, inside the Revit context, a user can assign a set of explanation tags to an element as a whole (element-global explanation tag) or to a particular parameter or attribute of a component (parameter-local explanation tag). In addition to assigning explanation tags to elements, the user may also browse and search for certain elements with particular explanation tags attached to them and utilize other sorting and filtering options.

The list of explanation tags that are already accessible may also be browsed or edited by the users. Users can also develop customized tags and add them to the library of preexisting explanation tags. (as shown in Figure 28)

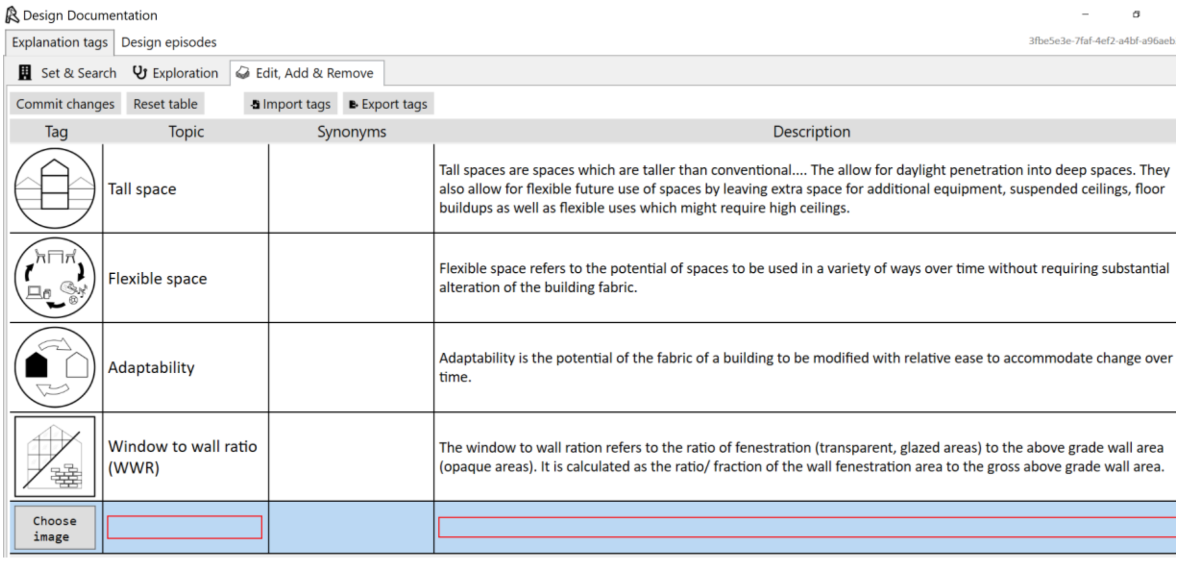


Figure 28 - Revit Plugin - Design Documentation – Add, Modify, Remove, Export or Import Explanation Tags

Within the scope of this plugin, an explanation tag can be created by providing it with a name, an icon, a definition or description, and zero or more synonyms. Different explanation tags that are synonymous with one another or have similar meanings are marked as synonyms. The explanation tags, within the scope of this plugin, are model-independent and retained under the user's application data. In other words, the explanation tags may be imported and exported to archives and used across various models.

The second purpose of the plugin is to create, manage and retrieve design episodes. Within the scope of this plugin, a design episode is modeled as an object with a name and description that contains a set of design elements from the Revit model. In other words, upon creating a design episode, the user selects the set of design elements (together with their attributes and possible explanation tags) that represent this episode or chapter of design and then provides a name and description for it, using storytelling techniques. For each episode of design, the user explains the design motive, intention, rationale, and argumentation in the form of free text. In contrast to the explanation tags, the design episodes are implemented in the plugin as model-bound rather than model-agnostic. It implies that the design episodes may be transferred together with the BIM model because they are stored within a Revit document. Like explanation tags, design episodes may be searched for and retrieved. Many search and filtering options are offered to make this function more convenient. Design episodes can also be edited, removed, and, if necessary, imported or exported to an archive. The plugin also provides the ability to export individual design episodes as CSV files for reporting purposes and as knowledge graphs exported to and stored in the Neo4j database.

In a nutshell, as depicted in Figure 29, this plugin enables architects to accomplish the following:

- They can elaborate on various aspects of design decisions by assigning explanation tags to different design elements or their specific attributes. (as shown in Figure 30)
- They can capture and document their tacit design knowledge for various cases using storytelling techniques and in the form of design episodes. (as shown in Figure 31)
- They can export their documented tacit design knowledge as knowledge graphs for future retrieval and possible reuse. (as shown in Figure 32)

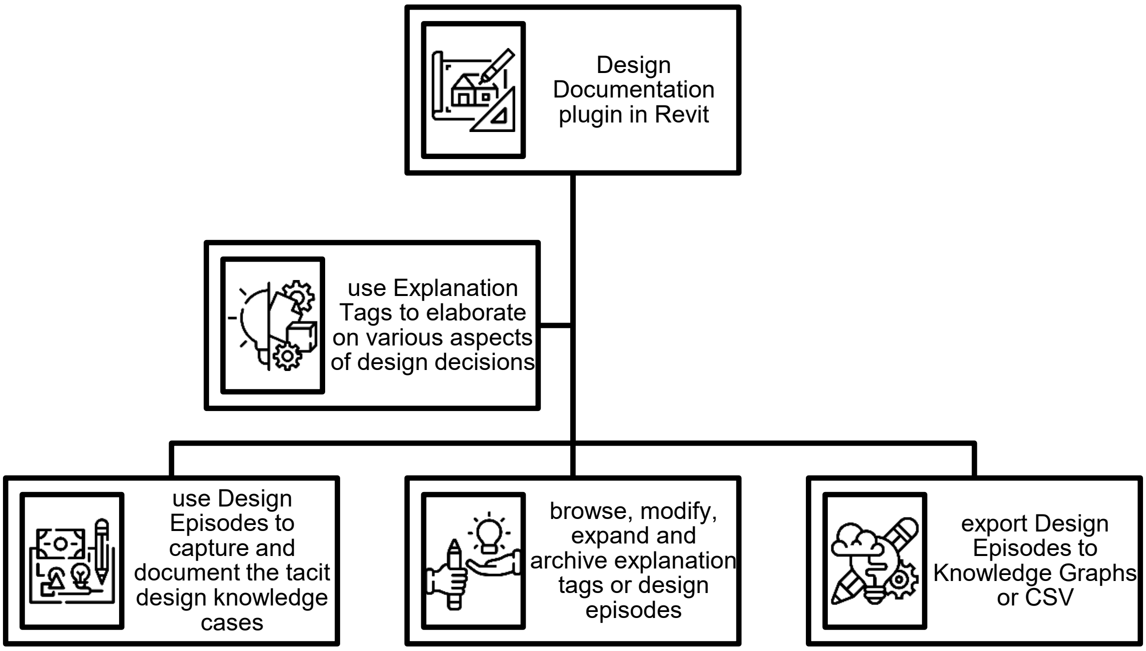


Figure 29 - Workflow of Revit Plugin for Design Documentation

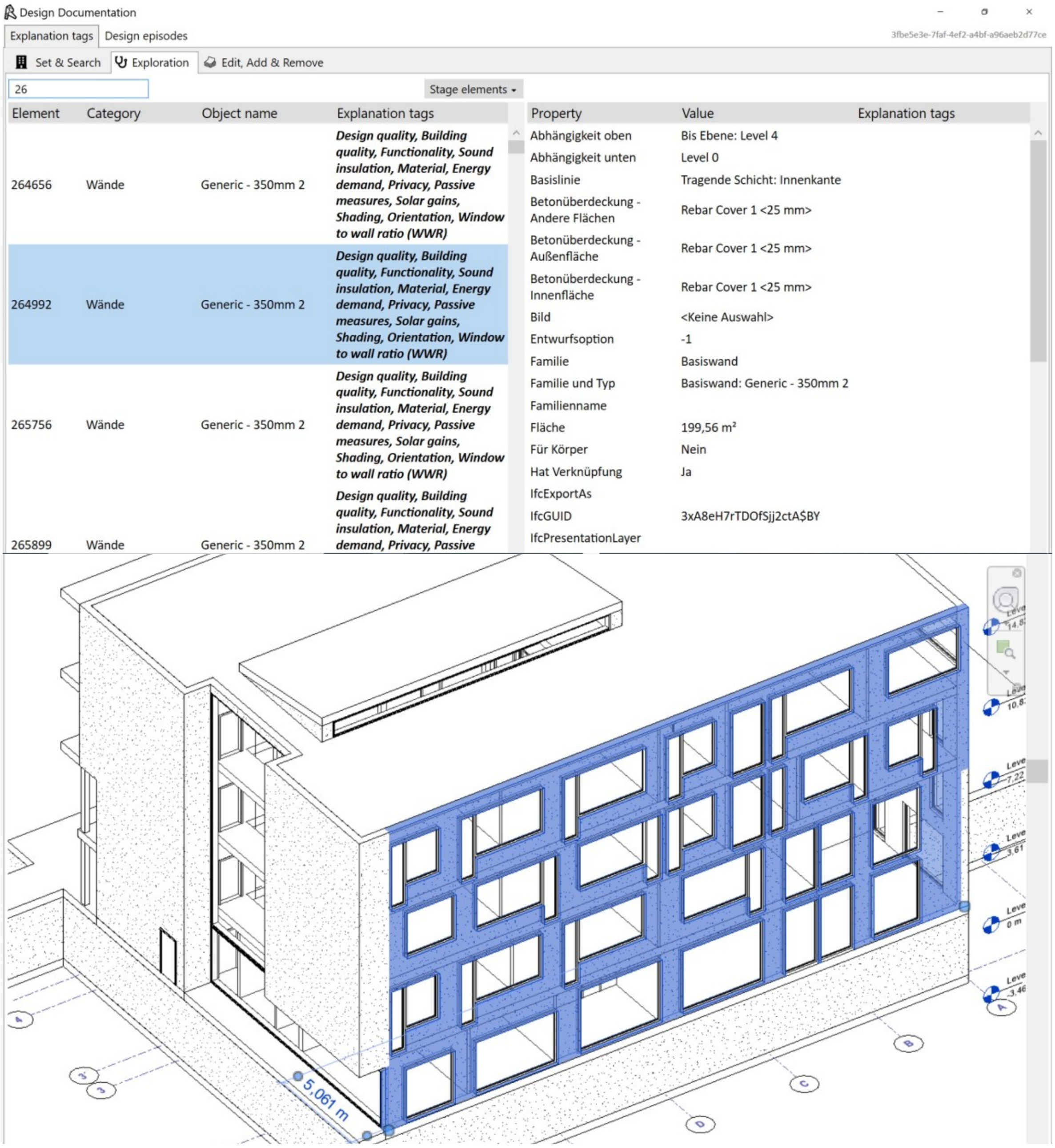


Figure 30 - Revit Plugin - Design Documentation - search for and explore elements with specific tags, sort and filter results

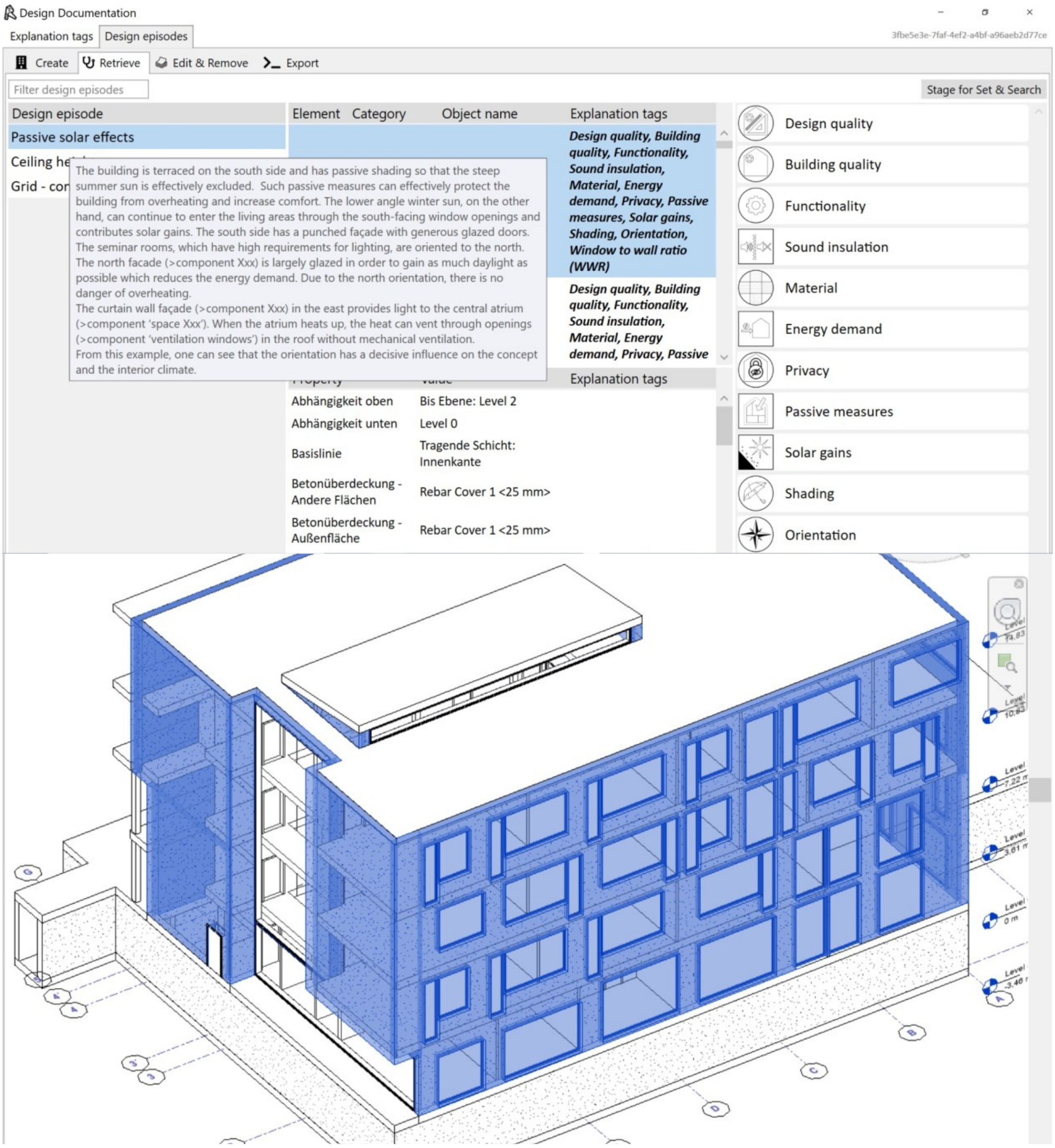


Figure 31 - Revit Plugin - Design Documentation – Retrieve Design Episode

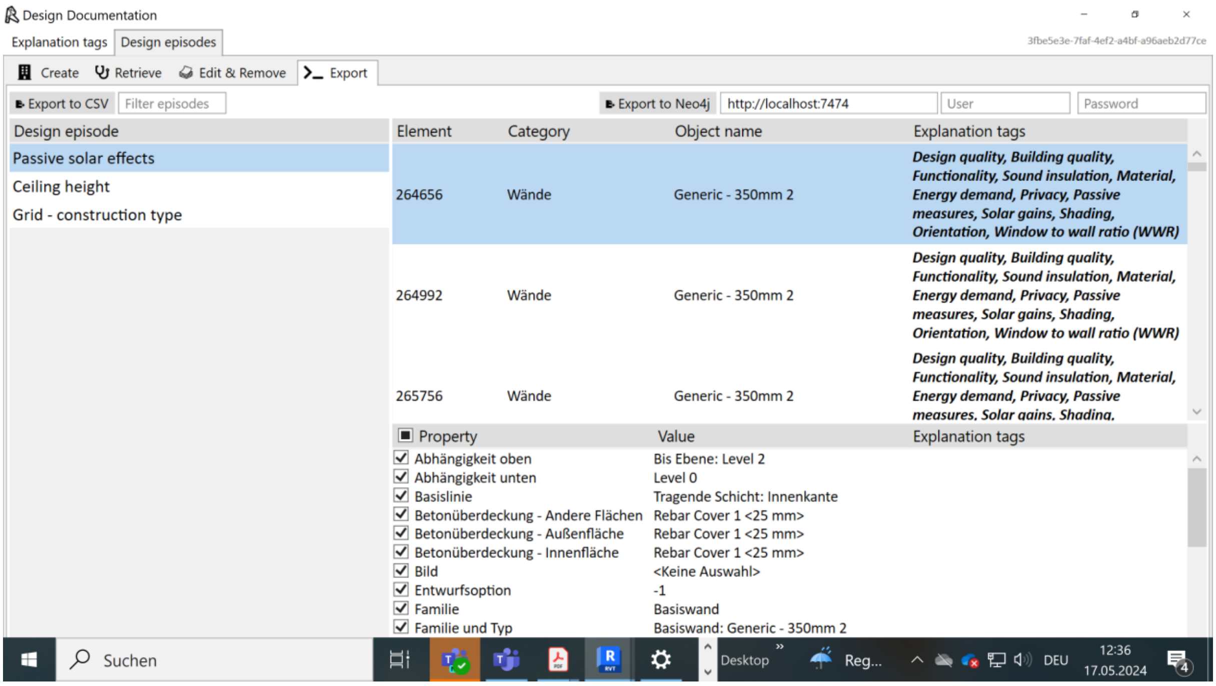


Figure 32 - Revit Plugin - Design Documentation – Export Design Episodes as CSV file or Neo4j Graphs

8.3. Methods for partial reuse of design knowledge

Partial results and implementations of the presented work in this chapter have been published in:

Master's Thesis in Informatics at TUM, by Subhan-Jamal Sohail, titled "Similarity determination and search in BIM models based on natural language text", supervisors: F. Petzold & A. Zahedi

Master's Thesis in Data Engineering and Analytics at TUM, by Wing Sheung Leung, titled "Sub-graph Isomorphism for Finding Similarities in Building Models", supervisors: F. Petzold & A. Zahedi

In this work, the final goal is to query the tacit design knowledge and information stored in BIM models. Two novel graph representations are introduced to achieve this goal, as discussed in sections 7.4.1 & 7.4.2. To demonstrate the effectiveness of these representations, two different approaches are proposed for searching and querying the design knowledge contained in them.

The first approach uses text, a list of desired design elements, and explanation tags as search input. More details about this are available in section 8.3.1. The second one utilizes subgraph matching techniques to search for similar graph patterns and related node and edge properties; more explanations follow in section 8.3.2. Both approaches were designed to allow adjustable weights that impact the search results.

The proposed system computed similarity scores throughout the database and presented the user with a ranked list of results. These methods offer a promising way to access and leverage the valuable design knowledge stored in BIM models, allowing architects to make more informed decisions and improve the efficiency of their design processes.

8.3.1. Text-, building-component- (design-element-) and explanation-tag-based search of design episodes

The data workflow starts by creating the design episodes, as explained in Chapter 7.3; afterward, they can be exported into the Neo4j database. On the other hand, the search workflow begins with a small introduction to the domain, and then the user can search for desired Design Episodes immediately. The Search Workflow is integrated into a web interface. To initiate the search, the user must enter a desired search description in plain text that describes what one is looking for. Upon writing, the user is prompted to include existing Explanation Tags and Building Components or add them to a list of desired tags or design elements. To make the search even more precise, Building Components can be combined with Explanation Tags, and the user can also set a flag for searching for exact matches regarding tags or building components or their combinations.

Furthermore, each inquiry section has adjustable weights impacting the overall search results. Upon searching, the similarity scores are computed throughout the whole database. The user is presented with a list of Design Episodes ranked by most similar to least similar. Each entry in the list has a call to action to further analyze the Design Episode on a detail page. This workflow is depicted in Figure 33.

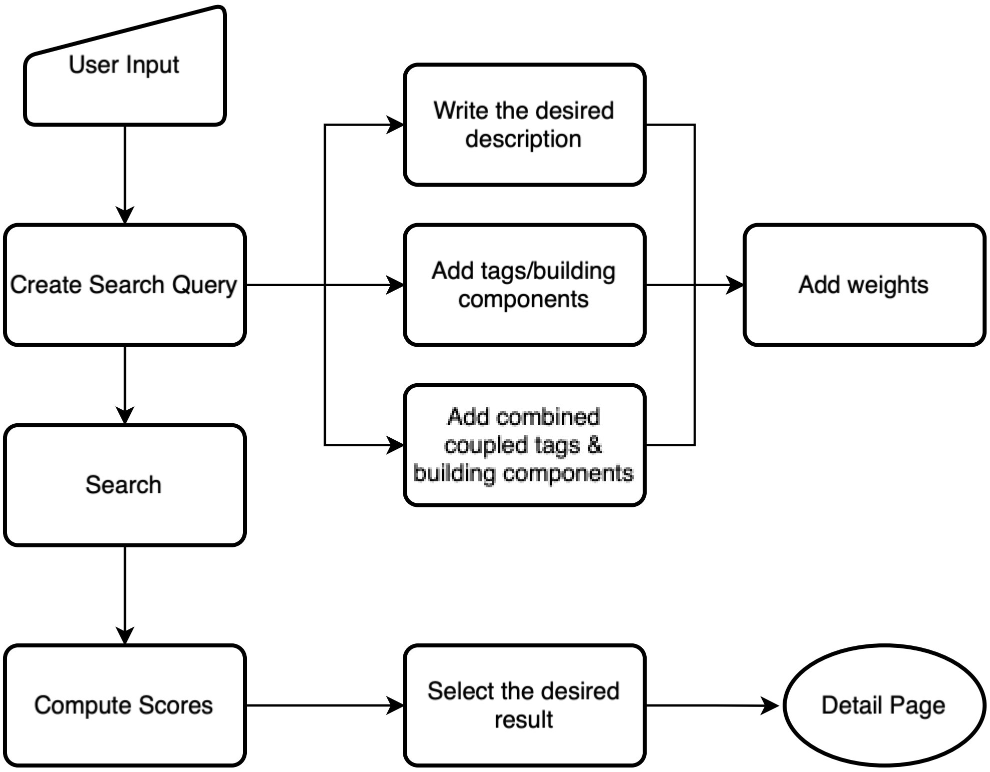


Figure 33 - Workflow of the Web-based UI for searching similar design episodes based on Text & Tags & building components

8.3.2. Subgraph machining of IFC and design episodes graphs

Based on the work discussed in section 7.4.1, as depicted in Figure 34, the implementation as proof of concept includes three main steps. The first step is the creation of a knowledge graph, which converts a building design described in an IFC model into a graph structure and stores the resulting knowledge graph in a graph database. The second step is subgraph matching, which searches for specific building design patterns within the knowledge graph database. Subgraph Matching is the process of finding a subgraph in a larger graph that is structurally similar to a given query graph. It is used to identify patterns in the graph data, such as groups of nodes that have similar relationships and/or properties. Subgraph matching can be performed either in an exact or approximate manner, depending on the specific application. It is worth mentioning that there is no direct implementation of subgraph matching in Neo4j. Instead, a pattern-matching function can be used to perform subgraph matching between a target subgraph and the graphs stored in the Neo4j database. Pattern matching in Neo4j is a smart way to implement subgraph matching because it breaks the matching problem into small parts (e.g., a short path pattern) and searches them one by one, and only the nodes and edges that meet the first pattern will be used for search in the next pattern. In this context, a path is the same as a pattern. Path matching in Neo4j preserves the idea of relationship isomorphism, which states that every edge in a record is unique. "Cypher makes use of relationship isomorphism for path matching and is a very effective way of reducing the result set size and preventing infinite traversals.[14]"

The final step is similarity calculation, which measures the similarity between the queried results and the targeted building design pattern based on the properties of the building elements. To better understand the flowchart depicted in Figure 34, some of the essential terms are defined as follows:

- **Target Subgraph *t*** is a desired graph to be searched. Its structure is defined in a web interface.
- **Target Properties *P(t)*** is the node properties of *t* that the user chooses for subsequent similarity measurement. Zero, one, or more properties for one or multiple nodes can be selected. At least one node property should be chosen for comparing the similarity between *t* and the queried subgraphs *Q*.
- **Queried Subgraphs *Q*** are results retrieved based on *t* from the Neo4j knowledge graph database. They share the same structure as *t* and are solutions to the subgraph matching between *t* and the knowledge graphs stored in the database. *q* represents a single retrieved subgraph.
- **Node Properties** of a queried subgraph ***P(q)*** is the set of all node properties of a retrieved subgraph *q*.
- Similarity (-distance) **Scores** are the computed distances representing the degree of similarity of all *q* members of *Q* to *t*. The lower the score, the shorter the distance between *q* and *t*, i.e., the higher the similarity.
- **Node label** represents the building component type in the domain. Each node has a label. For example, a node can be a room, a wall, or a door.
- **Edge label** is the relationship type between any two nodes in a subgraph. Each edge has a label. For example, two rooms (nodes) can be connected with an edge labeled as *connectsWithVirtualBoundary*. That is to say, there is no physical wall between these two spaces. The rooms are separated via a virtual wall.

[14] - https://neo4j.com/docs/cypher-manual/current/introduction/uniqueness/

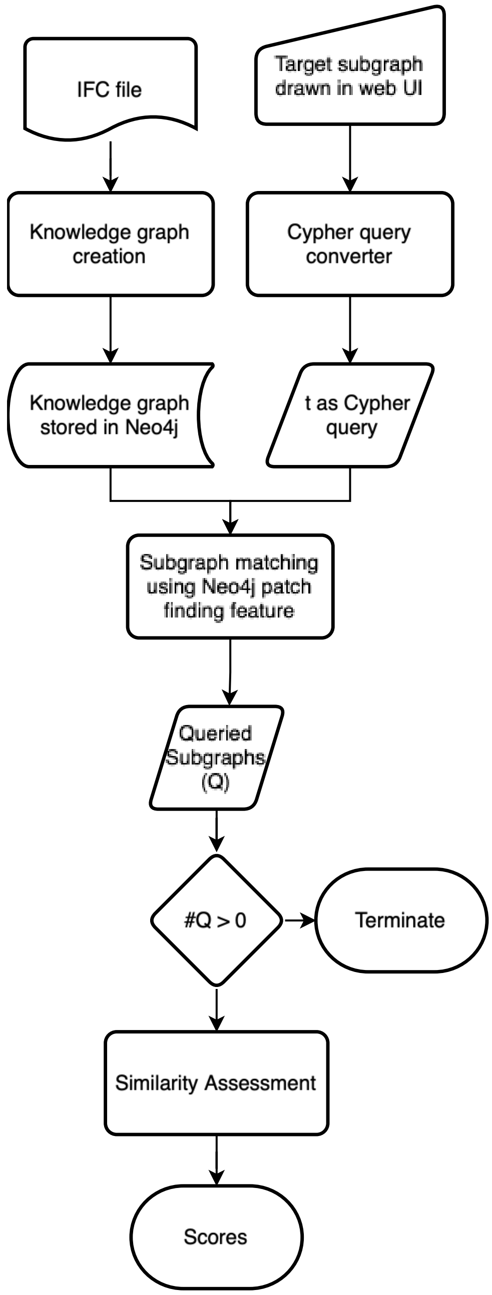


Figure 34 - General workflow for subgraph matching of IFC files

Additionally, a web interface has been created to facilitate the user interface and the evaluation of the methodology. Figure 35 illustrates how users can search for similar building models within the knowledge graph database through the web interface. The web interface allows users to search with multiple target subgraphs simultaneously. A subgraph isomorphism algorithm has also been implemented to check for any common subgraph structures within these graphs. These results indicate the similarity between the targeted subgraphs in terms of structure.

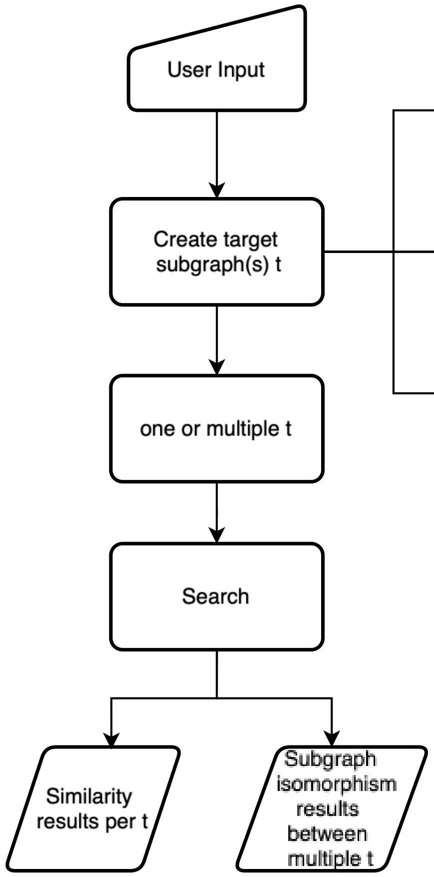


Figure 35 - Workflow of the UI for searching similar building patterns using subgraph matching

9. Discussion and outlook

This chapter draws upon the findings and insights gained throughout the dissertation to present the conclusions, engage in a comprehensive discussion, and offer an outlook for future research and developments in the field.

The primary objective of this chapter is to provide a synthesis of the key findings and outcomes resulting from the application of the proposed methods and concepts. It reflects on the effectiveness and impact of these innovations in achieving the goals outlined in this dissertation.

Additionally, this chapter serves as a platform for a comprehensive discussion, wherein it critically analyzes the strengths and weaknesses of the proposed methods and concepts. It also explores potential areas for improvement and further refinement, taking into account the practical considerations and constraints encountered during the implementation process. This discussion aims to foster a deeper understanding of these concepts' implications, limitations, and potential applications in the broader architectural context.

Furthermore, an outlook for future research in this field is provided. Avenues for further investigation are identified, and potential areas of expansion and enhancement for the proposed methods and concepts are explored. This chapter not only reinforces the significance and value of the proposed methods and concepts but also serves as a catalyst for further research and innovation in architectural design and knowledge management.

9.1. Recap on the research gap

The AEC industry is a vital sector of the global economy, as it is responsible for designing, constructing, and managing the built environment. Effective collaboration and communication are essential for success in today's complex projects. In other words, architects, as lead designers, must work closely with other experts and stakeholders, such as engineers, consultants, contractors, and clients. However, coordinating the efforts of multiple stakeholders can be challenging, particularly on large or complex projects. These stakeholders must constantly communicate with one another and exchange a lot of information for a construction project to be successful. At the moment, this usually entails the transfer of graphically represented technical drawings of the building project in the form of horizontal and vertical sections, views, and detail drawings (Borrmann et al. 2018b). And the communication and exchange of information happen in most cases over unstructured channels and formats, such as text, screenshots with annotations, and using general means of communication such as telephone, email, and so on.

Furthermore, the AEC industry is a knowledge-intensive sector that draws on diverse skills from various sources (Joe et al. 2013). For many years, the AEC industry has accumulated explicit information in the form of building codes, manuals, best practice guides, standards, processes, and so on. Furthermore, individuals with specific expertise and experience possess valuable tacit knowledge. If a strategy to capture such knowledge is not established as people retire, many knowledge-intensive organizations (e.g. architectural firms) will risk a constant loss of unrecoverable valuable knowledge (Calo 2008). However, it is very difficult to formalize, maintain, and exchange this sort of tacit design knowledge. The master-apprentice relationship was and still is a common method of passing on tacit knowledge. There is also a broad gap between research and practice, which implies that vital knowledge is sometimes overlooked. This can lead to 'reinventing the wheel' or making the same mistakes over and over again. Architectural firms need to adopt a systematic and consistent approach to design process documentation as construction gets more complicated and clients become more demanding. Documenting design knowledge, intentions, and decisions is a fundamental step for communicating with owners and domain experts. Additionally, it facilitates the future evaluation and re-use of completed projects, which can support decisions during the use and facility management of these projects and provide guidance when designing new projects.

9.2. Recap on the research hypothesis

This dissertation explores the architectural design process as a series of communications and argumentations with oneself or among experts based on relevant theories. From this perspective, there are two significant advantages to proper design process documentation. First, it can enhance the reuse of design knowledge and experience, leading to optimized design decisions in current projects. That means the design rationale contained in communications and decisions across various projects can be a valuable source of knowledge for better decisions if captured and documented appropriately. Second, model-based and machine-interpretable communications and documentation of design decisions will lead to more transparency and traceability in the design process.

As a result, the following research hypothesis is formulated:

Partial reusability and more transparency in BIM-based design process can be achieved through machine-interpretable documentation of design decisions and communications

This dissertation aimed to demonstrate the potential of the proposed approach and concepts and provide evidence for their effectiveness through practical examples and real-world applications. Thus, the initial research hypothesis could be confirmed through the concepts and methods discussed in chapters 7 & 8.

9.3. Recap on the proposed approach, methods, and concepts

BIM models have the potential to serve as procedural realizations of multidisciplinary knowledge, but currently, they store information rather than knowledge. Existing BIM models include raw geometries and semantics but lack any justification or explanation of design decisions. Existing methods, such as storytelling, can help transfer tacit design knowledge. However, a tool for documentation in this regard is missing for BIM authoring tools. Furthermore, while existing BIM–based communication standards such as BCF enable model-based communications, still machine-interpretable and minimized communication protocols are lacking in this field.

By utilizing proactive measures such as the concept of adaptive detailing (Zahedi and Petzold 2018), architects can receive suggestions from domain experts to incorporate missing details into the design model. This approach enables them to understand the implications of these suggested options/details for earlier requested analyses, thus addressing the absence of objectifiable assessments for critical early-stage design decisions.

This work developed an adaptive and machine-interpretable framework that can effectively facilitate communications and interactions across diverse building projects, thus ensuring analysis and deriving insights from these communications and collaborations for future reference. The framework is designed to handle the exchange of information between the architects and various experts and consultants through a model-based machine-interpretable protocol.

These recommendations and suggestions provided by consultants and other experts are managed by implementing a *Feedback Mechanism,* which is already elaborated on in sections 7.1, 7.5.1 & 8.1. Harvesting the existing capabilities of BIM methodology, this mechanism guarantees that all communications occur in an adaptive, minimized and machine-interpretable manner, ensuring adequate information flow and understanding.

I continued by posing the question of how design decisions can be explained and digitally documented based on existing conditions and assumptions. Accordingly, another primary objective of this dissertation was to present a BIM-based framework that incorporates an architectural lexicon encompassing diverse design aspects and assessment criteria. The purpose of this lexicon is to provide clarity in design rationale and reasoning. To address this challenge, this dissertation proposes an adaptive framework that can be expanded or customized to suit various projects' specific requirements and specifications.

Within this framework, an innovative solution is introduced for the architects to express their motives and argumentations for numerous design decisions. To this end, different *Explanation Tags* are defined to represent various architectural concepts and assessment criteria. These tags are then assigned to various design components, spaces, or specific attributes within the design. This approach facilitates a comprehensive elaboration of design rationale, justification, and argumentation, enabling a clearer understanding of the design decisions made throughout the process. By applying explanation tags, the motivation and reasoning behind design decisions are captured and envisioned in an understandable and graphical way. More detailed information can be found in sections 7.2, 7.5.2 & 8.2.

Furthermore, to manage different cases of tacit design knowledge better and in a scalable manner, this dissertation introduced the novel concept of Design Episodes, which provide s a flexible framework for breaking down the overall building design into more manageable segments. These segments are stored as solutions to specific design challenges encountered throughout the project.

Design episodes describe different design chapters via storytelling techniques that help others understand the process and the reasons behind certain decisions. Design Episodes can simplify the documentation of design decisions by organizing them according to specific tasks or challenges. Architects can navigate the information relevant to a particular design task or challenge, allowing for easier access and comprehension of the design process. This approach enhances transparency and traceability within the design documentation. Such documentation of tacit design knowledge coupled with explanation tags enhances the design documentation concerning both subjective (qualitative) and objective (quantitative) design aspects.

Moreover, the concept of Design Episodes opens up possibilities for the partial reusability of various design solutions in future projects when faced with similar design tasks. It promotes efficiency and knowledge transfer within architectural practices, as architects can draw upon and adapt existing design solutions to address similar challenges. Further details can be found in sections 7.3, 7.5.2 & 8.2.

To accomplish these goals, the abovementioned concepts and methods are integrated into the existing work process through mockup implementations for BIM authoring tools. The aim was to seamlessly support the design process without disrupting its flow. Additionally, application scenarios are discussed and demonstrated that showcased the benefits and relevance of using these concepts and methods.

The following are the benefits that can be achieved through this integration:

- By leveraging the Feedback Mechanism, the architect can ask for expert opinion and feedback based on simulation results during the early stages of design when facing critical decisions regarding the missing design details.
- The architect can explain and justify both subjective and objective aspects of their reasoning and argumentation for various design decisions by leveraging the Explanation Tags.
- The architect can document and transfer design decisions' reasoning to provide transparency and traceability for other stakeholders during the entire design process.
- The architect can preserve and capture individual tacit design knowledge by leveraging Explanation Tags and Design Episodes.
- The architect can transfer and reuse various design solutions in the form of Design Episodes in other projects.

Overall, this work aims to improve the design process by facilitating the management, documentation, and recording of design knowledge and providing support to architects in the early design phases to ask for expert opinions. One of the most remarkable results to emerge from this work is that a framework is presented to encapsulate not just the details of design models but also the subjective justifications behind design decisions and choices. This dissertation provides the blueprint for a new and holistic way to model-based machine-interpretable communications and design decisions documentation, more details of which can be found in chapters 7 & 8.

9.4. Validation of the proposed concepts and methods

As proof of concept, the feedback mechanism (7.1), explanation tags (7.2), and design episodes (7.3) were evaluated for applicability via two prototypes that were implemented as plugins in Autodesk Revit and put to the test and proven functional. Additionally, the methodology was applied and discussed in various use cases, including two real-world projects. Accordingly, the use cases have shown the suitability of the proposed methods and concepts for the current state of practice.

Moreover, the proposed concepts were extended to support the search for and reuse of design knowledge across various reference projects and multiple design options. Two novel knowledge-graph representations were introduced to ensure the partial reusability of the captured and documented tacit design knowledge, one for the IFC models (7.4.1) and the other for the design episodes (7.4.2). Accordingly, the effectiveness of the two knowledge graph representations discussed in sections 7.4.1 and 7.4.2 was verified via two mockup full-stack implementations, each applying different search and query methods, one employing subgraph matching (8.3.2) and the other through text and tag-based search (8.3.1). NLP techniques were then employed to query and match design requirements and episode descriptions in a natural text format.

9.5. Contributions and impacts

The contributions of this dissertation, followed by the corresponding introduced novel concept in this work, are listed as follows:

- Leveraging the adaptive and minimized machine-interpretable Feedback Mechanism will assist the architects with crucial design decisions during the important early stages of design by offering feedback and missing design details by domain specialists based on analysis and best-practice domain-specific scenarios leading to objectifiable assessments and better-informed decisions.
- The feedback mechanism supports a collaborative and iterative approach, allowing for the integration of expert opinions and suggestions at earlier stages. This strategy ultimately reduces the need for extensive revisions in later phases. It not only streamlines the negotiation process but also mitigates the potential for additional costs and delays associated with repeated modifications.
- Using the Explanation Tags, architects can clarify and legitimize their design decisions to the client, colleagues, and stakeholders, thus delivering more comprehensive design process documentation and recording design decisions' reasoning and rationale. It

ensures the BIM-based digital documentation of design decisions' argumentation and rationale, including both *subjective* and *objective* criteria.

- By leveraging the Design Episodes, architects can better manage and preserve their tacit design knowledge and make it visible and partially reusable. The design episodes can aid in storing and reusing the previous design solutions when facing similar challenges in new projects.
- Translate design episodes into knowledge graphs for future queries and partial reuse.
- Enable the search and query for desired design ideas and inspirations when facing similar design problems.
- Demonstrate the feasibility of the abovementioned concepts via prototypical implementations and demonstrative use cases based on real-world building projects.

9.6. Conclusion and future work

The feedback mechanism introduced in this work is a significant advancement in building design and construction. This model-based minimized machine-interpretable communication protocol leverages the benefits of BIM and multi-LOD meta-model to provide a structured and standardized approach to communications between stakeholders in the early design phases. Employing the feedback mechanism as a proactive measure promotes a collaborative and iterative approach, facilitating the integration of expert opinions and suggestions at earlier stages. This strategy ultimately reduces the necessity for extensive revisions in later phases. It not only streamlines the negotiation process but also alleviates the potential for additional costs and delays linked to repeated modifications. Illustrated by HOAI, negotiations, and exchanges between architects, specialist planners, and domain experts that typically extend sometimes even until LPH 8 could be addressed with full technical design and construction details as early as LPH 2 and 3. It results in improved collaboration, transparency, and efficiency in the communication process.

The ability to store valuable data on past communications is a key advantage of this BIM-based feedback mechanism and can potentially provide significant benefits for future building design projects. This data can be used to support future decision-making in several ways. Firstly, it provides a traceable record of all communications, variant evaluations, and decision-making, especially during the early design phases. This information can be used as a reference for future design decisions and to ensure that past experiences and insights are not lost. Secondly, the data accumulated from past communications can be analyzed and filtered for future use. It can provide valuable insights into patterns and trends in communications with- and feedback from- experts, which can be used to improve future design processes. For example, the data could be used to identify areas where communication is frequently unclear. Finally, the data collected by the protocol can support more sophisticated decision-making tools and techniques in the future. For example, the data could be used as input to artificial intelligence algorithms to support design decision-making based on historical data and best practices.

This dissertation provided the capacity to document various aspects and rationale of design decisions in digital BIM models in a transparent and scalable manner. While explanation tags provide the means to explain and clarify design rationale and reasoning, design episodes offer flexible means to capture and store various bits and pieces of tacit design knowledge in digital BIM models. This approach will benefit architectural firms and design teams in various ways. Clear explanations of design reasoning and rationale bring more transparency and traceability into the design process and facilitate teamwork while avoiding mistakes, misinterpretations, and redundancies. Furthermore, architectural firms can preserve and manage their intellectual property and design knowledge over time. This can be particularly important in cases where team members move on to other projects or leave the company altogether. Furthermore, this tacit design knowledge preserved in digital BIM models and design episodes could be a source of inspiration to answer similar design problems in other projects.

9.7. Recommendations and some limitations

It is essential to acknowledge that the concepts and methods presented in this dissertation do not claim to fully resolve the issues of inefficient design communications and insufficient design process documentation. Furthermore, implementing these methods may require additional effort or minor changes to the established working procedures of architectural firms, which could encounter resistance within the workplace. Consequently, it is crucial to conduct further testing and survey the effectiveness and consequences of these methods and concepts through future research in this field.

Moreover, it should be noted that while the proposed non-exclusiveness aspect of the explanation tag concept brings freedom to create and assign user-defined terms and descriptions, it should be advised to watch out for potential overuse of this feature that can increase the risk of semantic derivations, which in turn hinders the communication and reuse of design knowledge. That being said, the proposed frameworks in this dissertation are adaptive enough to adjust to various firms' needs and, if need be, act as a standardization approach for design process documentation, reflection, and possible future reuse.

Moreover, further evaluations via user studies are intended to enhance the understandability and usability of the developed approach. Furthermore, intensive and conclusive design documentation in sample projects, from start to end, is planned as future steps. The ultimate goal is to contribute to the ongoing evolution and advancement of the building design and construction field by developing and implementing innovative and practical concepts and methods.

10. List of publications written in the context of this dissertation

10.1. Peer reviewed journal papers

- **Ata Zahedi**, Jimmy Abualdenien, Frank Petzold, André Borrmann (2022): "BIM-based design decisions documentation using design episodes, explanation tags, and constraints." Journal of Information Technology in Construction. vol. 27, pages 756-780.
- Li, Chao, **Ata Zahedi**, and Frank Petzold. 2022. "Pragmatic Design Decision Support for Additive Construction Using Formal Knowledge and Its Prospects for Synergy with a Feedback Mechanism" Buildings 12, no. 12: 2072. https://doi.org/10.3390/buildings12122072.
- Jimmy Abualdenien, Patricia Schneider-Marin, **Ata Zahedi**, Hannes Harter, Hannah Exner, Daniel Steiner, Manav Mahan Singh, André Borrmann, Werner Lang, Frank Petzold, Markus König, Philipp Geyer, Martina Schnellenbach-Held (2020): "Consistent management and evaluation of building models in the early design stages." Journal of Information Technology in Construction vol. 25, pages 212-232.

10.2. Peer reviewed conference proceedings

- J Staudt, M Margesin, C Zong, F Deghim, W Lang, **A Zahedi**, F Petzold, P Schneider-Marin (2023): “Life cycle potentials and improvement opportunities as guidance for early-stage design decisions”. Proceedings of the 14th European Conference on Product and Process Modelling (ECPPM 2022), eWork and eBusiness in Architecture, Engineering and Construction 2022, CRC Press. pages 35-42.
- **Ata Zahedi**, Frank Petzold (2022): “Revit Add-In For Documenting Design Decisions And Rationale, A Bim-Based Tool To Capture Tacit Design Knowledge And Support Its Reuse”. Proceedings of the 27th International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA 2022).
- D Napps, **A Zahedi**, M König, F Petzold (2022): „Visualisation and graph-based storage of customised changes in early design phases”. Proceedings of the 39th International Symposium on Automation and Robotics in Construction (ISARC 2022).
- K Jaskula, **A Zahedi**, F Petzold (2021): “Archi-guide. Architect-friendly visualization assistance tool to compare and evaluate BIM-based design variants in early design phases using template-based methodology”. Proceedings of the 14th European

Conference on Product and Process Modelling (ECPPM 2021) - eWork and eBusiness in Architecture, Engineering and Construction, CRC Press. pages 153-162.

- Z Meng, **A Zahedi**, F Petzold (2020): "Web-Based Communication Platform for Decision Making in Early Design Phases", Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC 2020), pages 1000-1007, DOI: https://doi.org/10.22260/ISARC2020/0138.
- **Ata Zahedi**, Frank Petzold (2019): "Interaction with analysis and simulation methods via minimized computer-readable BIM-based communication protocol", Proceedings of the 37th Education and Research in Computer Aided Architectural Design in Europe and XXIII Iberoamerican Society of Digital Graphics Joint Conference (eCAADe and 23rd SIGraDi 2019) vol. 1, pages 241-250.
- **Ata Zahedi**, Frank Petzold (2019): "Adaptive minimized communication protocol based on BIM", Proceedings of the European Council on Computing in Construction (EC3) Conference 2019, vol. 1, pages 31-39.
- **Ata Zahedi**, Jimmy Abualdenien, Frank Petzold, André Borrmann (2019): "Minimized Communication Protocol Based on a Multi-LOD Meta-Model for Adaptive Detailing of BIM Models" Proceedings of the 6th International Workshop on Intelligent Computing in Engineering (EG-ICE 2019).
- **Ata Zahedi**, Frank Petzold (2018): "Seamless integration of simulation and analysis in early design phases" Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering (IALCCE 2018) pages 441.
- **Ata Zahedi**, Frank Petzold (2018): "Utilization of Simulation Tools in Early Design Phases Through Adaptive Detailing Strategies" Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2018), vol. 2 pages 11-20.

10.3. Supervised master theses

- Subhan-Jamal Sohail (2022): "Similarity determination and search in BIM models based on natural language text" Master's Thesis in Informatics, Department of Informatics, Technical University of Munich, Supervisors: Frank Petzold, **Ata Zahedi**.
- Wing Sheung Leung (2021): "Sub-graph Isomorphism for Finding Similarities in Building Models" Master's Thesis in Data Engineering and Analytics, Department of Informatics, Technical University of Munich, Supervisors: Frank Petzold, **Ata Zahedi**, Jimmy Abualdenien.

- Marija Rakic (2019): “Lean BIM-based communication and workflow during design phases“ Master’s Thesis in Informatics, Department of Informatics, Technical University of Munich, Supervisors: Frank Petzold, **Ata Zahedi**, Jimmy Abualdenien.

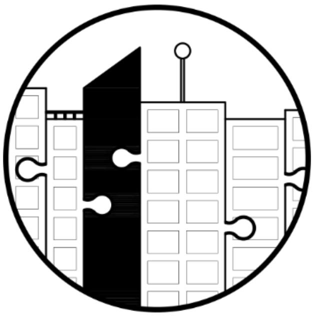
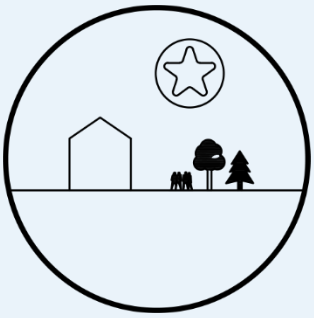
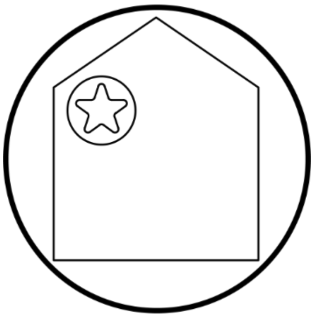
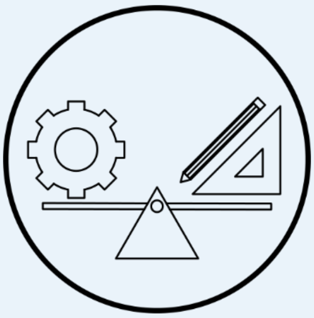
11. List of explanation tags

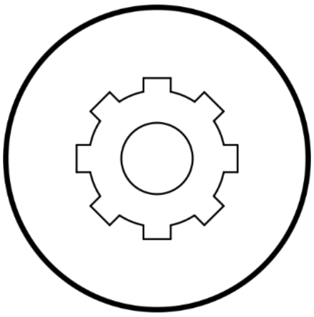
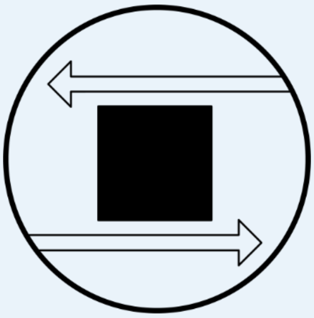
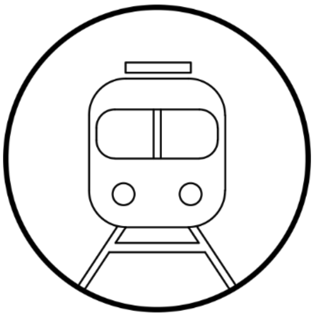
Drawing from both existing research and architectural literature, as well as incorporating sustainability recommendations from SNAP (Fuchs et al. 2013) and insights from the Early-BIM research group's domain experts, this work introduces a set of explanation tags, available here in this appendix. These tags encompass both qualitative and quantitative design aspects and criteria. While the icons for subjective tags are framed in a circle, the objective ones are placed in a box in order to distinguish between these two groups.

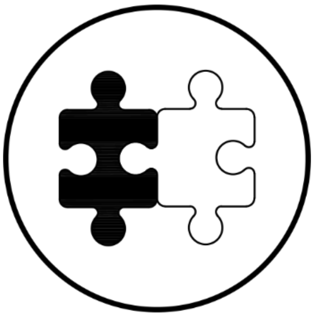
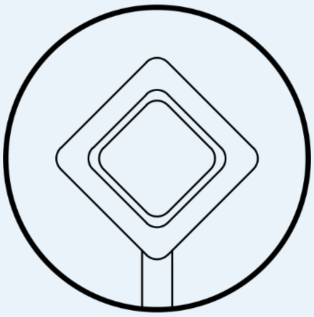
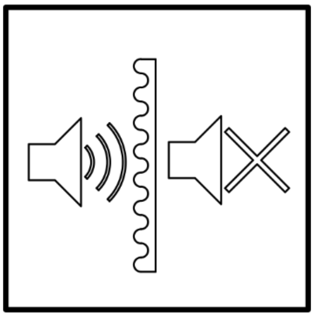
It is crucial to emphasize that this collection is neither final nor uniformly styled. Furthermore, it does not claim perfection. The framework, designed with adaptability in mind, caters to the diverse requirements of various projects, firms, or clients. The explanation tags presented may vary in detail or elaboration, showcasing the framework's inherent flexibility and adaptability to specific contexts.

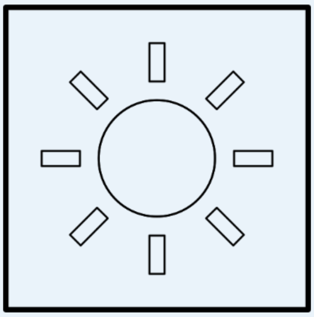
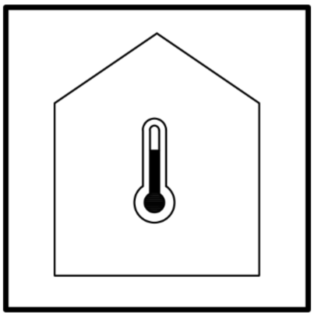
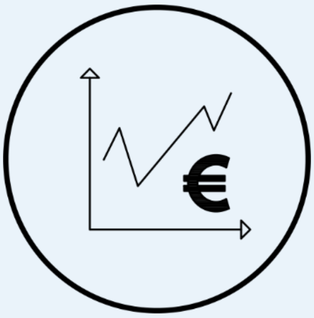
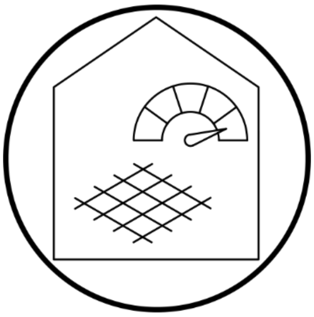
However, it is worth noting that while the collection might lack uniformity, it remains versatile and can be utilized in a unified manner for specific organizations or disciplines as needed.

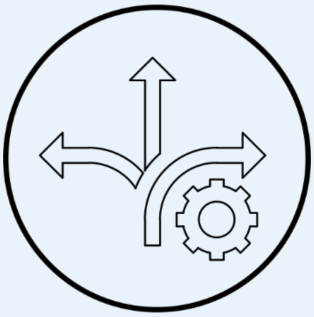
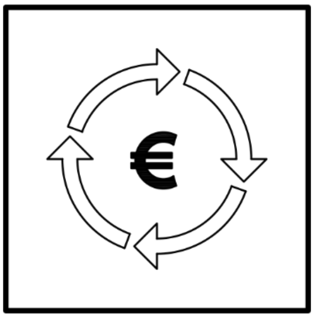
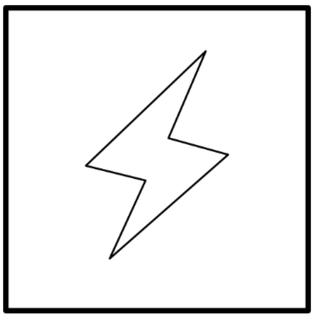
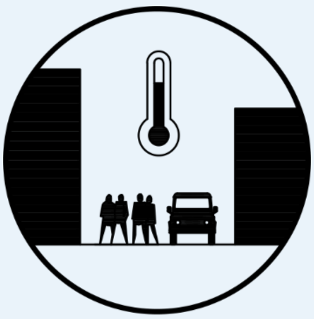
Table 2 - List of Explanation Tags

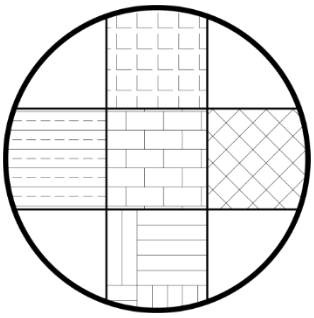
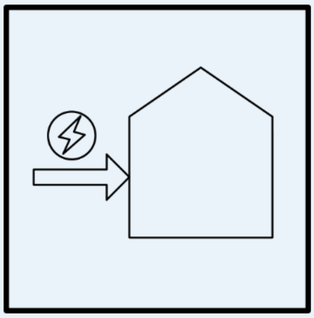
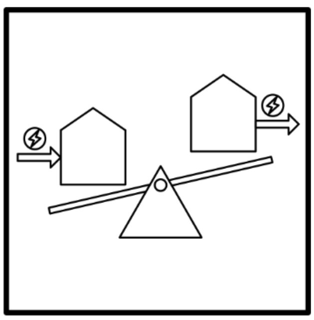
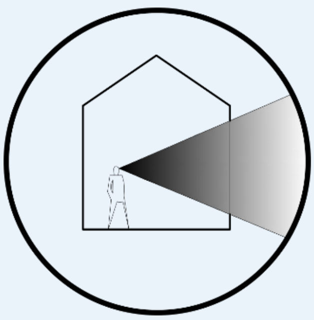
Nr	***Topic***	***Explanation Tag***	***Description***
01	**Design Quality**		Design quality may involve many aspects including client requirements to building codes and regulations. In general, it expresses how well the design meets client values and how its impact would be on the environment and the local community. It is also closely connected to urban integration and building as well as external space quality.
02	**Urban integration**		The building will significantly characterize the surrounding buildings and public street spaces. A solitaire is expected as an accent in the urban space, but at the same time, it should fit the neighborhood, blend with the environment, and altogether support the urban image of a place. (Fuchs et al. 2013)
03	**External space quality**		Creation of optimal local and user-specific social spaces for urban spaces and ground floor areas, as well as a roof design acting as a "Fifth facade to promote a three-dimensional cityscape.". (Fuchs et al. 2013)
04	**Building quality**		As a contribution to the building culture, the building ensemble should be of a high degree of design quality and should have a specific Identity, and it should contribute to solving current social problems.
05	**User and task-specific image**		Proper self-presentation and identity formation can be achieved through an equilibrium between usability and design.

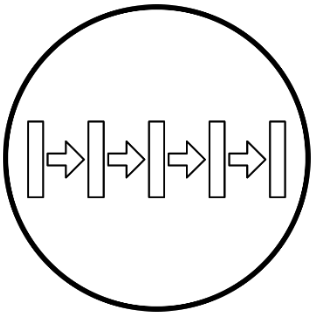
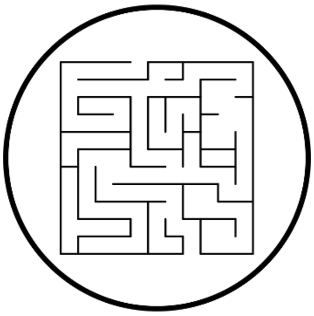
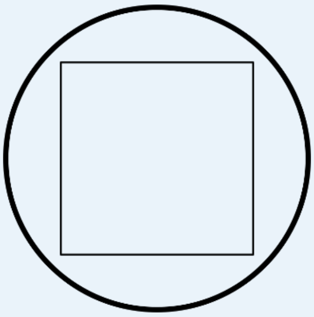
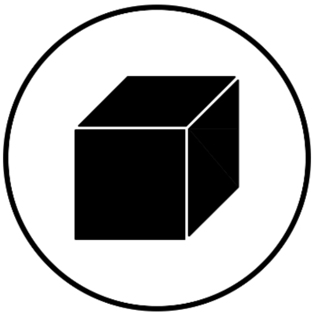
06	**Functionality**		Utilitas as one of three foundations and essential components of successful architecture by Vitruvius (the ancient Roman architect) means utility, **functionality,** or commodity and provides an efficient arrangement of space and mechanical systems to meet the functional needs of its occupants. Functionality is also closely connected to accessibility, spatial efficiency, and use flexibility.
07	**Accessibility**		Based on the existing or projected road and traffic network, an external and internal development concept is to be developed that ensures good networking with the neighborhood, unmistakable orientation options, good clarity, and secure accessibility. A high degree of cycling comfort should support the development of environmentally friendly mobility. **Excellence rating:** driveway considered; supply and disposal easily accessible; good access to the underground parking; good positioning of bicycle parking spaces; number of bicycle parking spaces fulfilled (e.g., 10 pcs.); main entrance easy to recognize; short internal ways (Fuchs et al. 2013)
08	**Public access**		A high degree of public accessibility promotes the integration and acceptance of the buildings within the neighborhood.
09	**Barrier-free access**		The barrier-free design should ensure unrestricted freedom of movement, increase communication in the building for people with disabilities and enhance the spatial qualities of architecture and open space. **Excellence rating:** barrier-free access to all rooms (elevator on each floor); barrier-free entrance (ramps in entrance area) (Fuchs et al. 2013)

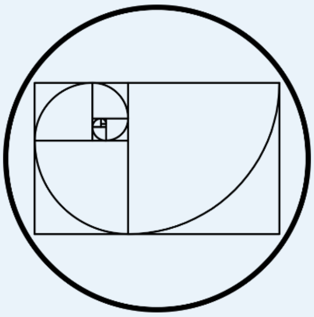
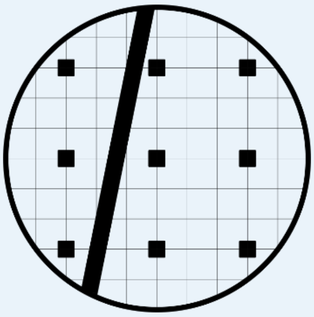
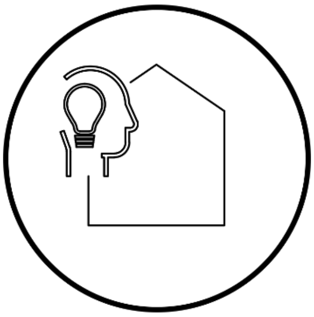
10	**Spaces for social integration**		Caring for social contacts supports responsibility, creativity, and building social networks. This is promoted by semi-public areas, communication-promoting develop-ment and meeting areas, and a well-coordinated interaction of the private, semi-public, and public areas of buildings and their environment. In addition, the widest possible range of accommodation options should promote communication.
11	**Comfort**		A sense of physical contentedness, which comes from many physically measurable conditions, such as light intensity, atmospheric humidity, temperature, air exchange, and noise intensity. Alongside the physical measures, a spatial situation also interferes with comfortableness, including room size, spatial proportions, and gestures.
12	**Health**		Health in building design covers a wide spectrum of physical, mental, and social well-being of the residents. It is also closely connected to the feeling of safety and security.
13	**Safety & Security**		Security contributes to social and economic stability. Users should feel safe in the building itself, as well as in its environment and be protected as far as possible. Accordingly, the objective hazard potentials (e.g. site-specific natural hazards such as flooding, stumbling blocks, fire, etc.) should be eliminated as far as possible and the subjective sense of security (e.g., clarity, social control/animation, good visibility, etc.) should be strengthened. Fire safety requirements and clear escape routes should be considered.
14	**Sound insulation**		Unwanted noise and acoustic conditions affect the well-being and can affect the health. By appropriate conceptual and structural measures, pleasant acoustic conditions are to be established. This applies equally to the structural sound insulation against external noise and noise pollution between different rooms. **Excellence rating:** favorable orientation of vulnerable areas; favorable orientation of private open spaces; structural noise protection measures considered; no conflicts of use. (Fuchs et al. 2013)

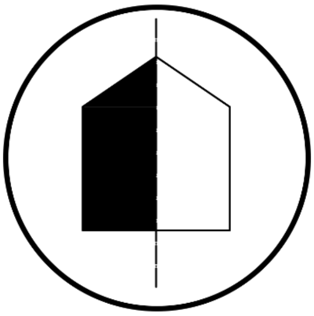
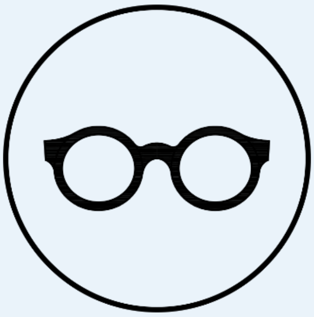
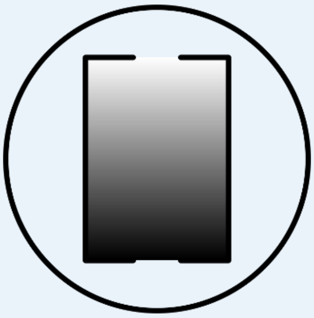
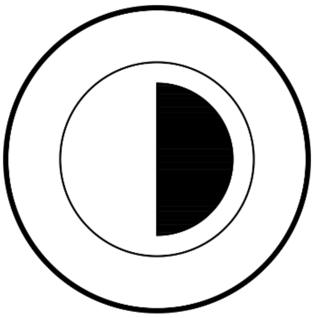
15	**Daylight**		Daylight influences the hormonal balance through the daily routine of the sun and synchronizes our "internal clock." Adequate daylighting should be ensured in workspaces and lounge areas. At the same time, a favorable availability of daylight contributes to a reduction of the artificial lighting requirement and thus of the energy demand. A visual connection to the outside is to be provided for all workplaces and lounges.
16	**Interior climate**		Thermal comfort has a significant influence on the human heat balance and has a direct impact on the energy consumption of buildings. It is to be optimized as far as possible by passive structural measures: e.g. generally by construction methods, coordinated window area ratio and components capable of storing heat; against overheating by sun protection devices and possibilities for night cooling. **Suggestion**: Sensible passive measures to optimize the indoor climate (construction, storage capacity of building components, orientation). Total glass area of exterior walls should not exceed 50-60% (differentiated by cardinal points and uses); highly effective sun protection; openable windows, possibility for night cooling; rooms with the same temperature should be located together within a building (zoning). (Fuchs et al. 2013)
17	**Economy**		Includes all the aspects that affect the cost and budget associated with the building project. It is also closely connected to material and resource efficiency, reuse, and recycling.
18	**Spatial efficiency**		Space efficiency cannot be optimized without limitations. However, taking into account the legal constraints (e.g., transit areas), the aim is to achieve the most efficient and economical utilization possible.

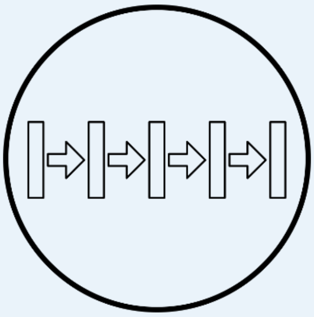
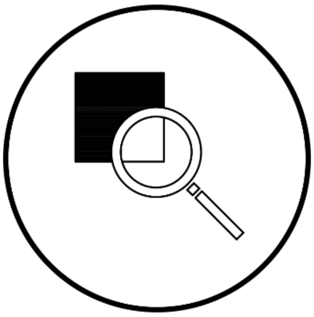
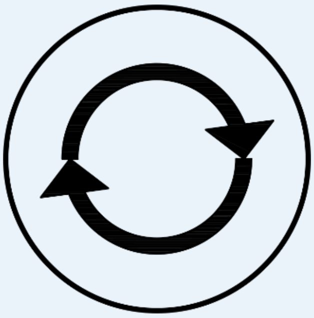
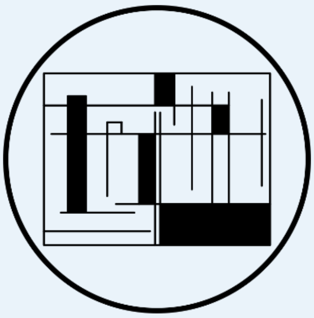
19	**Use flexibility**		A high degree of convertibility and flexibility is directly related to the sustainability of buildings. As a result, the building structure should be optimally designed to facilitate changes in use. Depending on the planned main use (e.g., office), the positioning of the access cores and toilets should ensure that the building can be divided into different units at a later date.
20	**Life-cycle cost**		Low investment costs can improve the accessibility of buildings for broad sections of the population, but in the case of long-lived buildings, they must not be at the expense of durability, ease of maintenance, and energy requirements during operation. Accordingly, an optimized ratio of investment-costs-to-utilization-costs (pre-design-relevance, primarily in terms of energy, maintenance, and cleaning) should be aimed for.
21	**Resources**		Sustainable and efficient use of resources including time, cost, and human labor are among the most important factors in designing a building. It is also closely connected to budget, life-cycle cost, and energy efficiency.
22	**Energy**		Energy in general is referred to the capacity to do work that takes several forms such as electricity, heat, light, wind, etc. The sources of energy could be renewable or nonrenewable. The energy aspect is closely connected to the energy demand of the building and how to cover that using efficient and sustainable sources.
23	**Surface sealing (Heat island effect)**		An economic land utilization and building density allows for a sensible use of scarce land resources. In addition, the degree of sealing must be minimized, and suitable compensatory measures must be taken when designing the exterior (extensive meadows and lawns, retention areas and biotopes, trees and hedges, roofs and green facades). The microclimate should be positively influenced by landscaping or construction measures. Its effect on the "heat island effect," the indoor climate and human well-being are of great importance.

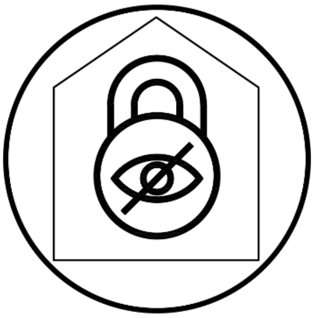
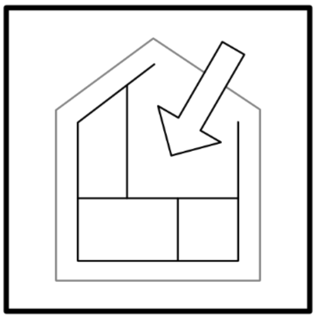
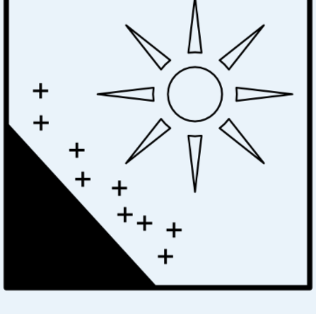
24	**Material**		In addition to the energy demand and the energy demand coverage (criterion 14-15), the selection of building materials and constructions with the lowest possible environmental impact offers a particularly high potential for the reduction of greenhouse gases. In addition, the durability of the building fabric is important for resource requirements. Choice of material and surface finish should ensure a long service life. **Excellence rating:** low proportion of sealed areas (32%); Compensatory measures provided (green roof, PV); low solar absorption BRI low (90%); covering area low (93%); building mass below ground low (83%); high proportion of renewable resources; façade durable (e.g. wooden shingles). (Fuchs et al. 2013)
25	**Energy demand**		Considering the climate protection and an economic total cost analysis, it is important to achieve an energy-optimized construction, which ensures a significantly reduced energy demand and thus reduced energy and operating costs. The target values of the applicable EnEV (e.g. 2009) are to be undercut (e.g.) by 50%. Structural and conceptual measures ensure the lowest possible energy consumption for the following energy services: building heating and possibly cooling, hot water preparation, air extraction, lighting.
26	**Energy demand covering**		By examining all locally available renewable energy sources, the obvious use of potentials and the convincing integration of solar technology into the building envelope, the best possible conditions must be created for using a high proportion of renewable energies to meet the energy demand. **excellent rating:** high PV power demand coverage (170%); high heat yields solar technology (60%); Solar technology formally integrated; used locally available energy potentials; high efficiency of building technology (PEF <0.4); Appropriateness of the technical areas considered average PV power demand coverage (80%); (Fuchs et al. 2013)
27	**View**		A double-sided visual trajectory for overcoming spatial division. Towards the outside, view takes part actively in the external surroundings. A view into the interior of a residence breaks open the separation and the protection of the realm.

28	**Sequence**		The linear succession of elements, in a way where each figure follows a previous one, with a switch between contrasting situations, which also endows a change in the mental state. E.g., the transition from a dark and confining space to a brighter and larger one gives the experience of expansion in the bodily sphere, the increase in room height stimulates a heightened posture.
29	**Readability**		The capability of conveying inherent contents or narrating stories, allowing the beholder to identify and comprehend the spatial structure or constructive principle.
30	**Complexity**		Complements and contradicts simplicity. Complexity generates an enjoyable sensation of overwhelming stimulus, which can be achieved via variety and richness of spatial situations—form, color, material, lighting, ambiguities, contrasts, and even contradictions. However, complexity highly depends on scale and angle of vision. What appears complex when viewed up close may seem simple when viewed as a totality from a distance, and vice versa. A special source of complexity is the diversity of a legible space design; a spatial complex is never perceived from a single viewpoint. Also, complexity leads to indeterminacy or a lack of orientation.
31	**Simplicity**		Complements and contradicts complexity and is connected to Gestalt. An intensity of experience in place of a multiplicity of stimuli, where the perception can focus on the details of the simple gestalt.
32	**Gestalt**		As a building never appears as a separate collection of its individual forms, the figure of a building and its surroundings are observed as a Gestalt, which represents the principle of “the whole is more than the sum of its parts.” Gestalts depend on a stimulus field or suggestive architecture, as our perception is able to render constructive configurations out of fragments. (Janson and Tigges 2014)

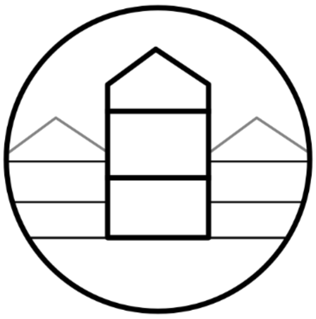
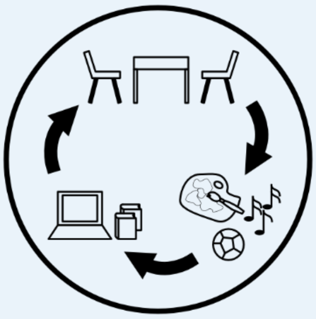
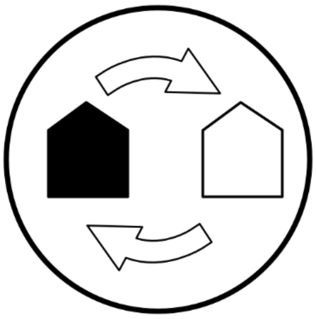
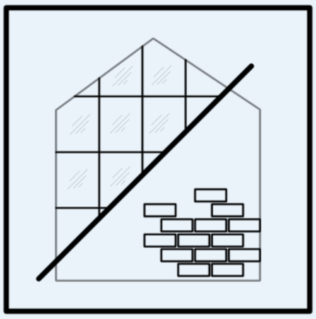
33	**Composition**		In a composition, the parts are assembled into an articulated unity in a way that can achieve equilibrium between the self-sufficiency of the parts and the integrative force of the whole. In a way, composition is a means of avoiding arbitrariness, as it reflects the intention of the structure, as well as demonstrates its meticulous crafting.
34	**Experience**		A total impression is given by the overall appearance of a room alongside its character, as having a special function, an invitation, a symbolic effect, or an emotional appeal. Perceivers are not only viewing the architecture as beholders but indulging and belonging to the architectural reality. An experience is an individual experiential event that is imbued with special meaning.
35	**Plan Libre**		As introduced by Le Corbusier as a free plan arrangement of non-structural partitions determined by functional convenience.
36	**Concept**		Concept is the guiding idea behind the design and the spatial creation. It is also the key to fully understanding the completed work, as the result will not be experienced as an object, but as a situation. Concepts also buys into the architectural fantasy, and can be an interpretation of the task of the building.
37	**Atmosphere**		An element that surrounds the viewer, generated from nearly all the elements of the architecture in totality. Common types of atmosphere include spatial gesture; giving an impression of being spacious or expansive, elevating or uplifting. Orientation, in which a space turns inwards or outwards. Atmospheric qualities include being melancholic, heroic, cozy, festive, and so on. An atmosphere may prompt the viewer to engage in certain behavior such as sitting down, falling silent, or stopping. "The character of a space or place is not merely a visual quality, as is usually assumed. The judgment of environmental character is a complex fusion of countless

			factors that are immediately and synthetically grasped as an overall atmosphere, feeling, mood, or ambiance.” (Böhme et al. 2014)
38	**Symmetry**		Symmetry is a formal quality for the arrangement of spaces. It is a design approach that makes e.g., the opposite sides of a floor plan the same. It is associated with the use of symmetrical shapes and forms. The term symmetrical is also used for a design that has a feel of being balanced.
39	**Personal Style**		Personal Style of design or an architectural theme lays claim to intellectual content having general validity. The architects have at their disposal several themes, which deal with a specific architectural phenomenon and bear their personal style.
40	**Expression**		Connected to Atmosphere. The impression given by the architectural forms, **e.g.** the steepness of a staircase, the closed appearance of a façade, or the protective gesture of a roof. Such expressions can be comprehended through direct perception of the architectural elements, without revealing the concealed subject matter, yet may remain at times quite diffuse and difficult to examine. Expression and Atmosphere cannot clearly be differentiated.
41	**Closure**		Restricted views, accessibility, and movement. Views can be restricted via canalization through intermediate spaces. Closure can vary between absolute impermeability and complete openness. Closure can also be connected to the sky view, as the less outer view is permitted, the more closed a building or a square would be.
42	**Contrast**		Contrast in general is defined as the state of being remarkably different from something else in comparison or close association. Contrast could be practiced by various sizes and various textures in a composition or in different combinations, e.g., the use of light vs dark.

43	**Transition**		Transition is defined as the process or a period of changing from one state or condition to another. In architecture, transition is defined as the connecting in-between spaces. It the passage from one state, stage, subject, or place to another and architectural spaces are incomplete without transitional spaces.
44	**Transparency**		Transparency means "permeability to light." We refer to elements and materials as transparent when we are able to see through them. We speak of translucency when light passing through a material produces only a schematic impression of the objects behind it. In general, transparency refers to the covering up, obscuring, or displacement of spatial delimitations. (Janson and Tigges 2014)
45	**Continuity / Space-Body Continuum**		Mass and space complement each other and merge together in a continuous fashion. Masses are turned outwards, while spaces conversely are directed inwards. However, masses contain spaces and also form spaces outwardly, creating a space-body continuum. Space-body continuum is related to the dual role of the surface (columns or projections), the reversal of the figure-ground relationship, and the transition between scales.
46	**Immensity**		Monumental effects of the size that are intended to overwhelm the viewer. However, it cannot be arrived at simply by continually increasing the volume of a building. Because the impression of architectural size cannot simply be equated with sheer dimensions, such effects are generated through special architectural measures, which are designed to avoid falling into banal gigantism. (Janson and Tigges 2014)
47	**Aesthetics**		***Venustas*** as one of three foundations and essential components of successful architecture by *Vitruvius* (the ancient Roman architect), is regarded as beauty or delight, and is responsible for aesthetic quality, imparted style, proportion, and visual beauty.

48	**Privacy**		"In a highly general sense, the interior stands for privacy, possession and in-gathering, the exterior for the public sphere, availability and dispersal."(Janson and Tigges 2014) Privacy could be defined and interpreted through other terms and concepts such as accessibility and exclusivity, protection, cell, facade, inside and outside, residence, screening, territory, view into/out of, closure to extensive openness, and the requirements of separation.
49	**DfD**		DfD - Design for Deconstruction is one of the design concepts supporting the circular economy in the construction industry. It ensures that at the end of the building's life span its elements can be removed without damaging them, which will increase the possibility of their reuse in the future.
50	**Passive measures**		Passive measures describe a variety of different permanent constructions or geometric characteristics of the building volume to achieve climatic and energetic advantages. Passive measures pursue the goal to conserve energy and reduce the energy demand of a building, as well as to gain additional energy passively. The passive use of solar energy aims at using natural solar radiation in the form of heat or light energy directly, without the use of special technologies, purely through structural and/or constructive measures as well as the energetically optimized orientation of buildings and floor plans according to the course of the sun, taking into account seasonal changes. Passive measures can be related, for example, to lighting, ventilation or heating. Passive also means that no or hardly any electricity is used to achieve the goal of the measure.
51	**Solar gains**		Solar gains refer to heat gain via solar radiation. They can be used effectively to heat buildings during the colder winter months in areas where enough sunshine is available (>passive measures). Solar gains can also pose a problem in warm and hot climates and during the summer months as they can lead to overheating (>shading). Simple glazed structures such as greenhouses can be used to capture solar gains and extend the months where these unheated spaces can be occupied comfortably. This is a strategy which has been used effectively by architects like Lacaton & Vassal.

52	**Shading**		Shading refers to a strategy where fixed or movable elements prevent solar radiation from entering through the building envelope/ windows. Shading is most effective when implemented on the outside of the window/ glass element. On south-facing façades (in the Northern Hemisphere), horizontal static elements are most effective since they keep out the steep summer sun and allow the lower winter sun to enter (>solar gains). On east and West facing façades movable elements are more effective since they can be closed during the hours of intense low sunshine (morning or evening respectively) and opened during the rest of the day or on days with no or less sunshine. Automated and manual versions exist and should be chosen based on use patterns and user requirements. Northern exposures generally don't require shading.
53	**Orientation**		Orientation is a passive measure that can refer to the orientation of the overall building as well as individual rooms (floor plans). Orientation can help to energetically optimize buildings based on the course of the sun, taking into account seasonal changes. As a rule of thumb for temperate climates, bedrooms should be oriented to the East (to capture the morning light and prevent overheating in the afternoon, which would result from Southern and Western exposure). Rooms that are not occupied much (storage, pantry, mechanical rooms, etc., especially during the winter should be oriented to the North.
54	**Façade Type**		e.g. punched facade, ribbon facade, curtain wall, etc.
55	**Ventilation**		Ventilation moves outdoor air into a building or a room and distributes it. The general purpose of ventilation in buildings is to provide healthy air for breathing by removing contaminants (Etheridge & Sandberg, 1996; Awbi, 2003). Three methods may be used to ventilate a building: natural (passive measure), mechanical, and hybrid (mixed-mode) ventilation.

56	**Tall space**		Tall spaces are spaces that are taller than conventional norms. They allow for daylight penetration into deep spaces. They also allow for flexible future use of spaces by leaving extra space for additional equipment, suspended ceilings, floor buildups, and flexible services that might require high ceilings.
57	**Flexible space**		Flexible space refers to the potential of rooms to be used in various ways over time without requiring substantial alteration of the building fabric.
58	**Adaptability**		Adaptability is the potential of the fabric of a building to be modified with relative ease to accommodate change over time.
59	**Window-to-wall ratio (WWR)**		The window-to-wall ratio refers to the ratio of fenestration (transparent, glazed areas) to the above-grade wall area (opaque areas). It is calculated as the ratio/ fraction of the wall fenestration area to the gross above-grade wall area.

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