www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

CONSISTENT MANAGEMENT AND EVALUATION OF BUILDING MODELS IN THE EARLY DESIGN STAGES

SUBMITTED: March 2019
REVISED: December 2019
PUBLISHED: March 2020
EDITOR: Amor R.
DOI: 10.36680/j.itcon.2020.013

Jimmy Abualdenien, M.Sc.,
Chair of Computational Modeling and Simulation, Technical University of Munich, Germany;
jimmy.abualdenien@tum.de

Patricia Schneider-Marin, Dipl.-Ing.,
Institute of Energy Efficient and Sustainable Design and Building, Technical University of Munich, Germany;
patricia.schneider@tum.de

Ata Zahedi, M.Sc.,
Chair of Architectural Informatics, Technical University of Munich, Germany;
ata.zahedi@tum.de

Hannes Harter, M.Sc.,
Institute of Energy Efficient and Sustainable Design and Building, Technical University of Munich, Germany;
hannes.harter@tum.de

Hannah Exner, M.Sc.,
Chair of Computing in Engineering, Ruhr University, Bochum, Germany;
hannah.exner@rub.de

Daniel Steiner, M.Sc.,
Institute for Structural Concrete, University of Duisburg-Essen, Germany;
daniel.steiner@uni-due.de

Manav Mahan Singh, M.Tech.,
Architectural Engineering, Department of Architecture, KU Leuven, Belgium;
manavmahan.singh@kuleuven.be

André Borrmann, Prof. Dr.-Ing.,
Chair of Computational Modeling and Simulation, Technical University of Munich, Germany;
andre.borrmann@tum.de

Werner Lang, Prof. Dr.-Ing.,
Institute of Energy Efficient and Sustainable Design and Building, Technical University of Munich, Germany;
w.lang@tum.de

Frank Petzold, Prof. Dr.-Ing.,
Chair of Architectural Informatics, Technical University of Munich, Germany;
petzold@tum.de

Markus König, Prof. Dr.-Ing.,
Chair of Computing in Engineering, Ruhr University, Bochum, Germany;
koenig@inf.bi.rub.de

Philipp Geyer, Prof. Dr.-Ing.,
Digital Architecture and Sustainability, Institute of Architecture, TU Berlin, Germany;
geyer@tu-berlin.de

Martina Schnellenbach-Held, Prof. Dr.-Ing.,
Institute for Structural Concrete, University of Duisburg-Essen, Germany;
massivbau@uni-due.de

ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

SUMMARY: *The early stages of building design involve the consideration of different design variants and their assessment regarding various performance criteria including energy consumption and costs. During the design process, the involved experts from different disciplines frequently exchange building information to develop a design that satisfies the project's requirements and objectives. In the course of this iterative process, the building design evolves throughout multiple refinement stages. At the same time, different variants are developed. In BIM-based projects, the maturity of the design information provided by the model is expressed by the notion of Level of development (LOD). So far, however, there is no method to formally define the information requirements of a LOD. In particular, there are no means for expressing the uncertainty involved with the provided information. By contrast, despite the insufficient information available in early design stages, a BIM model appears precise and certain. This situation leads to false assumptions and model evaluations, for example, in the case of energy efficiency calculations or structural analysis. Hence, this paper presents an overview of a set of approaches that were developed to alleviate and preserve the consistency of the designed solutions. The approach includes the development of a multi-LOD meta-model, which allows one to explicitly describe the LOD requirements of each building component type incorporating the possible uncertainties, e.g. concerning the building dimensions. On the basis of this multi-LOD model, methods for evaluating a building design's performance regarding the building's structure and life cycle energy performance are proposed that take the defined uncertainties into account. To support the management of design variants in one consistent model, a graph-based approach is introduced. Finally, a minimized communication protocol is described to facilitate the workflow and communicate the evaluation results for supporting the decision-making process.*

KEYWORDS: *Building Information Modeling (BIM), Level Of Development (LOD), Multi-LOD, Exchange Requirements (ER), Early Design Stages, Meta-model, Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA), Operational Energy Assessment, Embedded Energy Assessment, Sustainable Building Design, Design Variant, Design Management.*

REFERENCE: *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 (ITcon), Vol. 25, pg. 212-232, DOI: 10.36680/j.itcon.2020.013*

1. INTRODUCTION

The most fundamental decisions influencing the building performance are taken in the early design stages (Gervásio et al. 2014). In the beginning of a building project, designers capture the main intent by producing spatial models as variants, overviewing different solutions. Each of the developed variants consists of three main aspects: the structural system, the building's form and facade as well as the organization inside the building (Joedicke 1993; Steinmann 1997). Accordingly, these aspects within the developed variants are evaluated in terms of fulfilling the owners' requirements, building performance and cost. Once a variant is selected, its geometry and semantics are gradually detailed.

As the design of a building involves a large number of experts from different domains, an iterative and collaborative development of the design incorporating an intense exchange of information between the experts is required (Chiu 2002). The term Building Information Modeling (BIM) describes the process of development and consistent use of a digital building model to support the planning, design, construction, and operation of a facility. The concept of BIM is based on the exchange of semantically rich 3D-models between the different design disciplines. This exchange process encourages the early involvement of the various domains, which increases the design process' efficiency and quality.

The process of designing a building involves different stages and multiple refinements (Ernstrom et al. 2006). In BIM-based projects, the notion of Level of Development (LOD) expresses the maturity of the design information provided by the model, which comprises both a specification of the geometric detail as well as the semantic information required. The development process starts with a building model representing the rough conceptual design. The building model is subsequently continuously developed and refined, culminating in the specification of a highly detailed model. The level of development is a concept that defines the quality and quantity of the information contained within a BIM model (Hooper 2015).

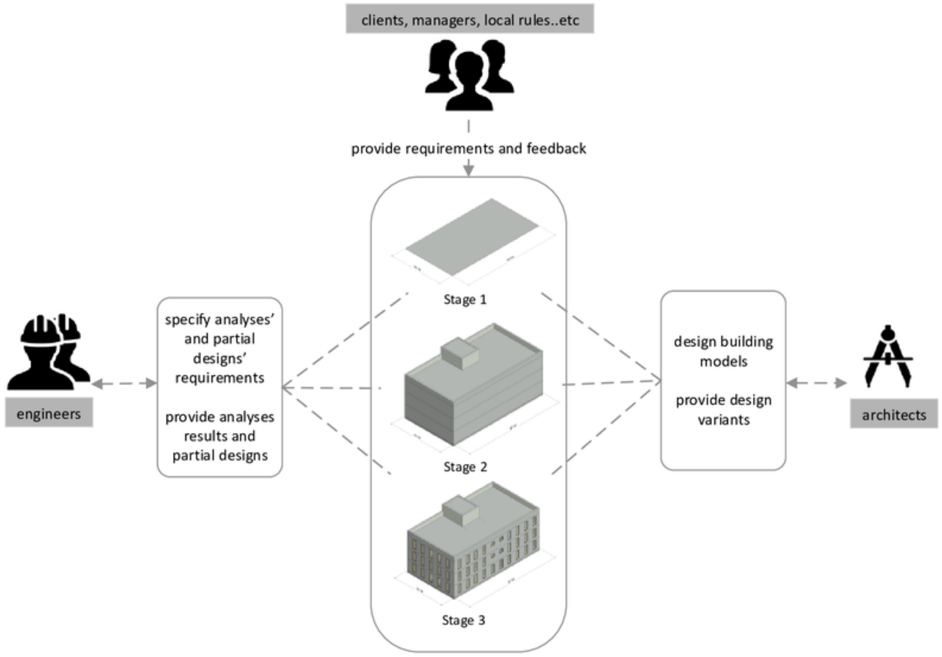


FIG. 1: Collaboration among several disciplines to define a building project's requirements and objectives.

In each design stage, the individual domain experts request detailed requirements for exchanging building information models. FIG. 1 illustrates the collaborative process between several actors in the process of developing a building. In every design stage, each discipline requires specific information to be present in the model to perform model analyses, such as Life Cycle Assessment (LCA) or developing a partial design, including the structural design of the building. Similarly, architects incorporate the clients' demand and engineers' analysis results in the building models. In this process, related design variants are produced. Supporting the different types of analyses and evaluations for the same model is a very challenging task, as the information needs to be present in the correct representation.

The management of the early design stages is critical to circumventing a substantial amount of rework (Ballard and Koskela 1998), increased costs, and reduced productivity (Kolltveit and Grønhaug 2004). Architects and engineers have a very high influence on the building design and consequently on its performance. However, during the early stages, information about the project activities and executions is insufficient to support the computational tools (Kolltveit and Grønhaug 2004). The earlier the assessment of the building model is, the higher is the influence of the changes on its performance. However, in the early stages, BIM information is not yet accurate as it is prone to multiple changes in the next design stages (Knotten et al. 2015).

Currently, the model-based design techniques produce highly detailed designs, even in the early design stages, where many decisions have not been decided yet. Today, neither the architects nor the engineers are able to communicate the potential geometric-semantic information vagueness. However, this knowledge is crucial for the model assessment, since its absence can lead to significantly false assumptions, which affect the design decisions taken throughout the design stages (Kraft and Nagl 2007; Gu and London 2010). In conventional drawing-based workflows, the drawing scale indicated the degree of maturity of the design. Scale, however, is a concept that is not available in digital building models. Instead, design maturity is now expressed by the notion of Level of Development (LOD) (BIMForum 2017). Still, a method for formally expressing the vagueness associated with each level does not yet exist.

At the same time, the current model-based design techniques lack the support of managing multiple levels of development, thus they are inadequate in linking the information refinement throughout the design stages in order to ensure its consistency. Hence, our solution is the development of a multi-LOD meta-model, which explicitly allows the definition of each LOD's requirements, representing the building model in multiple LODs and describing the detailed relationships between the building components.

The research project EarlyBIM (FOR 2363)[1], funded by the 'Deutsche Forschungsgemeinschaft' (DFG), aims to develop methods for evaluating building design variants in early design stages based on adaptive detailing strategies. The variants have elements at different LODs as well as incomplete and uncertain information. The main approach focuses on providing:

- Consistent management of multiple LODs
- Description of the information vagueness
- Consistent management of design variants
- Support for model analysis at the early design stages
- Evaluation of design variants based on simulation results
- Improved communication between the domain experts

As a foundation for managing the building elements on multiple LODs, the EarlyBIM project proposes developing a multi-LOD meta-model (Abualdenien and Borrmann 2018). The meta-model facilitates explicitly specifying LOD definitions for each building component type, incorporating the potential vagueness. The specified vagueness serves as a formal input for the different kinds of simulations and sensitivity calculations. Accordingly, all the project participants are aware of the possible combinations, which supports evaluating the relevant variants and making subjective decisions.

To support the management of design variants in one consistent model, a graph-based approach and multiple methods for evaluating the building performance are proposed. Additionally, a minimized communication protocol is described to facilitate the workflow and communicate the evaluation results to support the decision-making process among the project's participants.

This paper presents an overview of multiple methodologies developed by our research group to systematically manage the information uncertainties at the early design stages and highlight the benefits of checking exchange requirements between disciplines. In order to ensure the model's flexibility and applicability, its realization is based on the widely adopted data model Industry Foundation Classes (IFC). The IFC model specification is an ISO standard, which is integrated into a variety of software products (Liebich et al. 2013).

The paper is organized as follows: Section 2 presents the research method and collaboration. Section 3 discusses the background of our research. Section 4 provides an overview of the multi-LOD requirements and describes the

---

[1] https://for2363.blogs.ruhr-uni-bochum.de

design concepts as well as the meta-model design. In order to manage design variants, Section 5 introduces a graph-based approach. Section **Error! Reference source not found.** presents a minimized communication protocol and Section 7 proposes methods for evaluating building models. Section 8 applies the developed concepts to a case study. Finally, Section 9 summarizes our findings and presents an outlook for future work.

2. RESEARCH METHOD

The research project EarlyBIM comprises five subprojects, which include several architects and engineers specialized in embedded and operational energy as well as structural analysis. The common goal for the entire research group is to support developing consistent building models starting from the early design stages. FIG. 2 illustrates the subprojects and the interactions between them.

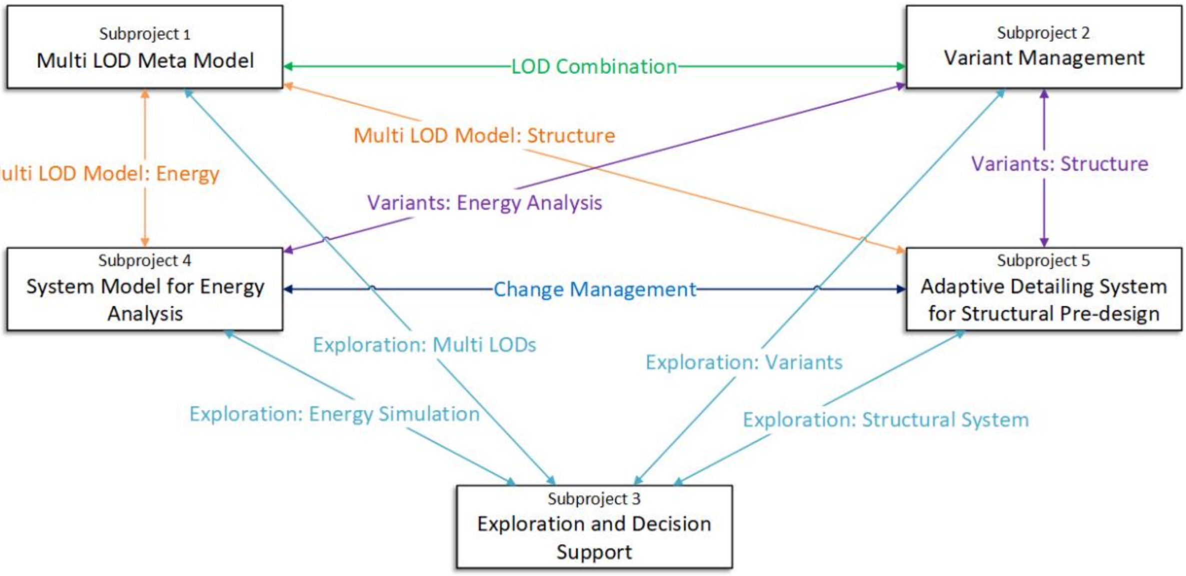


FIG. 2: EarlyBIM subprojects and the interaction between them.

This research was initiated by a comprehensive literature review focusing on the importance of the early design stages and understanding their characteristics. At the same time, each of the subprojects performed detailed research for the current best practices used to support these stages and manage their vague and uncertain nature. Based on the outcomes from the literature review and the identified gaps in (Abualdenien and Borrmann 2019a; Zahedi and Petzold 2018; Harter et al. 2018; Schnellenbach-Held and Steiner 2019; Mattern and König 2018; Singh et al. 2018; Abualdenien and Borrmann 2019b), we implemented the following approach:

- Developing a Multi-LOD meta-model for providing a systematic way to define LOD requirements, incorporating the potential uncertainties
- Developing a methodology for considering the information refinement across the LODs as consistent
- Developing a methodology for managing design variants in a consistent model across the design stages including different LODs
- Integrating the uncertain information as an input for the different kinds of model analysis
- Developing a minimized communication protocol for supporting a smooth exchange of analysis requests and feedback that is linked with building models
- Integration of engineering expert knowledge for decision support regarding energy analysis and structural design in the early stages
- Development of intelligent substitution models for a reliable statement regarding the carrying capacity, serviceability and constructiveness of a structure based on very little information
- Development of machine learning models for operational energy predictions
- Development of a parameter-based embedded energy calculation

The main goal of the proposed approach is to facilitate evaluating building models in the early design stages. Our approach supports the decision-making process by communicating the information uncertainty among the project participants. Additionally, the proposed methodologies for maintaining consistency across the LODs and variants preserve the decisions taken previously in the subsequent stages. The following sections provide an overview of the background and scientific goals of the research project. Subsequently, the above-mentioned subprojects are explained in more detail.

3. BACKGROUND

3.1 Design Process in Early Design Stages

In industrialized production, processes are usually clearly structured and managed. In the simplest case, Activity A needs to be completed before Activity B can start. This is seldom the case for the construction industry where several iterations are made making the early stages of design a complex process to manage (Knotten et al. 2015).

In general, the building design phase is divided into different stages with gradually increasing design precision and detailing. Designers face unique boundary conditions while working for clients with individual requirements. Furthermore, different planning domains are involved in the process requiring different information. Each of them is characterized by an individual team and working structure. In many cases, the interests of involved domains might even contradict each other. A structural designer, for example, might focus on massive construction due to a high load-bearing capacity. The architect, however, might prefer light and more slender structures, while the energy consultant recommends using renewable construction materials. In total, the design cost is 20% of construction costs, yet maintenance and building operating costs are five times of construction costs and business operating costs can be as much as 200 times the construction costs (Gilbertson 2006).

Especially the early design stages are of high importance for the later performance of the building. While the influence of the stakeholders is largest, this stage of the project is also most complex to understand, carry out and manage (Knotten et al. 2015). In general, questions or problems related to building design cannot be comprehensively stated and, especially at the early stages, design solutions are enormous in number (Lawson 2006; MacLeamy 2004).

Despite the technological progress in information technology as well as the CAD (Computer-aided design) sector, the design process of a building represents a predominantly manual process. In conventional practice, information is provided in separated CAD drawings and related external documents. With proceeding design progress, information needs to be exchanged among the involved parties, sometimes leading to duplicate processing of data. According to Flager et al. (2009), about 58% of the time is spent on managing the information in the design stages. The development of design variants represents a key process at the early design stages. According to the requirements of the client and external restrictions, the designer suggests possible variants. With proceeding planning process, preferred variants are specified in more detail while other drafts are discarded.

In this paper, design variants and options are differentiated, where variants are the designs developed by the architect as proposed solutions, and options represent the feedback and suggestions provided by the involved domain experts, including structural as well as embedded and operational energy specialists.

3.2 Information Uncertainty

The terms uncertainty and vagueness are used in various domains and application contexts. Information uncertainty is an umbrella-term that describes the lack of knowledge or information causing the occurrence of an uncertain future state (Hawer et al. 2018). On the other hand, vagueness, as a synonym to ambiguity, is related to a specific state of a specific object, and it refers to having imprecise or incomplete information (Hawer et al. 2018; Klir 1987). By performing energy or structural analysis, using mathematical and physics-based approaches it is possible to predict the building's future performance. These types of analysis require a set of deterministic design parameters as an input to work. However, in the early stages, the design parameters are characterized by high uncertainty, which leads to uncertainties in the output of the analysis.

In this paper, uncertainty represents two aspects, (1) design uncertainty, i.e. the unknown variables affecting design variants and their fulfillment of the project's requirements and objectives. This means that changes to these variables require performing fundamental changes to the proposed design, like changing the building's structural system or increasing the building's height to add a new storey, and (2) the uncertainty of the building performance results, which depends on the design uncertainty and vagueness of the calculation input parameters. This vagueness is related to the reliability of the building elements' attributes and their refinement through the LODs, for example the exact openings percentage or position and the internal walls' material.

3.3 Levels of Development (LOD)

The LOD concept improves the efficiency of designing and exchanging building models by providing a common understanding among the project participants of the information expected to be present in the model. Additionally, it formalizes the development of the elements through the different stages of the building life-cycle, which enhances the quality of the decisions taken (Hooper 2015).

Different information is required by the project participants in every stage to design and perform their analysis (Singaravel et al. 2018). The LOD concept facilitates defining BIM-based exchange requirements throughout the design process. The American Institute of Architects (AIA) introduced a definition of the term LOD that comprises five levels, starting from LOD 100 reaching LOD 500. The BIMForum working group developed LOD 350 and published the *Level of Development Specification* based on the AIA definitions (BIMForum 2017). The first LOD 100 (conceptual model) is limited to a generic representation of the building, meaning, no shape information or geometric representation. The second LOD 200 (approximate geometry) consists of generic elements as placeholders with approximate geometric and semantic information. On LOD 300 (precise geometry), all the elements are modeled with their quantity, size, shape location and orientation. Next, to enable detailed coordination between the different disciplines, such as clash detection and avoidance, LOD 350 (construction documentation) is introduced, which includes the interfaces between all the building systems. Reaching LOD 400, the model incorporates additional information about detailing, fabrication, assembly, and installation. Lastly, in LOD 500 (as built), the model elements are a field verified representation in terms of size, shape, location, quantity, and orientation.

The term *Level of Detail* is commonly used in correspondence to the Level of Development (Gigante-Barrera et al. 2018). It has been introduced in the AEC industry by VicoSoftware in 2005 (VicoSoftware 2005). The VicoSoftware specification has been used as the basis for the AIA's LOD definitions. Since that time, multiple guidelines, that have been published in the UK, used the Level of Detail term (Gigante-Barrera et al. 2018). However, the BIMForum's specification differentiates between the Level of Detail and Development; Level of Detail represents the amount of information included in the model, whereas the term Level of Development describes the reliability of the included information (BIMForum 2017).

In the UK, the *Level of Definition* (BSI 2017) has been introduced. It consists of seven levels and introduces two components: Levels of model detail representing the graphical content of the models, and Levels of model information (LOI) representing the semantic information. The Danish definition includes seven *Information Levels* that correspond roughly to the traditional construction stages (van Berlo and Bomhof 2014).

In this paper, the abbreviation LOD stands for the Level of Development comprising both Level of Geometry (geometric-oriented) and Level of Information (semantics, non-geometry-oriented). The recently published ISO19650 propagates the term Level of Information Need (LOIN) distinguishing LOI and LOG to clearly distinguish and separate semantics from the geometric detailing grades (Hausknecht and Liebich 2017).

3.4 Performance assessment in The Early Design Stages

The focus in the early design stages is to provide different initial workable concepts for the building project. Therefore, the decisions taken in these stages have a strong impact on the building performance, cost, and the subsequent stages (Steinmann 1997; Kraft and Nagl 2007). Additionally, as the efforts of making changes in these stages are less than the subsequent stages, the costs of these changes are also lower (Kolltveit and Grønhaug 2004). However, due to the lack of information and since the building projects involve complex tasks, many decisions that rely on others cannot be taken early on.

Typically, the conceptual design process is complex due to the existing demands, constraints and boundary conditions as well as the wide range of possible solutions including combinations and variants. Some may improve the performance of the building more than others in one aspect, and simultaneously worse than other variants in other aspects. Thus, it is important to support a model evaluation in the early design stages while maintaining the information refinement consistency.

The industry has well understood the need for informed decision-making at the early stages of design to improve building performance (MacLeamy 2004). In order to provide information to clients and designers as a useful basis for decision, multiple consultants need to provide input. For this research, life cycle energy assessment and structural design are chosen as examples for developing a process for early design phases, as these kinds of analyses are typically involved in the design of a building.

3.4.1 Life Cycle Energy Assessment in Early Design Stages

LCEA (Life Cycle Energy Assessment) should be performed in the early design stage as it enables the designer to make informed decisions from an energy perspective. Since the design parameters are inherently uncertain, the assessment needs to be performed considering the uncertainty in the design (Tian et al. 2018). There are numerous attempts to streamline energy prediction activity with the design process (Ahn et al. 2014; Negendahl 2015). These attempts represent the automatic translation of design information to develop building energy models using a deterministic approach. While these approaches are useful in making energy predictions using the design information from BIM models, they do not consider the uncertainty in the design parameters attributed to the evolutionary nature of the design process (Sawhney and Maheswari 2013). This inherent uncertainty in the design parameters poses a severe challenge, rendering a deterministic approach and traditional energy prediction tools obsolete (van Gelder et al. 2014). Probabilistic energy predictions are needed to reflect the uncertainty of the design parameters in the energy prediction results.

The building design in early design stages is incomplete, i.e. available information is not sufficient to provide accurate LCEA results unless it is estimated using engineering knowledge. Another origin of uncertainty is the range of available LCA-datasets, used as a basis for the calculations: different databases and datasets render differing results (Mahler and Schneider 2017). Moreover, buildings are generally prototypes, i.e., unlike mass-produced industrial products, they are built only once. For each individual building, a new LCEA needs are performed as the results from one building cannot be easily transferred to another.

In early design stages, a coherent model evaluation can help decision-makers in gearing the design towards a lifecycle-based energy-efficient approach by supporting the design process with an evaluation of different building variants. Uncertainties must be calculated and represented to avoid the false impression that LCEA results in the early stages of design are final and will not change due to finer detailing in later design stages.

3.4.2 Structural Analysis in Early Design Stages

The common process of supporting structures' assessment in the early design stages is based on engineering knowledge for different levels of detailing and development. Referring to the included comprehension and information, requirement analyses lead to an applicable configuration of design stages together with related parameters. Essential requirements arise from criteria like usability, load-carrying capacity and cost-efficiency of a supporting structure. Especially, the principal model parameters are identified through the analyses, which are necessary for the representation of a level of development and for the continuative structural design, which allows the increase of the development status. The application of Fuzzy Logic-based methods enables the consideration of uncertainty of the design parameters. The varying designs, which usually result from the variety of possible structural solutions, are included in the model in the form of design options (Steiner and Schnellenbach-Held 2018).

4. MULTI-LOD META-MODEL

Currently, there is no approach for formally defining and maintaining multiple levels of development of a Building Information Model as well as incorporating its information uncertainty. To close this gap, (Abualdenien and Borrmann 2019a) developed a multi-LOD meta-model, which enables and supports the following activities:

- Define a building model's requirements throughout the design stages
- Define component types' LOD requirements
- Model the information vagueness
- Represent building elements on multiple stages
- Describe the relationships between LODs
- Check the consistency across the design stages

To manage the requirements of the individual building component types for a specific LOD, a component type is associated with multiple LOD definitions. A LOD definition consists of two separate groups: one for defining the geometric representation and alphanumerical attributes, and another for specifying the semantic alphanumerical attributes. This separation helps to achieve and maintain the semantic-geometric coherence of the overall model (Stadler and Kolbe 2007; Clementini 2010). Finally, the building model is presented by multiple instances of the defined component types.

The flexibility provided by the meta-model approach supports defining and managing LOD requirements for a specific country or a project. The LOD concept used in this paper is based on the BIMForum's definitions (LOD 100 - 500). Additionally, we introduce intermediate levels, LOD 150 and 250, to enable estimating information in an earlier stage of design. This way, the consistency of models is preserved by capturing the information refinement in minimal steps.

4.1 Meta-model design

To manage the information on multiple LODs, the proposed model should not only represent the building elements on multiple LODs but also provide a formal specification of the required information on each LOD. The multi-LOD meta-model design provides means for defining a project-specific data-model, incorporating formal LOD definitions for individual component types. It introduces two levels: *data-model level* defines the component types as well as their geometric and semantic requirements for each LOD. The *instance level* represents the building model by instantiating multiple instances of the component types defined on the data-model level.

The meta-model design complies with the object-oriented modeling principles, which offers high flexibility and extensibility. It allows a dynamic definition of any component types as well as their properties for the different LODs. This provides the flexibility required when dealing with different construction types, different domains, and different analysis tools. Additionally, a *Building Development Level* (BDL) concept is introduced to describe the maturity of the overall building model. A BDL can be conceived as a milestone where specific decisions need to be made.

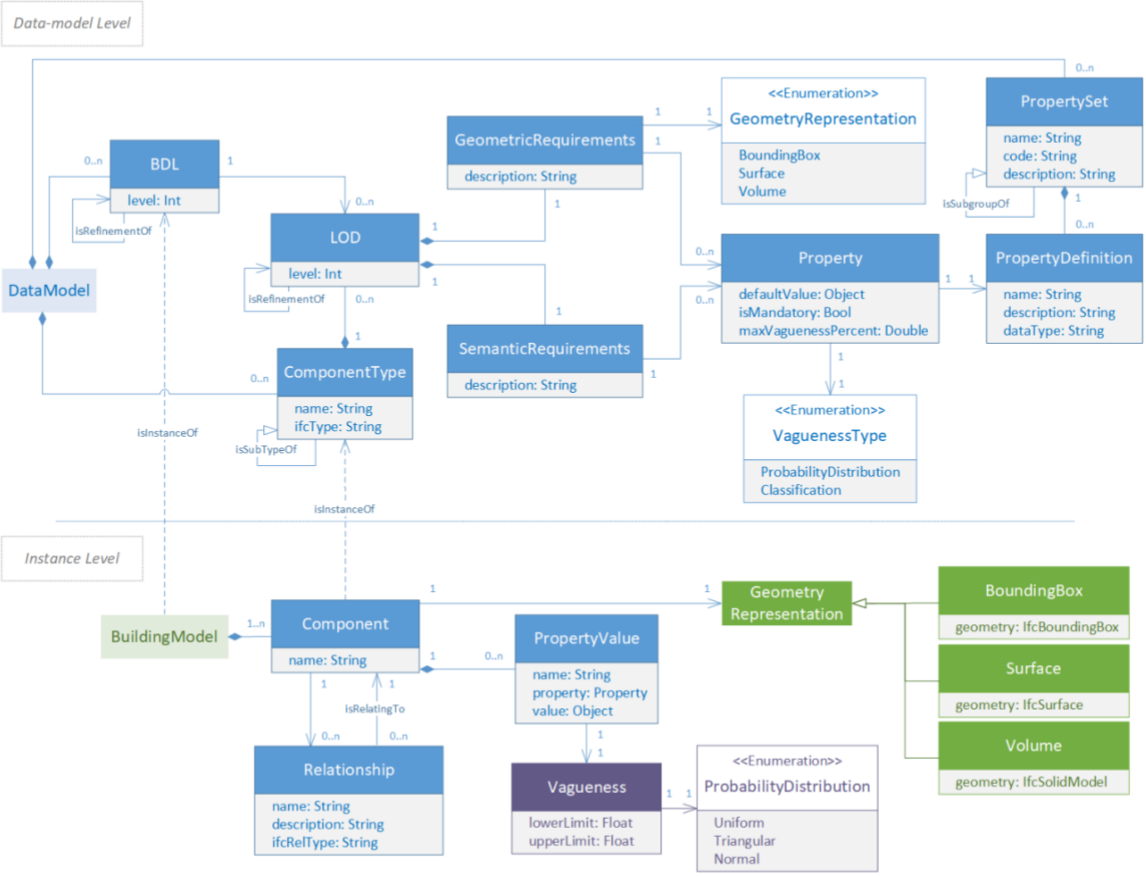


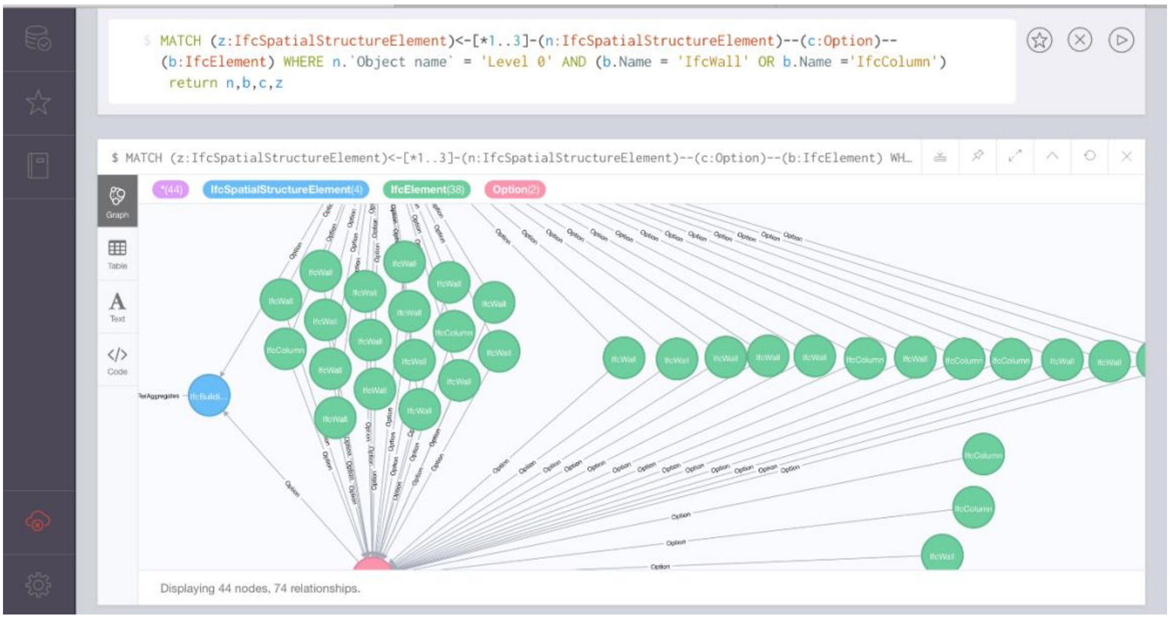
FIG. 3: Multi-LOD meta-model (UML diagram).

At the same time, the meta-model provides a consistent way to query information about LOD definitions on both the data-model level and instance level. Thereby, as illustrated in FIG. 3, a component type definition is represented as a separate class, where it is linked to an IFC entity, *IfcWall* as an example, and associated with a list of LOD definitions. The component types are mapped to instances of the IFC data model. This allows on the one hand to make use of the rich geometry representations provided by IFC and on the other hand to experiment with real-world data produced by IFC-capable BIM authoring tools. A LOD definition is composed of two parts, geometric and semantic requirements. Both requirements are explicitly described in the form of properties. The details of each property are determined in addition to the permissible vagueness and geometry representation. Finally, a BDL is comprised of a set of component types' LOD definitions to form the requirements of the overall building model. A detailed explanation and evaluation of the meta-model can be found at (Abualdenien and Borrmann 2019).

5. VARIANT MANAGEMENT

Besides the definition of a Multi-LOD concept, an approach to manage variants and options across the different planning stages needs to be established. The main intention is to manage design variants (provided by the architect) and options (provided by domain experts) in a consistent BIM model. The developed managing concept helps to prevent the creation of redundant objects, which might lead to inconsistent use of object identifiers. Furthermore, the relation between single variants and their influence on the subsequent design process becomes traceable. In correspondence with the proposed Multi-LOD concept, the management of variants is based on the IFC data model. This section provides an overview of the proposed approach. Complete details and a case study can be found in Mattern and König (2018).

Results are models containing multiple design variants, which might lead to highly complex data structures. To increase transparency and traceability, the use of a Graph Data Model (GDM) is proposed to clearly describe and store multiple variants as well as extract single model instances from the database (FIG. 4). A GDM provides a structured overview of affected elements and interdependencies between objects.



```
$ MATCH (z:IfcSpatialStructureElement)<-[*1..3]-(n:IfcSpatialStructureElement)--(c:Option)--
  (b:IfcElement) WHERE n.`Object name` = 'Level 0' AND (b.Name = 'IfcWall' OR b.Name ='IfcColumn')
   return n,b,c,z
```

```
$ MATCH (z:IfcSpatialStructureElement)<-[*1..3]-(n:IfcSpatialStructureElement)--(c:Option)--(b:IfcElement) WH…
```

Displaying 44 nodes, 74 relationships.

FIG. 4: Extracting a Structural Variant from the Graph Database.

The current version of the IFC standard (IFC 4) does not support the management of variants. For this reason, the existing schema is expanded by corresponding entities.

The main work packages of the variant management include:

- Implement a transparent graph-based realization of the BIM model.
- Define classes and relationships to implement design options within a consistent model.
- Develop graph transformation rules to extract and combine options.
- Develop a rule and checking mechanisms to prevent invalid combinations.

In this approach, a categorization is proposed to handle the complexity that might derive from developing variants and options over different design stages. The following subsections provide a summary of each category. A detailed explanation and evaluation can be found at (Mattern and König 2018; Exner et al. 2019).

5.1 Structural variants

Structural variants refer to the overall building structure. This includes exterior enclosures and geometry or the floor plan layout (e.g., different positions of walls and columns for the same storey). Structural options may also refer to non-physical objects such as zones or spaces, which might derive from changing the floor plan layout. To reduce the number of modifications to a reasonable scope, certain prerequisites are required. The building type (high-rise or flat building) and its main use (residential, commercial, public) should not be changed as these two factors show a high influence on the overall building structure, size, layout, equipment, and requirements. FIG. 5 shows an example of possible variants to structure the floor plan of a building storey. While Variant 1 (left) contains interior walls in the upper left section that result in three small offices, these walls are missing in Variant 2 (right).

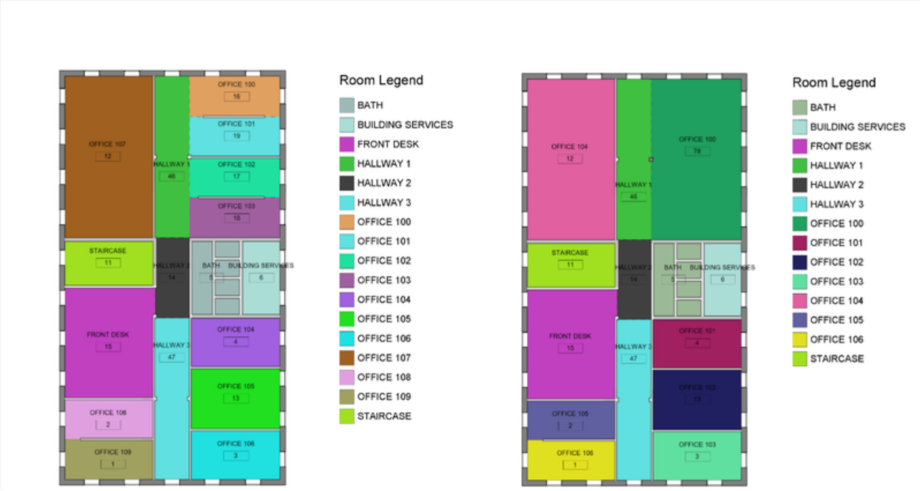


FIG. 5: Structural Variants caused by a Modified Room Division (Mattern and König 2018).

5.2 Functional variants

This category refers to different building objects belonging to systems sharing the same function. The application of different insulation systems (e.g., internal and external insulation) represents a common example of a functional variant. Further examples derive from applied building systems (e.g., various types of HVAC systems) as well as the structural dimensioning of a building (e.g., using a column instead of installing a load-bearing wall while not changing the spatial division of the storey) (see FIG. 6).

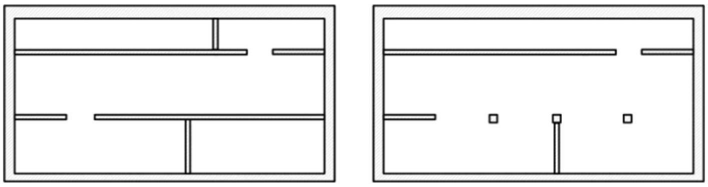


FIG. 6: Functional Option proposed by a Structural Engineer: Replacing load-bearing Walls by Columns (Mattern and König 2018).

5.3 Product variants

Replacing one object by another similar object or changing the attributes of an object represents the simplest form of creating variants. This category shows no influence on other building elements. In most cases, numerous objects of the same type are affected by the creation of a product variant (e.g., all windows of a certain size with different property sets). The generation of product variants requires a higher level of planning precision, which is observed at more advanced LODs.

5.4 Expansion of IFC Schema

It is proposed to expand a given BIM model by inserting “Option Objects” representing the existence of design variations. These objects are added to the given structure by using relationship objects indicating the existence of a variant. The resulting meta-model supports a flexible and transparent approach as single variants might be added, removed and traced easily. Due to its object-oriented structure, this can be easily integrated into the existing IFC schema.

Throughout the design stages, the proposed methodology is employed to manage and ensure consistency among the proposed variants. When a particular variant is selected for further detailing in a subsequent stage, the multi-LOD meta-model validates the consistency of information refinement against the previous stage. In order to consider the refinement of a building model consistent, it needs to at least conform to the decisions taken in a previous stage.

6. MINIMIZED COMMUNICATION PROTOCOL

To avoid sending back and forth actual digital BIM files, we propose a communication protocol that is focused on minimizing the exchange requests and feedbacks through a set of parameters as illustrated in FIG. 7 (Zahedi and Petzold 2018).

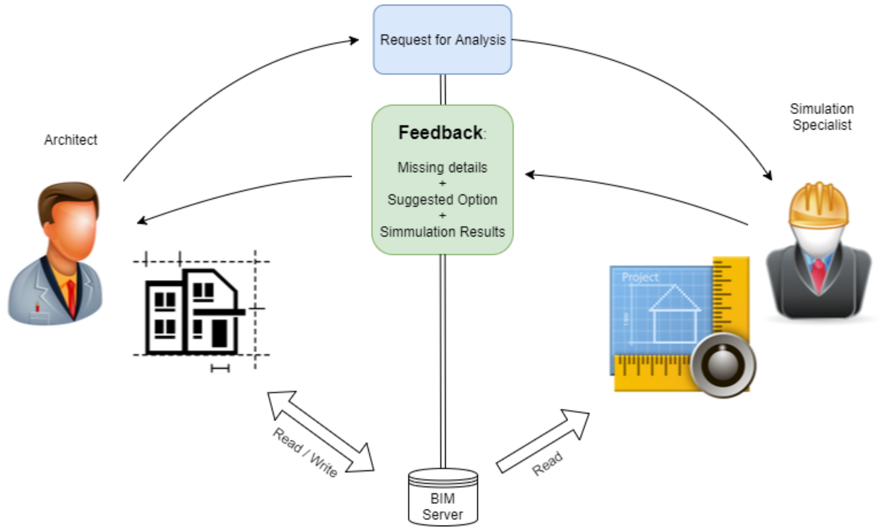


FIG. 7: Minimized Communication Protocol (*Zahedi and Petzold 2018*).

The proposed communication system consists of two parts. One part is an issue tracking system or so-called ticketing system. This part handles storing and managing of communication interactions between different actors. In this system, each request for analysis will trigger the issuing of a Ticket. The communication system consists of the following main features:

- Register a request for analysis (or a ticket)
- Assign an owner, or person responsible, to the ticket
- Assign additional interested parties to the ticket
- Track changes to the ticket
- Inform interested parties of these changes
- Launch activity based on ticket status and priority
- Report on the status of one or more ticket(s) - an overview
- Finish with, or close, the ticket once the activity is concluded.

Additionally, the system contains handling the feedback provided by various consultants and domain experts. Furthermore, the issues and messages traded between different actors using this protocol are computer-readable by means of predefined schemas. Using this protocol, all communications, variant evaluations, and decision-making will be documented and traceable afterward for further use cases. A detailed demonstration of the above-mentioned communication protocol is presented through multiple use-cases in the following publications (Zahedi and Petzold 2019; Zahedi et al. 2019)

7. PROPOSED METHODS FOR MODEL EVALUATION

As described in section 3, LCEA and structural design serve as sample processes for developing methods to inform the design process at early design stages about the performance of different variants. Information to perform a complete and accurate analysis is not available in early design stages, therefore missing data needs to be requested from the architect or estimated based on domain experience. The developed concept is capable of incorporating the defined vagueness (from the multi-LOD meta-model presented in Section 4) in the simulation input, and at the same time, providing feedback, including an evaluation of the uncertainty of calculated values.

7.1 LCEA Calculations

LCEA for buildings comprises two interconnected parts: first, calculation of the embedded energy (life cycle stages ‘Construction’: A1-A5, ‘Use’: B1-B5, ‘Disposal’: C1-C4 and ‘Recycling, Reuse and Reutilization’: D according to DIN 15978-2012-10) and a calculation of the operational energy demand (life cycle stage B6). The results of both can be merged using appropriate databases for primary energy.

The challenge of uncertain information is addressed by the appropriate use of the proposed multi-LOD BIM data structure (presented in Section 4) to capture the uncertainty in design parameters. A probabilistic estimation of the energy is performed using Monte Carlo method and the results are integrated back in BIM model. To fill the gap of missing information in early design stages, the required information is estimated within a range of vagueness depending on the LOD.

There are several points of interconnection between operational energy and embedded energy: The overall geometry of the building and the u-values of the exterior building parts affect both the use stage as well as the construction and end-of-life stage. Other parameters relevant for both operational energy and embedded energy are window-to-wall-ratio or the system of energy generation and distribution within the building. The type of structural system or materials influences almost exclusively the embedded energy, whereas, e.g. the hours of operation, have an impact on operational energy only.

The evaluation process is represented in FIG. 8. Although the methods used for operational and embedded energy calculations are different, both calculations use the same design information from BIM model with the same uncertainties. The models generated by the sampling process are evaluated using the methodology for operational or embedded energy respectively. For user feedback, the results are merged using primary energy values from the same database, in our case the German Ökobaudat (BMI 2018). Thus, the results for the total life cycle energy demand are evaluated and communicated back into the design process, such that possible synergies or trade-offs between embedded and operational energy demand are addressed.

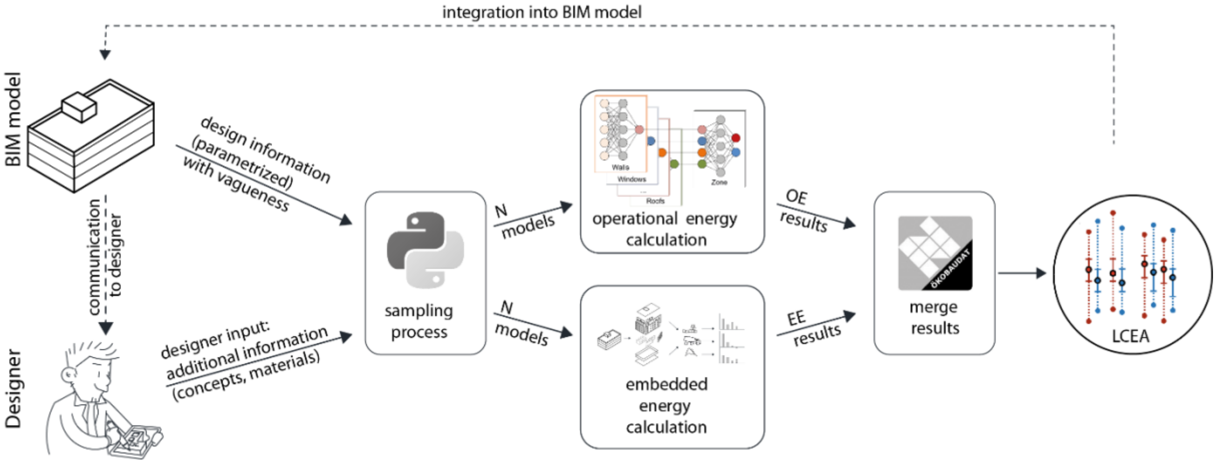


FIG. 8: Life Cycle Energy Analysis, adjusted from (Harter et al. 2019).

To enable a valid calculation of embedded energy in early design stages, while considering also the uncertainty of estimated information, an embedded energy prediction tool was developed in this project. Information to the user can be provided as comparative LCEA results for different variants including uncertainties, options for missing components or material information and prioritization of decision making for the most relevant parameters. In addition, the development of a knowledge database for embedded energy for early design stages is explored to provide data for typical building parts with the corresponding data uncertainties.

We are using a component-based machine learning (ML) approach developed by Geyer and Singaravel (2018) to perform operational energy predictions. The ML models perform the calculation of energy flows through components and serve to check the energy requirements. The inherent uncertainty in the input parameters is entered using user inputs and stored in the BIM model according to the proposed data structure. Several energy models are developed using the Monte Carlo method. They are evaluated using ML models to quickly provide results. The ML approach drastically reduces the effort for energy modeling and computation time.

This research investigates the various types of interactions between the design process and energy prediction activity at different BDLs. We distinguish three types of interactions: analyze variants, generate and analyze options, and provide recommendations for the next BDL. Design vagueness is evaluated by sensitivity analysis. The results help designers to prioritize decisions as they show the influence of available building data on the results and accuracy of LCEA. A detailed description of the process can be found in (Harter et al. 2019).

7.2 Structural preliminary design featuring a specialized development level system

For the structural preliminary design (pre-design), a specialized level system (see Table 1 and FIG. 9) is developed based on the requirements that originate from the pattern of the engineering knowledge for the rough design of supporting structures. The system is compatible with the proposed multi-LOD meta-model presented in Section 4. The proposed system comprises five adaptive levels of development (aLOD). Additionally, transfer functions are included, which enables the increase of the development status of a model by determination of the necessary additional model data in the higher aLOD. The included and required decision processes must be executed on the basis of limited information in the lower aLOD. To address the problem of design uncertainty and model incompleteness (section 3.2), intelligent substitution models for structural design in early stages are developed. They allow assessing and completing the model according to design targets, including parameters for uncertainty analyses, such as material quantities and masses (Steiner 2018; Steiner and Schnellenbach-Held 2018; Schnellenbach-Held and Steiner 2019).

TAB 1: Levels of Development for structural pre-design based on Steiner and Schnellenbach-Held 2018.

aLOD	Name	Content
0	Blackbox	Global information, environmental conditions and external dimensions
	Substitution model grid	Determination of a construction grid or specified by the architect
1	Geometry	Floor plan, construction grid, and component geometries
	Positioning method	Determination of idealized elements or from a substitution model grid
2a	Positions	Idealized structural elements
	Substitution model possibility	Determination of the applicability of the elements
2b	Possibility	Suitability of different designs and constructions
	Substitution model pre-design	Determination of the design target parameters
3	Pre-design	Pre-designed structural solutions, materials, quantities and masses

The design of supporting structures is characterized by various parameters that influence each other, including iterative sub-processes, construction-related effects on connected elements, applications of alternative calculation methods and the use of special construction technologies or components. Concepts of adaptive detailing enable the developed aLOD system to comprise such additional parameters, information correlations and development levels of the model. By format-compliant methods, the important parameters can be queried, analyzed and influenced between the aLODs. The resulting communication is independent of the substitution models and is activated when required.

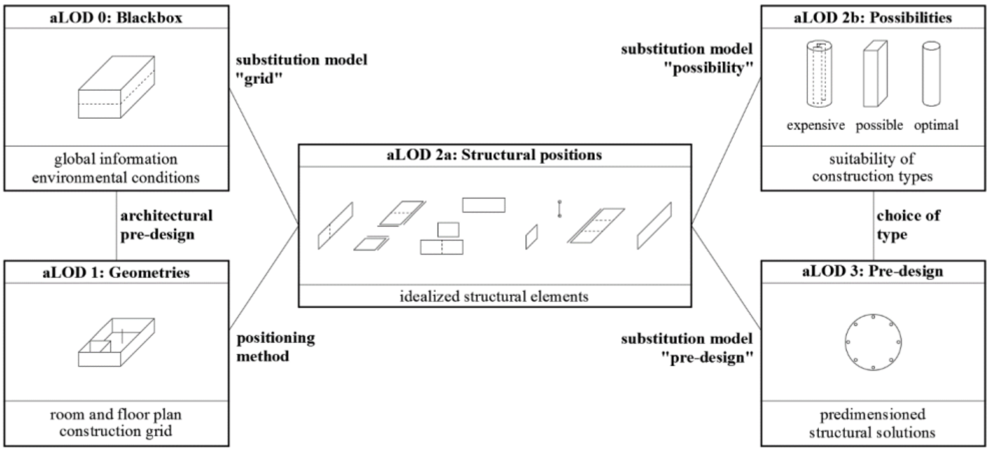


FIG. 9: Development system for structural pre-design based on Steiner and Schnellenbach-Held 2018.

For instance, the possibility of a slab (aLOD 2b) may influence the geometry of a column (aLOD 1), if larger column dimensions are needed due to shear punching. A column head can be arranged alternatively (aLOD 2a) if additional parameters like the column head geometry (aLOD 1) are provided in the model. For a reliable integration of this additional information, further interfaces are developed, that allow the inclusion of individual specifications, such as the usage of assembly parts or precast elements. The interfaces between development levels and substitution models also allow the integration of alternative or supplemental substitution models as well as complementary development levels. For an existing substitution model, for example, the application of a trained Artificial Neural Network (ANN) instead of the Fuzzy inference system is enabled. This also allows the extension of the detailing system, like the inclusion of a new aLOD 4 for the consideration of a complimentary design aspect (Steiner and Schnellenbach-Held 2018; Steiner 2018).

8. CASE STUDY: DESIGNING THE TAUSENDPFUND BUILDING

In this case study, the proposed approaches were applied to define exchange requirements and support the decision-making process during the early design stages of a real-world construction project depicted in FIG. 10. Two scenarios are discussed in detail: Evaluating multiple structural systems and selecting different main materials for the exterior walls.

FIG. 10: Ferdinand Tausendpfund GmbH & Co. KG office building, in Regensburg, Germany built-in 2017. © Bauer | bauerwerner.com courtesy of F. Tausendpfund GmbH

The building’s structural system has a significant influence on the applicability and efficiency of the design solution. Incorporating structural engineering knowledge in the early stages facilitates making informed architectural decisions. Using the multi-LOD meta-model, the exchange requirements are defined and assigned to component types. For each design stage, a set of components and their LOD definitions, including vagueness information, are specified. Estimating the attributes with a vagueness percentage makes performing the different kinds of simulations in the early stages viable. In this way, the impact of each attribute on the calculation results can be assessed. This makes it possible to make better decisions that improve the building's performance during the building's life cycle and fit into the design intentions (Hopfe and Hensen 2011).

FIG. 11 illustrates the integration of the structural expertise into the design process at the early stages. In the beginning, after deciding on the height of the building and the number of storeys, the architect sends a ticket to the structural engineer specifying the scope of the required analysis. The structural engineer, as the recipient of the ticket, checks the model against the requirements defined in the meta-model to identify any missing information. In case any of the information is missing, the architect or engineer needs to estimate some values with vagueness. Based on the information provided and engineering knowledge, the structural engineer employs the intelligent substitution models for developing preliminary structural designs. The produced structural options include different types and formations of the structural elements. Here, the structural engineer provides several options with varying dimensions of the horizontal and vertical elements of the load-bearing structure. Furthermore, the structural engineer also provides options with ratings according to their structural performance (see section 7.2). At the same time, the architect may have also other criteria in mind for making design decisions, such as spatial layout flexibility or preferred window-to-wall ratio.

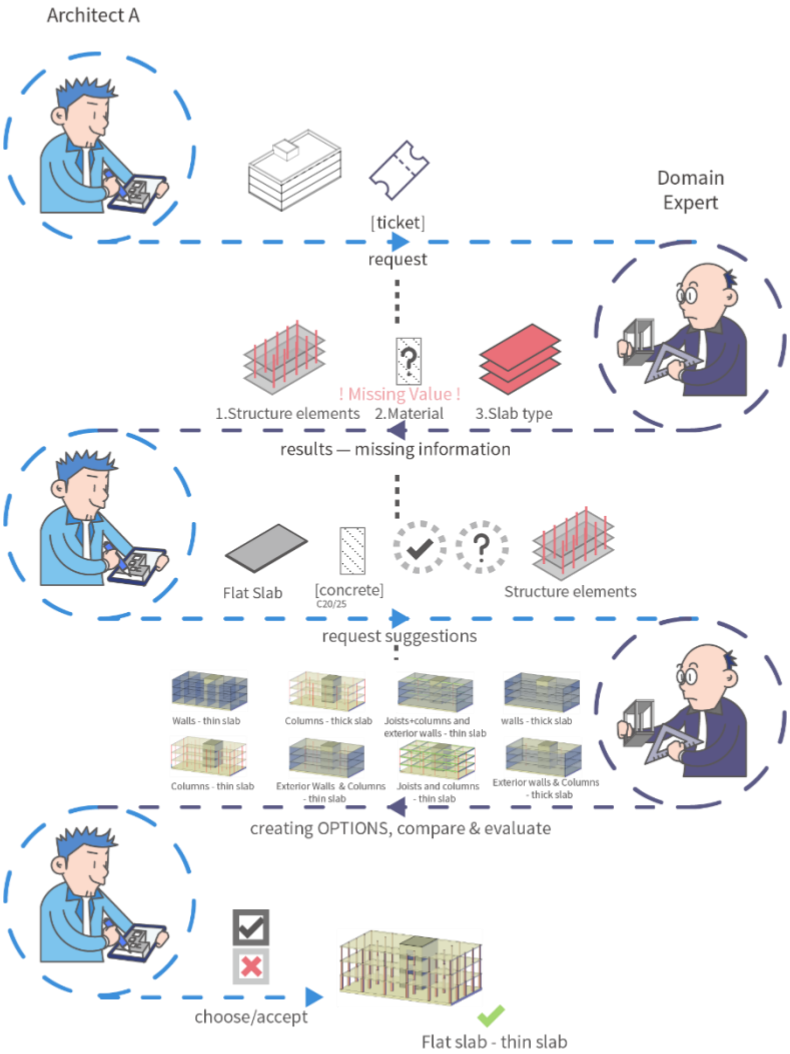


FIG. 11: Scenario 1: structural analysis at the early design stages (Zahedi et al. 2019)

The second scenario (FIG. 12) involves an energy expert in the design process to evaluate the impact of selecting the main material of the exterior walls on building performance. The process starts when the architect requests an energy analysis by issuing a ticket that clarifies the scope of the requested analysis to the LCEA specialist. The domain expert receives the ticket, which contains a link to access the digital model. Afterwards, the expert checks the model's quality for compliance with the analysis exchange requirements. Accordingly, a report of the missing information is sent back and appropriately visualized to the architect, indicating the shortcomings of the exchanged model. In this simplified example, the exterior walls' material and thickness and the window-to-wall ratio for the overall building are missing. The architect estimates 0.4 for the window-to-wall ratio and a wall thickness of approximately 40 cm with some vagueness.

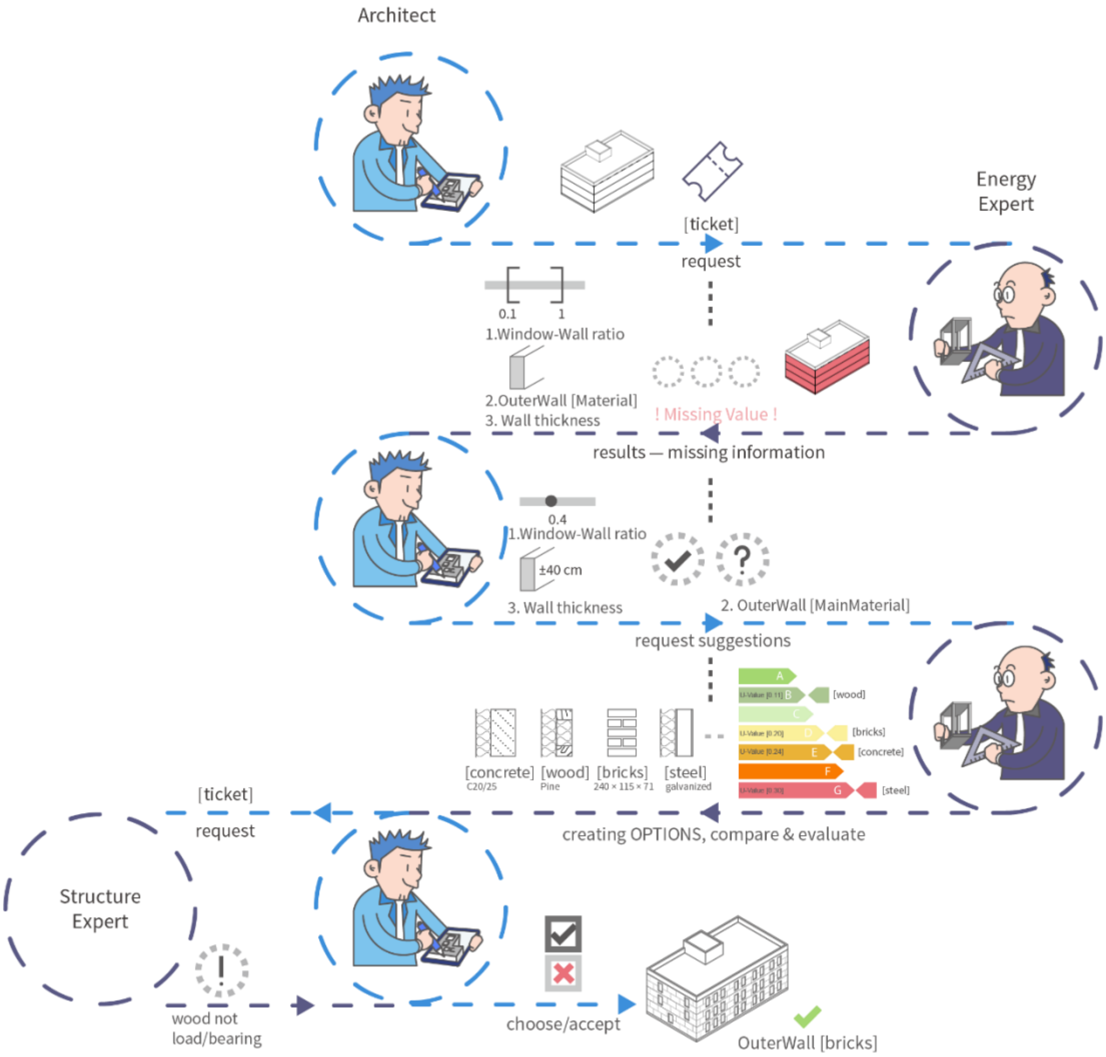


FIG. 12: Scenario 2: energy analysis at the early design stages (Zahedi and Petzold 2019)

However, a decision regarding the exterior wall material is still pending as it has a high impact on the building's performance. Therefore, the architect asks for suggestions and the respective evaluation from the domain expert. The specialist creates four possible options for material, namely steel, bricks, wood, and concrete and evaluates each of them. The generated options along with a comparison of their evaluation results are sent back to the architect. The architect has the possibility to forward these options to other consultants for further evaluation, in our case the structural engineer, who provides additional evaluation, e.g. that an exterior wood wall should not be load-bearing. This way the architect can decide intuitively for the better option according to the evaluation results and the system will automatically add the details (outer-walls material) to the exchanged model.

9. CONCLUSION AND FUTURE WORK

The early design stages are usually lacking detailed requirements for building performance simulations. The approach presented in this paper facilitates managing the building information uncertainty and integrating the model analysis in the early stage of design. Additionally, a methodology for managing design variants as well as communicating their performance among the project participants is proposed.

The multi-LOD meta-model offers a high-level interface for formally defining the LOD requirements, incorporating the potential vagueness. Using the meta-model, each property is associated with a vagueness type and maximum percentage on a particular LOD, which makes the LODs interconnected and their properties' vagueness controlled and alleviated during the design stages by the different specialists. The defined vagueness in the meta-model is used as an input for the different performance simulations. Accordingly, the input is formalized in a way that building performance models can use it to integrate the different possibilities and get results that are more realistic. In this context, this paper proposed employing the different engineering knowledge and machine learning models to account for the information vagueness in their simulations as well as supporting the decision-making process by demonstrating the impact of the input vagueness on the simulation results.

The proposed methodology for managing design variants prevents creating redundant or contradicting information and ensures integrating different designs in a consistent BIM model. In this regard, a graph-based concept to manage design variants based on the structure and scope of IFC 4 is developed. Graph Data Models enhance the transparency of resulting models despite complex interdependencies and the linkage to IFC offers a wide application range. The presented variant management concept enables the description of the design history of a project and related decisions. Incorporating the building information vagueness and propagating its impact to the model simulation results provides great advantages in making subjective decisions in the early design stages. Evaluating the different variants throughout the design stages prevents substantial amount of rework and assists in developing a consistent building model fulfilling the project requirements.

Future work comprises the optimization and knowledge generation for the creation and evaluation of designs based on the above-described results. By ensuring a smooth collaboration and exchange between the different project parts, design assistance can be increased even in early design stages. In this context, innovative research methods are developed further and applied, including the adaption of the detailing process between design variants and developing a knowledge database for variant generation.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the German Research Foundation (DFG) for funding the project under grant FOR 2363. We thank Ferdinand Tausendpfund GmbH & Co. KG for providing their office building as a sample project.

BIBLIOGRAPHY

Abualdenien, Jimmy; Borrmann, André (2018): Multi-LOD model for describing uncertainty and checking requirements in different design stages. In : Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2018). Copenhagen, Denmark.

Abualdenien, Jimmy; Borrmann, André (2019a): A meta-model approach for formal specification and consistent management of multi-LOD building models. In *Advanced Engineering Informatics* 40, pp. 135–153. DOI: 10.1016/j.aei.2019.04.003.

Abualdenien, Jimmy; Borrmann, André (2019b): A multi-LOD model for visualizing building information models' vagueness. In : Proceedings of The 2019 ASCE International Conference on Computing in Civil Engineering. Atlanta, U.S.A.

Ahn, Ki Uhn; Kim, Young Jin; Park, Cheol Soo; Kim, Inhan; Lee, Keonho (2014): BIM interface for full vs. semi-automated building energy simulation. In *Energy and Buildings* 68 (PART B), pp. 671–678. DOI: 10.1016/j.enbuild.2013.08.063.

Ballard, Glenn; Koskela, Lauri (1998): On the agenda of design management research. In : Proceedings IGLC, vol. 98, pp. 52–69.

BIMForum (2017): 2017 Level of Development Specification Guide. Available online at http://bimforum.org/lod/, checked on 1/11/2018.

BMI (2018): Ökobaudat. Available online at http://www.oekobaudat.de, checked on 12/7/2018.

BSI (2017): PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. Available online at http://shop.bsigroup.com/Navigate-by/PAS/PAS-1192-22013/, checked on 1/11/2018.

Chiu, Mao-Lin (2002): An organizational view of design communication in design collaboration. In *Design studies* 23 (2), pp. 187–210.

Clementini, Eliseo (2010): Ontological impedance in 3D semantic data modeling. In : 5th 3d Geoinfo Conference (Ed. by TH Kolbe, G. König & C. Nagel), ISPRS Conference, vol. 38, p. 4.

Ernstrom, Bill; Hanson, David; Hill, Damian; Clark, J. J.; Holder, M. K.; Turner, D. N. et al. (2006): The contractors' guide to BIM. In *Associated General Contractors of America*.

Exner, H.; Abualdenien, J.; König, M.; Borrmann, A. (2019): Managing Building Design Variants at Multiple Development Levels. In : Proc. of the 36th International Council for Research and Innovation in Building and Construction (CIB W78). Newcastle, UK.

Flager, F.; Welle, B.; Bansal, P.; Soremekun, G.; Haymaker, J. (2009): Multidisciplinary process integration and design optimization of a classroom building. In : ITcon, vol. 14, pp. 595–612. Available online at http://www.itcon.org/2009/38.

Gervásio, Helena; Santos, P.; Martins, R.; da Silva, L. Simões (2014): A macro-component approach for the assessment of building sustainability in early stages of design. In *Building and environment* 73, pp. 256–270.

Geyer, Philipp; Singaravel, Sundaravelpandian (2018): Component-based machine learning for performance prediction in building design. In *Applied Energy* 228, pp. 1439–1453. DOI: 10.1016/j.apenergy.2018.07.011.

Gigante-Barrera, Angel; Ruikar, Darshan; Sharifi, Soroosh; Ruikar, Kirti (2018): A Grounded Theory Based Framework for Level of Development Implementation Within the Information Delivery Manual. In *International Journal of 3-D Information Modeling (IJ3DIM)* 7 (1), pp. 30–48.

Gilbertson, Alan L. (2006): Briefing: Measuring the value of design. In *Proceedings of the Institution of Civil Engineers - Municipal Engineer* 159 (3), pp. 125–128. DOI: 10.1680/muen.2006.159.3.125.

Gu, Ning; London, Kerry (2010): Understanding and facilitating BIM adoption in the AEC industry. In *Automation in construction* 19 (8), pp. 988–999.

Harter, H.; Schneider-Marin, P.; Lang, W. (2018): The energy grey zone - uncertainty in embedded energy and greenhouse gas emissions assessment of buildings in early design phases. In : Proceedings of the Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018). Ghent, Belgium.

Harter, Hannes; Singh, Manav Mahan; Schneider-Marin, Patricia; Lang, Werner; Geyer, Philipp (2019): Uncertainty Analysis of Life Cycle Energy Assessment in Early Stages of Design. In *Energy and Buildings*, p. 109635. DOI: 10.1016/j.enbuild.2019.109635.

Hausknecht, Kerstin; Liebich, Thomas (2017): BIM-Kompendium: Building Information Modeling als neue Planungsmethode: Fraunhofer IRB Verlag.

Hawer, Sven; Schönmann, Alexander; Reinhart, Gunther (2018): Guideline for the Classification and Modelling of Uncertainty and Fuzziness. In *Procedia CIRP* 67, pp. 52–57.

Hooper, Martin (2015): Automated model progression scheduling using level of development. In *Construction Innovation* 15 (4), pp. 428–448.

Hopfe, Christina J.; Hensen, Jan L. M. (2011): Uncertainty analysis in building performance simulation for design support. In *Energy and Buildings* 43 (10), pp. 2798–2805.

Joedicke, Jürgen (1993): Entwerfen und Gestalten: Krämer.

Klir, George J. (1987): Where do we stand on measures of uncertainty, ambiguity, fuzziness, and the like? In *Fuzzy sets and systems* 24 (2), pp. 141–160.

Knotten, Vegard; Svalestuen, Fredrik; Hansen, Geir K.; Lædre, Ola (2015): Design management in the building process-a review of current literature. In *Procedia Economics and Finance* 21, pp. 120–127.

Kolltveit, Bjørn Johs; Grønhaug, Kjell (2004): The importance of the early phase: the case of construction and building projects. In *International Journal of Project Management* 22 (7), pp. 545–551.

Kraft, Bodo; Nagl, Manfred (2007): Visual knowledge specification for conceptual design: Definition and tool support. In *Advanced Engineering Informatics* 21 (1), pp. 67–83.

Lawson, Bryan (2006): How designers think: The design process demystified. 4. ed. Amsterdam: Elsevier/Architectural Press.

Liebich, T.; Adachi, Y.; Forester, J.; Hyvarinen, J.; Richter, S.; Chipman, T. et al. (2013): Industry Foundation Classes IFC4 official release. In *Online: http://www.buildingsmart-tech.org/ifc/IFC4/final/html*.

MacLeamy, Patrick (2004): MacLeamy Curve (WP-1202). Available online at http://www.msa-ipd.com/MacleamyCurve.pdf, checked on 9/29/2015.

Mahler, Patrick; Schneider, Patricia (2017): The influence of databases on the Life Cycle Assessment of building components – A comparison of databases using three different wall constructions. In : Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure, pp. 967–974.

Mattern, Hannah; König, Markus (2018): BIM-based modeling and management of design options at early planning phases. In *Advanced Engineering Informatics* 38, pp. 316–329.

Negendahl, Kristoffer (2015): Building performance simulation in the early design stage: An introduction to integrated dynamic models. In *Automation in construction* 54, pp. 39–53. DOI: 10.1016/j.autcon.2015.03.002.

Sawhney, Anil; Maheswari, J. Uma (2013): Design Coordination Using Cloud-based Smart Building Element Models. In *International Journal of Computer Information Systems and Industrial Management Applications* 5, pp. 445–453.

Schnellenbach-Held, Martina; Steiner, Daniel (2019): Structural design in early planning phases using engineering expert knowledge and intelligent substitution models. In : Proceedings of the 36th CIB W78 conference, Newcastle.

Singaravel, Sundaravelpandian; Suykens, Johan; Geyer, Philipp (2018): Deep-learning neural-network architectures and methods: Using component-based models in building-design energy prediction. In *Advanced Engineering Informatics* 38, pp. 81–90.

Singh, M. M.; Singaravel, S.; Geyer, P. (2018): Information Exchange Scenarios between Machine Learning Energy Prediction Model and BIM at Early Stage of Design. In : Proceedings of the Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018). Ghent, Belgium.

Stadler, Alexandra; Kolbe, Thomas H. (2007): Spatio-semantic coherence in the integration of 3D city models. In : Proceedings of the 5th International Symposium on Spatial Data Quality, Enschede.

Steiner, Daniel (2018): Formulierung und Generierung von Expertenwissen zur Entwicklung intelligenter Ersatzmodelle für die Tragwerksplanung in frühen Entwurfsphasen (in German). In : Tagungsband 30. Forum Bauinformatik, Weimar.

Steiner, Daniel; Schnellenbach-Held, Martina (2018): Intelligent Substitution Models for Structural Design in early BIM Stages. In : Publications of the Sixth International 2018.

Steinmann, Frank (1997): Modellbildung und computergestütztes Modellieren in frühen Phasen des architektonischen Entwurfs.

Tian, Wei; Heo, Yeonsook; Wilde, Pieter de; Li, Zhanyong; Yan, Da; Park, Cheol Soo et al. (2018): A review of uncertainty analysis in building energy assessment. In *Renewable and Sustainable Energy Reviews* 93, pp. 285–301. DOI: 10.1016/j.rser.2018.05.029.

van Berlo, LAHM; Bomhof, F. (2014): Creating the Dutch national BIM levels of development. In : Computing in Civil and Building Engineering, pp. 129–136.

van Gelder, Liesje; Janssen, Hans; Roels, Staf (2014): Probabilistic design and analysis of building performances: Methodology and application example. In *Energy and Buildings* 79, pp. 202–211. DOI: 10.1016/j.enbuild.2014.04.042.

VicoSoftware (2005): BIM Level of Detail. Available online at http://www.vicosoftware.com, checked on 5/13/2019.

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.

Zahedi, Ata; Petzold, Frank (2018): Utilization of Simulation Tools in Early Design Phases Through Adaptive Detailing Strategies. In : 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018, vol. 2. Beijing, China, pp. 11–20.

Zahedi, Ata; Petzold, Frank (2019): Adaptive Minimized Communication Protocol based on BIM. In : 2019 European Conference on Computing in Construction.