Technical University of Munich

Department of Civil, Geo and Environmental Engineering

Chair of Computational Modeling and Simulation

Categorization and visualization of model-based informational distance during the BIM-based design process

Master thesis

for the Master of Science program Civil Engineering

Author: Fritz Beck

Student number: [redacted]

Supervisors: Prof. Dr.-Ing. André Borrmann

M.Sc. Jimmy Abualdenien

Date of issue: 10th of October 2018

Date of submission: 2nd of May 2018

Abstract

Planning mistakes represent a major reason for project risks in construction projects and the responsibilities concerning the major costs are located in early design phases. Thus, the improvement of planning-/ design quality is relevant for the achievement of project goals regarding costs, quality and time. The iterative nature, insufficient knowledge and further restrictions of the planning process lead to uncertainties and fuzziness respective to the development and selection of adequate alternatives and variants. The usage of three-dimensional digital building with additional semantic information in terms of Building Information modeling (BIM) is a promising approach to increase the efficiency of building projects and its planning processes. A significant benefit, compared to the two-dimensional, conventional planning processes, is the interactive visualization of the building model. Although planning processes are accompanied by uncertainties and fuzziness, these characteristics are neglected in current visualizations: Building Information Models appear to be accurate and truthful. Hence, BIM-based decision- and communication processes are often based on insufficient information. As a result, the investigation regarding the visualization of fuzziness is relevant for the improvement of the planning quality to achieve the goals in a building project. In this thesis, a proposal for a fuzziness visualization for the BIM-based planning process is elaborated. For this, the concept fuzziness is defined and categorized in the context of the BIM-based planning process and potential visualization techniques are reviewed. Finally, the intuitiveness of the developed visualization approach is evaluated through conducting a survey. The major results are that adequate fuzziness visualization depends on the tasks to carry out and some of the developed visualization requires additional explanations to be understood.

Zusammenfassung

Planungsfehler stellen einen der größten Risikofaktoren für Bauprojekten dar und Entscheidungen in den frühen Entwurfsphasen ist für einen Großteil der Projektkosten verantwortlich. Eine Verbesserung der Planungs-/Entwurfsqualität ist daher maßgeblich für die Erfüllung der Projektziele hinsichtlich Kosten, Qualität und Zeit. Der iterative Charakter, unzureichendes Wissen und weitere Randbedingungen des Planungsprozesses führen zu Unsicherheiten und Unschärfe bei der Entwicklung und Auswahl geeigneter Alternativen und Varianten. Die Verwendung eines dreidimensionalen, digitalen Gebäudemodells mit zusätzlichen semantischen Informationen im Sinne von Building Information Modelling (BIM) ist eine vielversprechende Methode, um Bauprojekte und deren Planungsprozesse effizienter zu gestalten. Ein wesentlicher Vorteil gegenüber der konventionellen, zweidimensionalen Planung ist die interaktive Visualisierung des Gebäudemodells. Obwohl Unsicherheiten und Unschärfe integraler Bestandteil der Planungsprozesse sind, werden diese Eigenschaften in bisherigen Visualisierungen vernachlässigt: Gebäudeinformationsmodelle (BIM-Modelle) erscheinen stets genau und wahrheitsgetreu. BIM-basierte Entscheidungs- und Kommunikationsprozesse finden daher oftmals auf einer unvollständigen Informationsgrundlage statt. Folglich ist eine Untersuchung der Visualisierung von Unsicherheiten und Unschärfe in der BIM-basierten Planung relevant für die Verbesserung der Planungsqualität und der Erfüllung der Ziele in Bauprojekten. In dieser Masterarbeit wird eine Unschärfevisualisierung im BIM-basierten Planungs-/ Entwurfsprozess erarbeitet. Auf Grundlage einer Literaturrecherche wird der Begriff Unschärfe mit Bezug zu BIM definiert und kategorisiert und potenzielle Visualisierungstechniken aufgezeigt. Anschließend wird die erarbeitete Visualisierung auf Verständlichkeit mittels einer Umfrage überprüft. Als übergeordnetes Ergebnis lässt sich festhalten, dass eine geeignete Unschärfevisualisierung abhängig von der jeweiligen Aufgabe und die entwickelte Visualisierung nicht ohne Weiteres intuitiv verständlich ist.

List of Content

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Planning mistakes represent the major project risks in building construction projects (Werkl, 2013, p. 18) and most costs are determined in early planning phases (Steinmann, 1997, p. 5). Thus, a higher planning quality is essential for the fulfilment of project goals concerning quality, cost and duration of building projects. A high planning quality is defined by the intellectual anticipation of future acts (Grunwald, 2012, p. 164), which fulfil the contractual services/ requirements and expectations of the client on the building object. Recent developments in the construction industry demonstrate that the planning process can be supported efficiently by digital planning tools and methods (Zimmermann & Eber, 2015, p. 3). The creation, modification and maintenance of a three-dimensional digital building model including additional semantic information by appropriate digital planning tools is the basis of Building Information Modelling (BIM), which is considered as promising approach to increase the efficiency in building projects (see for instance Borrmann, König, Koch, & Beetz, 2018; Menz, 2015, p. 2). The interactive visualization of Building Information Models is a significant benefit regarding the planning process (see for instance Tulke, 2015, p. 271; McGraw Hill, 2009, p. 5). Based on these visualizations, a deeper understanding of the building project can be created (Tulke, 2015, p. 271) and tasks like decision-making can be carried out more effective (Munzner, 2015, p. 1). However, the visualization of Building Information Models without considering uncertainties and fuzziness assumes that the represented information is correct, accurate and truthful. To avoid wrong decisions based on the represented data, the building information model should provide an illustrative, holistic view on the necessary geometrical and semantical information including deviations to an accurate description. As a result, the visualization of uncertainties and fuzziness could significantly improve the planning quality and reduce project risks. Thus, the examination of a suitable representation of uncertainties and fuzziness is relevant for the successful application of BIM-based software tools in the planning process.

1.2 Problem

Efficient visualization of Building Information Models for the design process is the key to effectively communicate data with the objective to amplify cognition for the respective planning process step. The exclusion of necessary information yields to inaccurate representation and communication and to undesired results in the respective steps of the planning process. Among others, uncertainty and fuzziness accompany the design process and need to be visualized to communicate the data efficient and amplify cognition. However, visualization research in the AEC industry has often neglected the representation of uncertainty and fuzziness. The difficulties concerning fuzziness in the BIM-based planning process is originated in the need of an exact value as input in current CAD-systems. Especially in early design phases, geometrical and semantical building information cannot be determined accurately what contradicts the exact input under compulsion in current CAD-systems. This issue is simplified illustrated in Figure 1, where the variable of interest is the color of a house. Here, the designer is not sure which kind of blue the building shall be painted and wants to share his ideas with another person using a CAD-system as communication tool. Since the CAD-system needs an exact value as input, the designer must choose one particular blue from the set of potential blues. The receiver of the message perceives the information in form of the one particular blue, what leads to differences in the understanding of the building project between both persons. This simplified example serves as a brief illustration of the nature of the problem and does not represent the problem in a holistic manner.

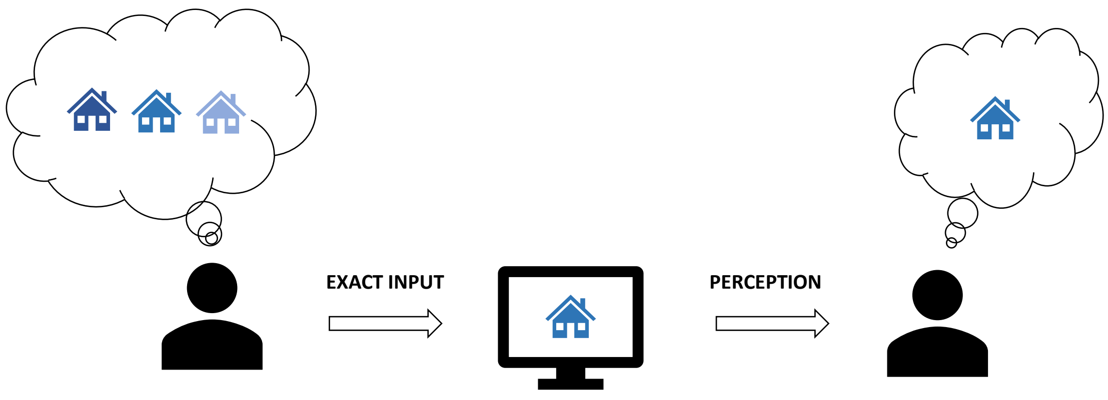


Figure 1: Illustration of communication problems based on the exact input of CAD-tools

1.3 Objective

The objective of the thesis is to design and evaluate adequate ways to visualize fuzzy building information for an efficient communication of semantic and geometric model information in the BIM-based design- and planning processes. Consequently, the informational distance between the mental models of the sender and receiver shall be reduced by visualizing fuzziness in an adequate way (Figure 2). The developed visualization approach will be verified concerning its intuitiveness and a basis for further research investigation shall be elaborated. Some limitations concerning the objective have to be done to ensure good scientific practice: The objective is neither to deduce an adequate way to model fuzzy information making fuzziness computer accessible nor to deduce an adequate way to communicate fuzziness in terms of collaboration or cooperation processes. Furthermore, the primary objective of the thesis is not to conceptualize and define fuzziness in general or in terms of BIM-based planning- and design processes, although a major part of the thesis covers the conceptualization and definition of fuzziness.

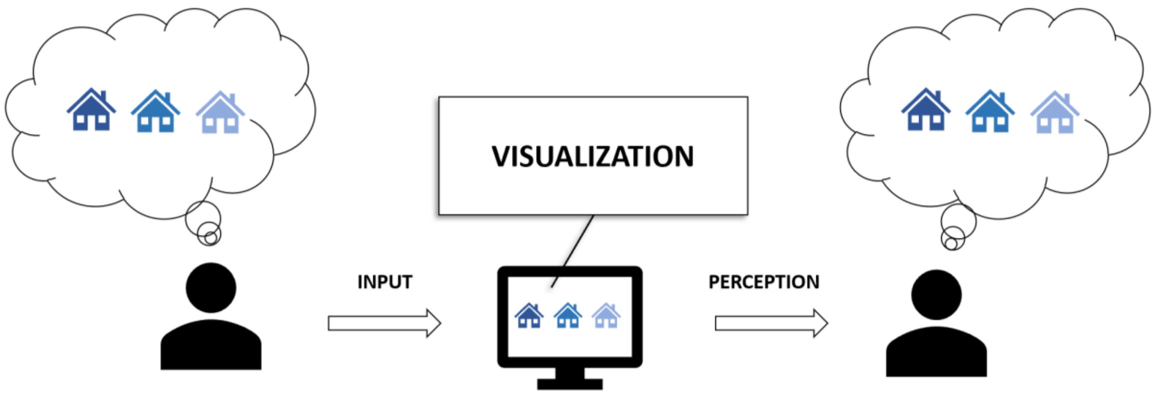


Figure 2: Illustration of objective of the thesis

1.4 Structure

The “lack of these [uncertainty] representations can be attributed, in part, to the inherent difficulty in defining, characterizing, and controlling this uncertainty, and in part, to the difficulty in including additional visual metaphors in a well designed, potent display.” (Bonneau et al., 2014, pp. 3–4) Following this statement, the research of fuzziness visualization address both the nature of fuzziness and the visualization theories and techniques. Based on basic theories and the deduction of limitations and categorization of fuzziness and visualization possibilities, a visualization proposal will be developed (Figure 3).

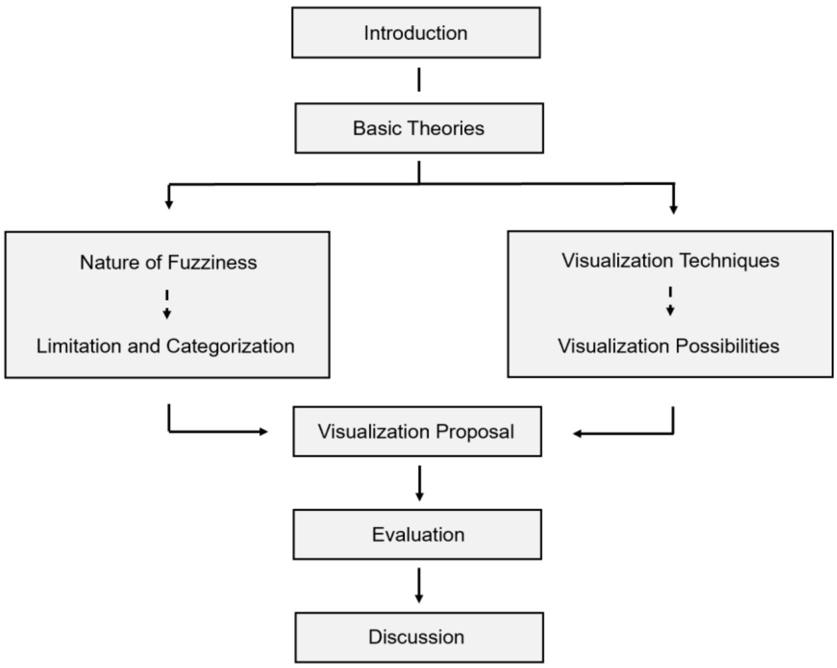


Figure 3: Representation of the structure of the master thesis

A brief introduction of BIM is provided in the second chapter to create a common understanding of Building Information Modelling. Among others, the motivation for the usage of BIM during the whole life-cycle of a building is covered in this chapter. Furthermore, various considerations of the term and concept BIM, obstacles concerning the introduction of BIM and further technical basics are explained.

After the brief introduction of Building Information Modelling, the fundamentals of basic theories for the thesis will be conveyed and explained in the third chapter. The general model theory, CAD-models and modelling, Building Information Models and procedural models will be discussed in the first part of the third chapter. The discussion of the term model is essential, since the ambivalent usage of the term model often result in problems of comprehension (Steinmann 1997, S. 68). In the second part of the chapter, insights into the planning- and design theory are provided, and assumptions are made for the further thesis to create a basis for the discussion of fuzziness in the design process. Since communication is an important component of the design process itself (Steinmann, 1997, p. 51) and of the computational visualization process, a closer look on communication theories is provided in the third part of the chapter.

In the fourth chapter the nature of fuzziness will be discussed to derive a categorization and characterization of the fuzziness, which shall be visualized. For that, a literature review about fuzziness and uncertainty (since that term is often used in similar context) is provided and a comparison of different categorizations is carried out. Additionally, the research fields of fuzziness and uncertainty in design, computational visualization and BIM were identified as relevant and are discussed in the second and third part of the fourth chapter. The chapter fuzziness in design, follows the fuzziness categorization according to Steinmann (1997), which address primarily the model-oriented fuzziness. The uncertainty in computational visualizations covers the occurrence of fuzziness in the process form data acquisition to visualization. In the end of the chapter assumptions concerning the categorizations and characteristics of fuzziness were made.

The fifth chapter is intended to conclude potential visualization techniques to amplify the user to understand the fuzziness in a Building Information Model. For that, the basics of visualization and perception are covered, which convey the fundamentals for a discussion and reasonable conclusion. In these parts, the purpose of visualization is explained, and essential visualization and perception models are introduced. Afterwards, a literature review concerning current visualization is provided and different means and methods of visualizing fuzziness are explained.

Based on the information from the fourth and fifth chapter, potential applications of the visualizations approaches for the visualization of the respective kind of fuzziness and their characteristics are derived and a visualization approach is developed. In the end of the chapter the proposed visualization approach is explained.

The seventh chapter covers the repetition of the research task. Furthermore, the structure, the documentation and the results of the evaluation are described.

The results are interpreted in the eight chapter. Subsequently, a conclusion based on the results of the evaluation and their interpretation. The conclusion refers rather to the visualization approach than to the whole fuzziness communication process. In the last part of the chapter, research question concerning the categorization, externalization, formalization and visualization of fuzziness within the BIM-based design-process are listed.

1.5 Evaluation

According to Bonneau et al. “visualization research is too often neglected by industry and other potential expert users. One of the reasons is the lack of a proper evaluation of the results.” Hence, the development of a suitable evaluation method is an essential part of thesis and decisive for its success. Bonneau et al differ between three types of evaluations:

- “Theoretical evaluation: the method is analyzed to see if it follows established graphical design principles,
- Low-level visual evaluation: a psychometric visual user study is performed to evaluate low-level visual effects of the method,
- Task oriented user study: a cognitive, task-based user study is conducted to assess the efficiency or the usability of the method.” (Bonneau et al., 2014, pp. 11–12)

For the evaluation of fuzziness visualization for an efficient communication of semantic and geometric model information, the task-based user study seems to be promising to assess the efficiency or the usability of the respective visualization approach. However, before setting up a time-expensive user study based on tasks, the evaluation of the adequateness of the individual symbols and colors for the representation of the respective kinds of fuzziness seems to be senseful. Thus, the evaluation of the thesis covers rather a survey for the identification of the adequateness of the individual symbols and colors than a user study to assess the efficiency or usability of the method. Therefore, the result is not intended to confirm the potential application of the developed fuzziness visualization in the BIM-based communication process, but to identify adequate visualization approaches for the different kinds of fuzziness.

1.6 Clarification of concepts

Since some thesis-relevant concepts have ambiguous meaning across the expert literature and conceptualizations of these terms is often missing, a clarification is necessary to ensure an objective-oriented research approach and to prevent misunderstandings. Due to the limited scope and the main focus of the thesis, the following conceptualizations are not based on an exhaustive literature review. However, the reviewed literature is considered as sufficient for a conceptualization in the course of the thesis.

1.6.1 Data, information and knowledge

The concepts *data, information* and *knowledge* are ubiquitous in the context of communication, Building Information Modeling and fuzziness. For instance, fuzziness is often defined as lack of knowledge (Hawer, Schönmann, & Reinhart, 2018, p. 53) and visualization can be defined computer-supported, interactive, visual representations of data to amplify cognition (Card, Mackinlay, & Shneiderman, 2007, p. 6). However, a general definition of these concepts does not exist and a definition in expert literature is often neglected. A clarification of the terms *data, information* and *knowledge* should be in the respective context, since definitions are often based on the respective discipline and domain. A definition of the terms with respect to knowledge-based systems in AEC industry can be found in (Beetz, 2009, p. 16):

> *"Data is a collection of observations without a specific purpose or intention. Light being reflected from an object in the world into the eye of an observer can be described in form of data, capturing its wavelength, location on the retina etc. It has no meaning unless there is a method of interpretation. The bits representing a line in a computer system that have been created by a specific application are not interpretable and identified able as a line by a computer system that does not have the information about the structure of the data model it has been created in.*
>
> *Information is data put into a specific context and related with other data. From the data received by the retina and processed by the visual cortex, the source of light reflection can be interpreted as an object of some nature. An informed application can interpret a stream of 256 bits as being four 8-byte blocks representing four double values on an axis in a coordinate system to compose a line. This information can be interrelated using systems like natural language or computer languages to form models.*
>
> *Knowledge is the learned ability how to operate with information."*

These clarifications of the concepts *data, information* and *knowledge* are assumed to be suitable and will be used in the thesis. In Table 1, simplified descriptions of the respective concepts are depicted.

Table 1: Clarification of the concepts data, information and knowledge according to Beetz (2009, p. 16)

Concepts	**Description**
Data	collection of observations without a specific purpose or intention
Information	data put into a specific context and related with other data
Knowledge	learned ability how to operate with information

1.6.2 Operative design- and planning processes

Since fuzziness and Building Information Modeling are often related to design- and planning process, a shared-understanding of both processes is essential for a successful discussion of fuzziness within this thesis. Thus, a conceptualization of both *design-* and *planning process* respective to the context of the thesis is necessary.

A common definition of *planning* is the process of thinking about the activities required to achieve a desired goal (see for instance Stachowiak, 1970). The steps of a planning process can be represented in a procedure model. This procedure model can address the time under consideration covering a few seconds or longer time periods like weeks or months (chapter 3.1.4). Operative models (or cognitive models) are based on a moderate granularity respective to the considered time. Lindemann (2009, p. 59) discuss operative planning models in the field of product development. After a literature review, he has deduced that a major number of operative planning models covers three major steps: analysis, synthesis and evaluation. Comparable to these three steps, Schmid (2015, p. 8) has conducted in his doctoral thesis that planning is "indirect part of a task- and problem solution identify by the design and development of alternatives and variants[1] and by the evaluation of the most expedient means and measures for the execution." [translated by the author][2]. Schmid (2015, p. 8) writes further that the planning goal is the "realization of a chain of action, which consists of design of a concepts, the development of potential solutions and the preparation of processes of implementation" [translated by the author][3].

Regarding the concept *design*, there is the distinction between *representational* and *processual design*. The *representational design* is the summary of all representation to produce a building. The *processual design* is the sequence of design actions and the subject of interest for this section, since it can be represented as procedure model. A variety of procedure models respective to design processes consist of the three major steps analysis, synthesis and evaluation (see for instance Page, 1973; Steinmann,

[1] Alternatives: The nature of potential solution are different
Variants: The nature of potential solutions are similar, however some characteristics are different

[2] Original: *„Planen ist dabei mittelbarer Teil einer Aufgaben- und Problemlösung, um durch das Entwerfen und Entwickeln von Alternativen und Varianten sowie das Bewerten und Abwägen die zielführendsten Maßnahmen und Mittel für die Umsetzung zu identifizieren.“* (Schmid (2015, p. 8))

[3] Original: *„Das Planungsziel besteht darin, eine Handlungskette zu realisieren, die aus dem Entwurf eines Konzepts, der Entwicklung eines Lösungswegs und der Vorbereitung von Umsetzungsprozessen besteht.“* (Schmid (2015, p. 8))

1997, p. 51). These steps can be enhanced by further activities like communication or organization (Steinmann, 1997, p. 51). The three major design steps are comparable to the three major steps in the planning process. In contrast to the planning process, the design process lay the focus on creative activities and the before-representation of the architectonical object. Consequently, the *operative design process* covers the creative activities and the creation of a before-representation of architectonical objects and models. In contrast to that, the concept *planning* is used when the purpose of the operative process are the processes of realization. The literature review in chapter 3.2 covers both *planning* and *design*, because a distinction between these concepts is often neglected in literature. In the thesis, the fuzziness visualization refers to the creation of a Building Information Model. Hence, the concept *design* is used for the discussion of fuzziness and its visualization in the BIM-based design- or planning process.

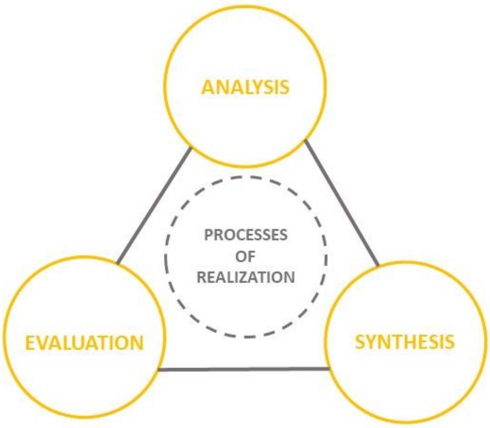


Figure 4: Simplified procedural model for the operative planning process

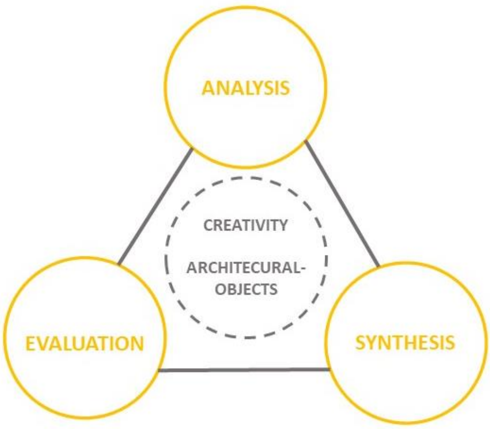


Figure 5: Simplified procedural model for the operative design process

1.6.3 Uncertainty and fuzziness

A distinction of the concepts *uncertainty* and *fuzziness* is provided by Hawer et al. (2018, p. 53) which is comparable to the definition from Forte (2002, pp. 74–75):

> *"We define uncertainty as being related only to the occurrence of events (future environmental states), whereas fuzziness can be attributed to different reference objects (RO), e.g. models, data, linguistic variables. […] Uncertainty is therefore defined as follows: A lack of knowledge or information that causes the occurrence of an event or future environmental state not to be known with certainty. Uncertainty can further be differentiated by the degree to which each state is known and can be attributed a probability of occurrence."*

Unlike the concept *uncertainty*, the definition of *fuzziness* is always based on its object of reference, e.g. a model. A definition of fuzziness respective to models is provided by Steinmann (1997, p. 96): “Fuzziness is the informational distance to the degree of a complete, accurate description, which can be achieved in a particular model world.” [translated by the author][4] This definition is simplified illustrated in Figure 6, where the particular model worlds are represented by three different models: mental-, BIM- and required model. The degree of complete, accurate description is represented by a house painted in a particular blue. An incomplete or inaccurate description within the particular model worlds is represented by missing color or a set of different kind of blues. Additionally, another kind of informational distance introduced for the scope of that thesis: the *horizontal informational distance* between descriptions of the same original across particular model worlds. An original is the base object from which other models are derived. A closer look on models and model theory is provided in chapter 3.1. The fuzziness across particular model worlds is simplified illustrated in Figure 7, where the particular model worlds are represented by mental-, BIM-, and required model. In contrast to the previous illustration the horizontal informational distance refers to models from different particular model worlds. The Figure 8 illustrates the *vertical* and *horizonal informational distance* according to the problem specification of the thesis. The informational distance of the mental model of the sender has to be visualized to reduce the horizontal informational distance between mental model of the sender and the mental model of the receiver.

[4] *Original:* „Unschärfe ist der informationelle Abstand zum Grad der vollständigen, exakten Beschreibung, der in einer bestimmten Modellwelt erzielt werden kann.“

Table 2: Definition of uncertainty and fuzziness according to (Hawer et al., 2018, p. 53) and (Steinmann, 1997, p. 96)

Concepts	Definition	Related to
Uncertainty	A lack of knowledge or information that causes the occurrence of an event or future environmental state not to be known with certainty	Occurrence of events (future environmental states)
Fuzziness/ Vertical informational distance (within model world)	The informational distance to the degree of a complete, accurate description, which can be achieved in a particular model world	Objects (*e.g. mental-model, BIM-model, required-model*)
Horizontal informational distance (across model worlds)	The informational distance between descriptions of the same original across particular model worlds	Object (*e.g. mental-model, BIM-model, required-model*)

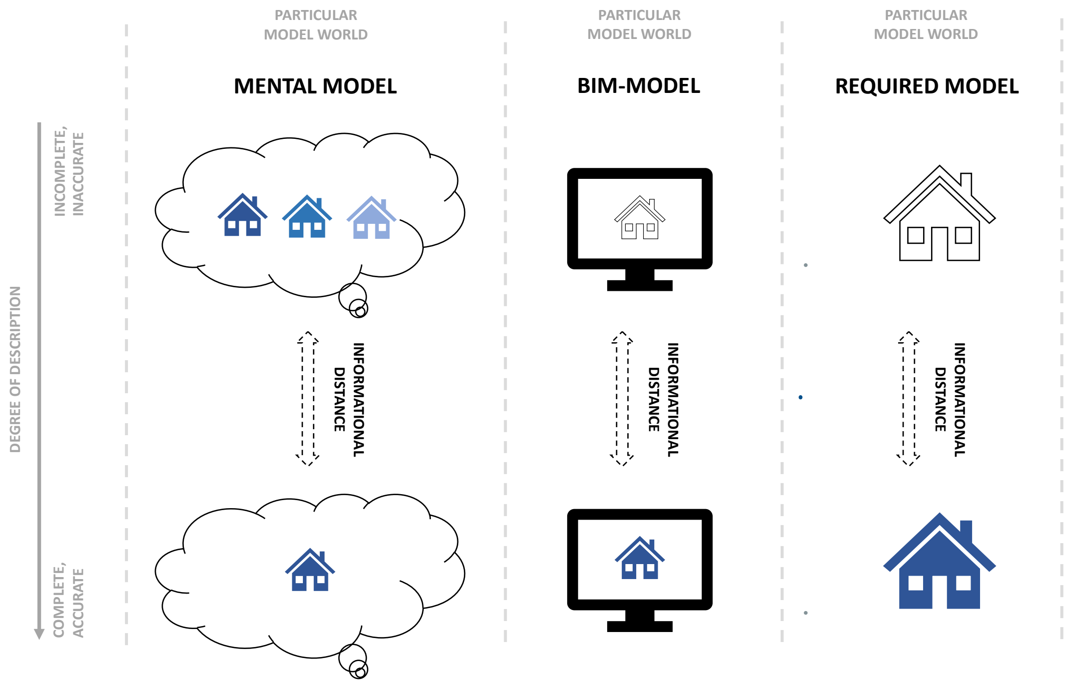


Figure 6: Illustration of fuzziness as informational distance to the degree of a complete, accurate description in a particular model world

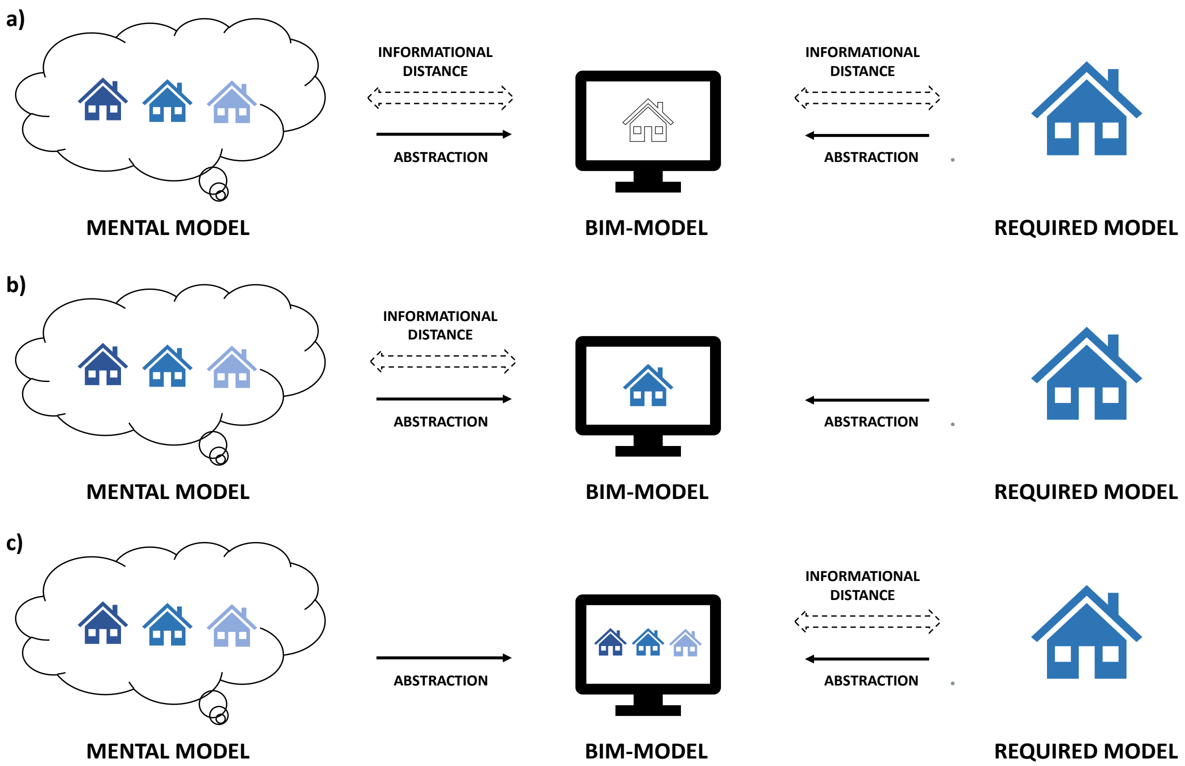


Figure 7: Illustration of fuzziness as informational distance across particular model worlds: a) mental model and BIM-model, BIM-model and required model b) mental model and BIM-model c) BIM-model and required model

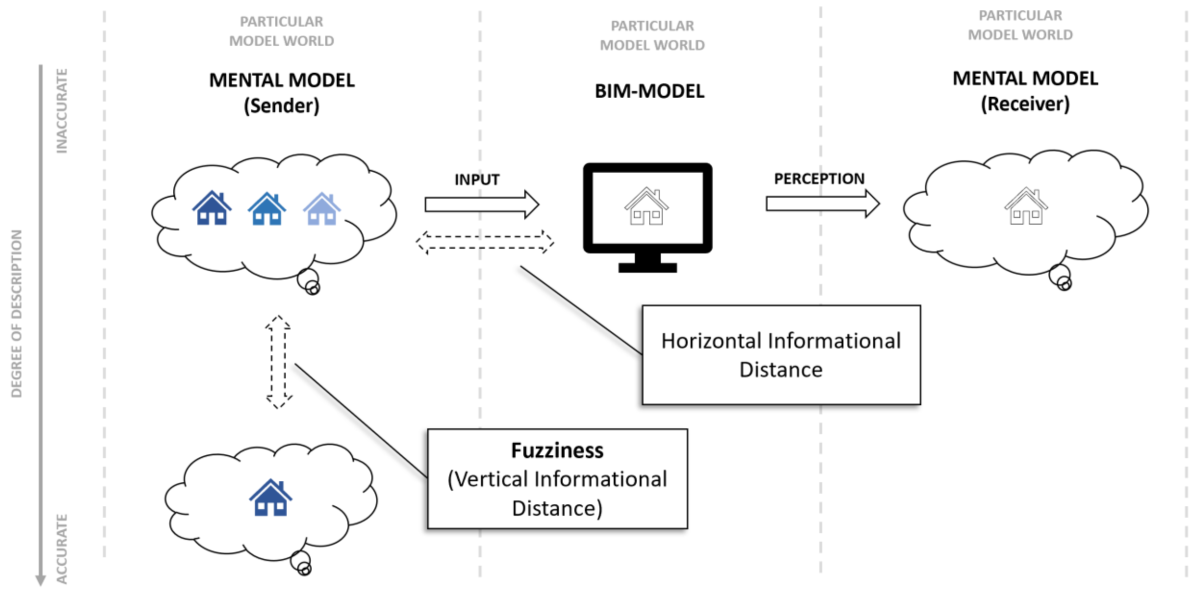


Figure 8: Vertical and horizontal distance within the fuzziness communication process

2 Brief introduction to Building Information Modelling

According to the research of Paul Teicholz published in 2007, the productivity of the construction industry stagnated over years in contrast to other nonfarm industries. The productivity in non-farm industries (including construction) has almost double within 44 years, while in construction industries the productivity index remained almost unchanged (Eastman, Liston, Sacks, & Teicholz, 2008, p. 8). Due to these developments and the considerable proportion of the gross domestic product (GPD) in Germany[5] for the constructions industry an integral the usage of a digital building model according to Building Information Modelling (BIM) could enforce significant cost savings. Until now, a general definition of the term Building Information Modelling could not be established. Thus, a definition is based on the view of the author (Albrecht, 2015, p. 17). For instance, the term Building Information Modelling can be used for the creation, modification and maintaining of Building Information Models (Borrmann, König, Koch, & Beetz, 2015, p. 17) or for the process of integral planning and usage of a digital building model over all life cycle phases (Tulke, 2010), which is illustrative depicted in Figure 9. The “Stufenplan digitales Planen und Bauen”, which was developed by planen-bauen 4.0 for the Bundesministerium für Verkehr und Infrastruktur (BMVI), states that BIM is a cooperative working method, which can be applied based on digital models of a building to acquire and maintain consistent data and relevant information for the life cycle. This data and information can be communicated transparent between involved person or provided for further processing (Bundesministerium für Verkehr und digitale Infrastruktur, 2015, p. 4). In distinction to the term Building Information Modelling, the term Building Information Model address the model but the process. With the use of a three-dimensional geometry and semantic information (additional non-geometric information) a digital building model (Building Information Model) can be created. For that, three-dimensional building objects are used, attributes like material or color can be added and connected with relations to other objects (Borrmann, 2015, p. 602). A Global Unique Identifier (GUID) for identification and simpler maintenance can be assigned to each building object. Furthermore, information concerning the

[5] The percentage of the GPD in Germany was 9.8% in the year 2015, what correlates to 297.7 billion Euro. (Hauptverband der Deutschen Bauindustrie e.V.)

building process (4D-model) and concerning cost (5D-model) can be added (Borrmann, 2015, p. 603).

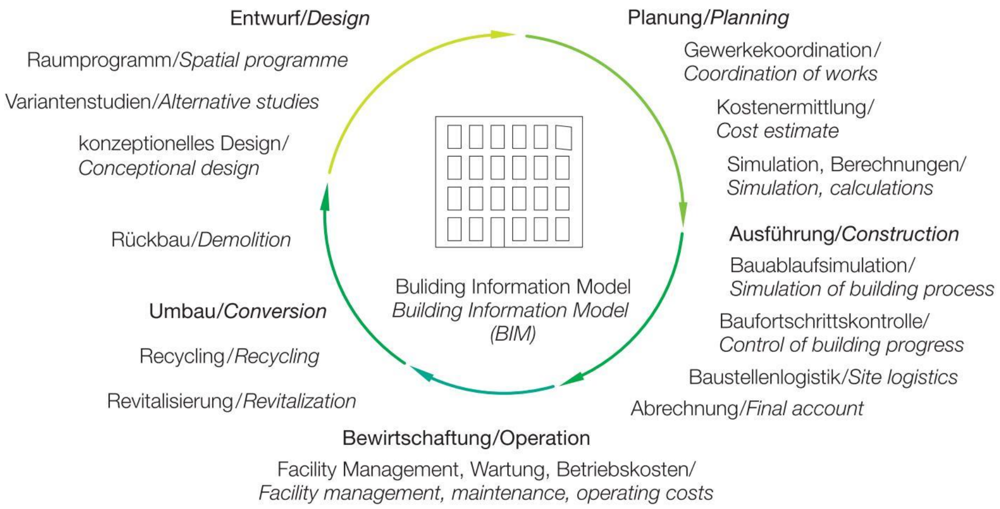


Figure 9: The BIM Life Cycle (Borrmann, 2015, p. 602)

Data of building models in current information- and communication technologies is often in digital but not in interoperable and exchangeable form provided. Thus, the collaboration between the principal and contractual partners is impeded. As result, the current state of the project, several planning consequences, execution problems and the project risk are often discussed on the basis of incomplete information (Scherer & Schapke, 2014, p. 4) Because of that, the so called "big open BIM" is desirable for the efficient collaboration within BIM-based processes. The term "big" is used, when BIM-Models are applied, and BIM-information are used over several domains. The term "open" means that the used software is from different vendors and the exchanged format is not proprietary. The terms "little" and "closed" mean the corresponding inverse, which are represented in the well-known analogy provided by Hannus et al. (1987/1998). In that metaphor isolated computational tools are depicted as Islands of Automation in the sea of building and construction (Figure 10). This well-known metaphor has established as common reference for a lacking interoperability in the construction industry.

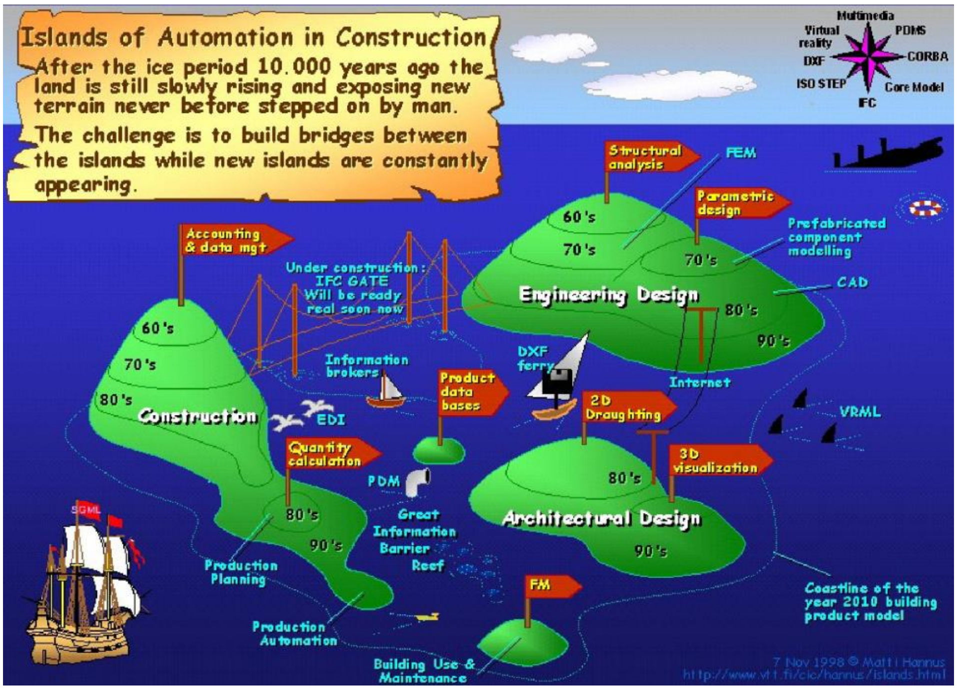


Figure 10: The metaphor Island of Automation (Hannus, 1987/1998)

The application of a digital building model through the whole life cycle shall, among others, reduce or pretend the loss of information and facilitate the early identification of mistakes during the planning process. (Borrmann, 2015, p. 602) The consistent storing of information in the digital building model enables simulations and calculations without expensive and error-prone repletion of entering of data. Benefits in the planning phase are, for instance, the clash detections, the checking for adherence of regulations and requirements and the simplified quantity-take-off. According to MacLeamy the application of Building Information Modelling yields to a shift concerning the effort in construction projects with respect to the phases of a building project. (see Figure 11) While in traditional design process the most effort is spent in the phase of construction documentation, the aimed BIM-based design process has the most effort in earlier design phases. Because of this, decisions can be made when the influence of costs is still big. Furthermore, effort-intensive tasks like quantity take off, simulations, etc. (see section about advantages of BIM) could be simplified using BIM and other tasks like modelling are getting more important and time-intensive. The exchange of information with a building information modelling yields to a change of processes concerning communication, cooperation and collaboration. Concerning the obstacles respective to the introduction of BIM, Naumann (2011) differs between organizational, technical, pricewise, juristic obstacles and user- and acceptance problems. One of the most important organizational obstacles is the adaption of the Honorar Ordnung für Architekten und

Ingenieure (HOAI), since the main effort of the planning process is earlier phases compared to the conventional planning process. Juristic obstacles are, for instance, legal obligations concerning the information in the model and safety of data and business secrets of the user. Beside of numerous benefits, the introduction of Building Information Modelling means also challenges, which must be faced. Only then, the whole potential of the integral usage of Building Information Modelling can be fully raised.

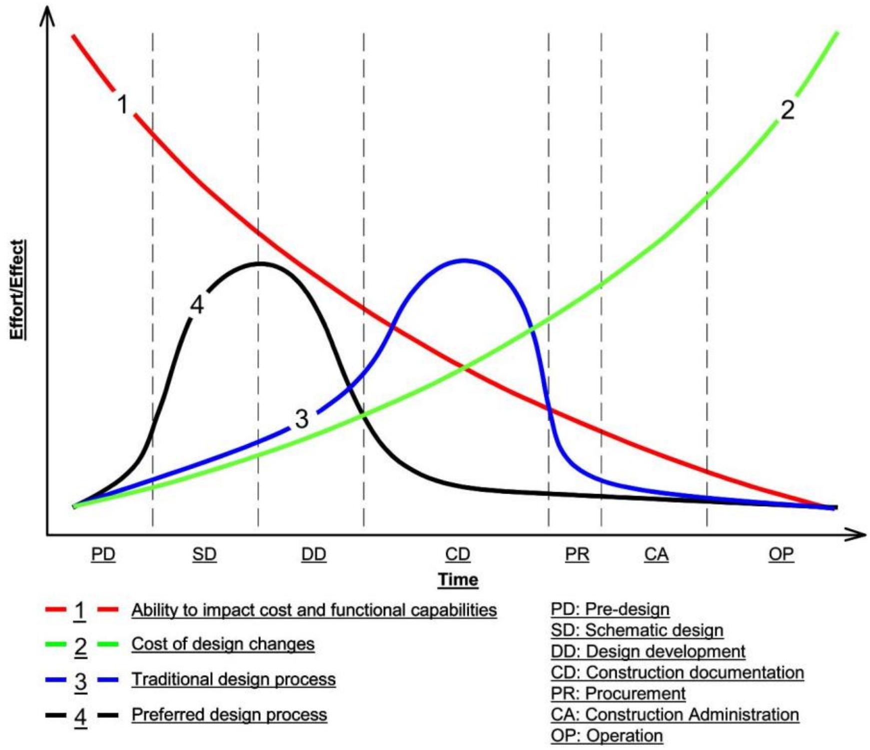


Figure 11: Influence of Building Information Modelling on spent effort during a construction project (MacLeamy, 2004, p. 8)

3 Basic theories and assumptions

Basic theories are covered in this chapter to provide the basis for the discussion and development of fuzziness visualizations. First, relevant basics concerning models are reviewed (General model theory, CAD-models and modelling, Building Information Models and Level of Development, procedure models). Additionally, a closer look on communication theory and design- and planning theory is provided.

3.1 Models and model theory

The usage of a three-dimensional digital building model including additional semantic information over all phases across several disciplines indicates to the ubiquitous presence of the concept model in the BIM-based planning process. However, a clarification of the concept is often missing, what can lead to misunderstandings and misinterpretations. Concerning a successful discussion of the planning- and design process based on Building information Modelling, there is the need to understand both: the CAD-Model and the procedure model.

3.1.1 Model theory

A clear definition of the term model without attention to a specific discipline is not available. According to Stachowiak (1973, p. 131) there exists three features describing a model, which are depicted in Table 3. The mapping feature states that the model is based on an original. For instance, the original could be the planned building itself or the processes which are needed to build it. The reduction feature means, that only a relevant selection of the originals properties is reflected by the model. The pragmatic feature says that a model needs to be usable in place of an original with respect to some purpose.

Since there are variety of purposes regarding the usage of a model, following categorization can be applied (Table 4): Demonstration models are used for the visualization of (less illustrative) context, experimental models serves for the verification of hypothesis, theoretical models convey logical insights about circumstances and procedure models (e.g. operative models) provide decision- and planning assistance (Stachowiak, 1973, pp. 138–139).

Table 3: Three features of a model according to Stachowiak (1973, p. 131)

Feature	Description
Mapping	A model is based on an original
Reduction	A model reflects only a relevant selection of an originals properties
Pragmatic	A model needs to be usable in place of an original with respect to some purpose

Table 4: Different kinds of models according to Stachowiak (1973, pp. 138–139)

Model	Purpose
Demonstration	Illustration of unclear context
Experimental	Verification of hypothesis
Theoretical	Logical insights about circumstances
Procedure	Assistance for decisions or planning operation

According to Stachowiak (1973, p. 139) an extension or simplification (also known as generalization and abstraction) of the original is necessary due to several reasons:

- To make the nature of the original clear
- When the modelling of the original is too complex, time-expensive, etc.
- When complex circumstances should be reduced, simplified or concretized
- When manifold facts should be explained or predicted by their basic context

In general, attributes of the original are excluded and new model attributes are included to extract the information respective to the original (Stachowiak, 1973, p. 139). General statements and regularities can be formulized on the basis of generalized models (Steinmann, 1997, pp. 67–68). The gained knowledge and insights can be transferred to the original and the model builder achieves new knowledge and insights respective to the modelled original. Subsequently, the model of the original can be modified regarding its purpose, such that the new model serves as improved tool for new operations (Stachowiak, 1973, p. 140).

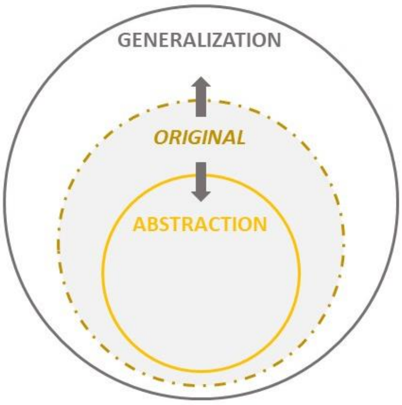


Figure 12: Abstraction and generalization of original adapted from Steinmann (1997, p. 68)

3.1.2 CAD-models and modelling

To create an external model from a mental model (*not* meta-model) in the model-based design process, the adequate model-elements from the domain-model have to be selected and adapted. The selection of the model-elements is determined by the intension of the user and the available elements in the element supply of the domain-model. The general model-elements will be concretized, and the mental model will be abstracted. The representation of the generalized and abstract elements is based on symbols, which can be associated to both the mental and domain model (Steinmann, 1997, pp. 68–69). This process is illustrated in Figure 13.

The before-thinking of building models is a complex task, which need to be controlled to achieve the project goals respective quality, costs and duration. According to Steinmann (1997, pp. 66–67) following techniques must be applied to face this complexity: the abstraction, decomposition and cooperation. The abstraction means the informal reduction of models, such that purpose-oriented design operations can be facilitated. The decomposition yields to structuration of the design problems. By that, a complex model can be decomposed in less complex partial models. Both the abstraction and decomposition are represented in Figure 14. The cooperation is based on the creation and interpretation of adequate representations to achieve a good coordination within communication processes.

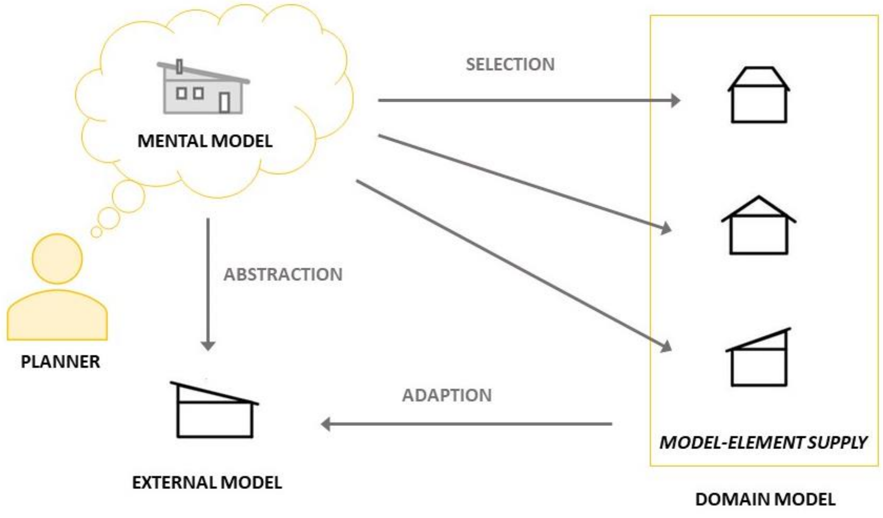


Figure 13: The creation of an external model by abstraction, selection and adaption (Steinmann, 1997, p. 69)

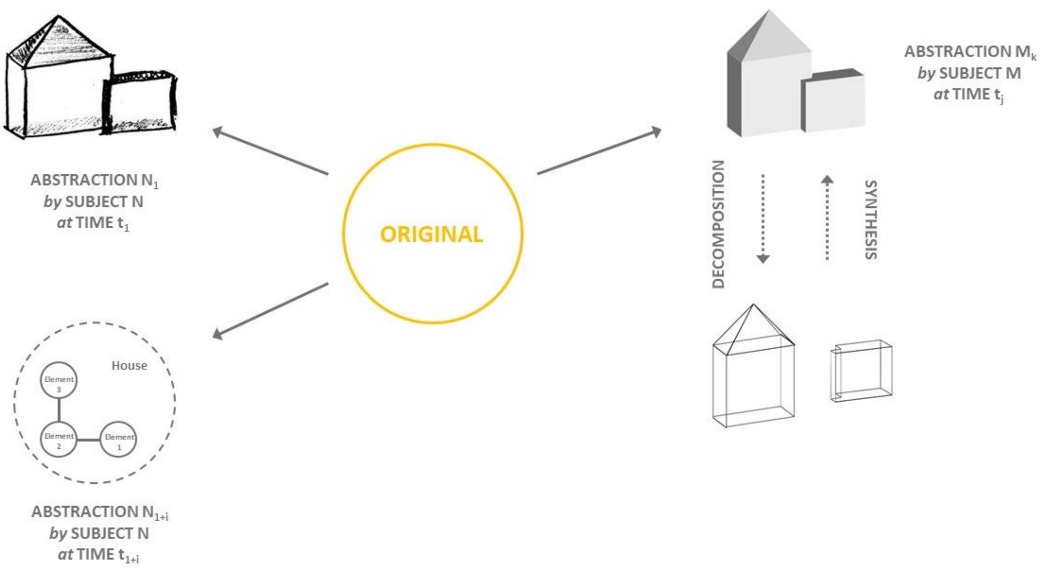


Figure 14: Abstraction of an original and its decomposition (Steinmann, 1997, p. 66)

Steinmann (1997, p. 68) distinguish between the building model, domain model and meta model, which are descriptively represented in Figure 15. The domain-model is a generalized model and the basis for product modelling. For example, boundary-representation models (B-rep models) are rather a general framework to create representation of concrete geometries than pure geometry models. B-rep models provide the basis for a variety of potential models. Next to B-rep models, this holds also for e.g. data definition languages (DDL) like EXPRESS, which is a basic schema for Industry Foundation Classes (IFC). The generalized models are provided by software-developers. The user's access to these models is very limited, since they can neither extend nor modify these generalized models. Furthermore, the users cannot read the generalized models from the software products (Steinmann, 1997, p. 68). The variety of expression means to explicitly represent a variety of domain models is called meta-model. The means of expression for the representation of domain- and object-models are not part of these models and have to be declared in the meta-model (Steinmann, 1997, p. 202).

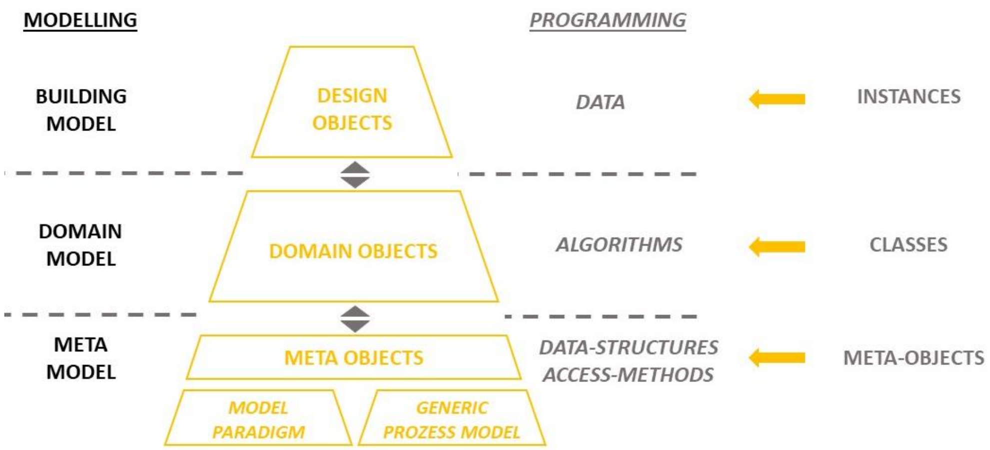


Figure 15: Relation of building-, domain- and meta-model according to Steinmann (1997, p. 103)

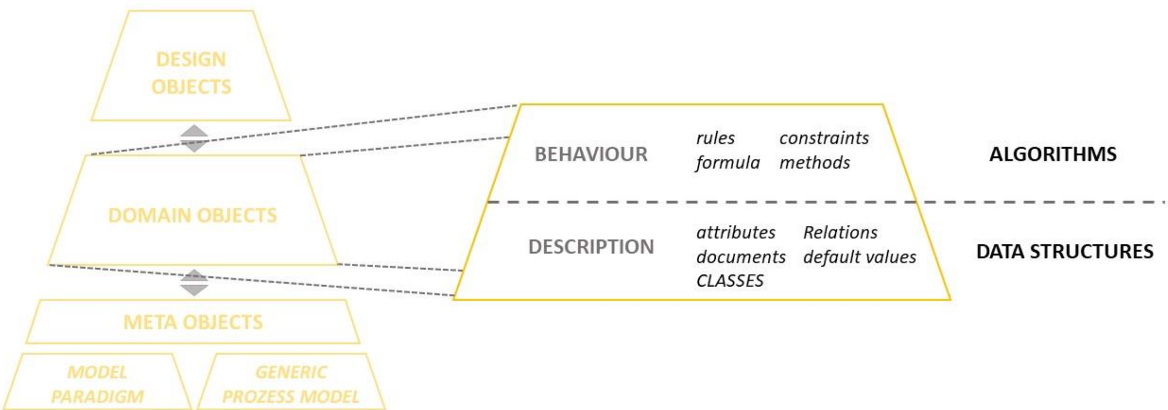


Figure 16: The Domain Objects according to Steinmann (1997, p. 102)

3.1.3 Building Information Model and Level of Development

A BIM-model represents an abstracted model regarding a specific discipline, since BIM-models are created by several domains and project members with different tools and different intension. In the literature, several different terms respective to BIM-models can be found: architectural model, structural model, product model, production model, energy model, simulation model, etc. According to Scherer and Schapke (2014) the application model is an umbrella term for models, which refers to a specific discipline. The meta data of application models can be structured by the concepts projects phase, model domain, status, detail and organization. A description of these concepts is provided in Table 5.

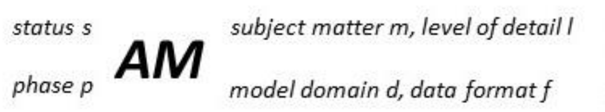


Table 5: Structuration of application models regarding meta data according to Scherer and Schapke (2014, p. 70)

Meta-Data Class	Description
Project Phase	Hierarchical classification of project phases (e.g. on basis of HOAI)
Model Domain	Classification of application models respective to software tool, model domain, data format and subject matter
Status	e.g. request, draft, approved, deprecated
Detail	Detail steps e.g. Level of Detail
Organization	Software tool, actor, created

Furthermore, Scherer and Schapke (2011, p. 586). write, that between different application models exists horizontal, vertical and longitudinal interdependencies. Horizontal interdependencies occur for instance, when in different domains the same objects with different discipline-specific information are represented. Vertical interdependencies describe the relation between two models with different detail levels. Longitudinal interdependencies are available between different versions of a discipline-based model.

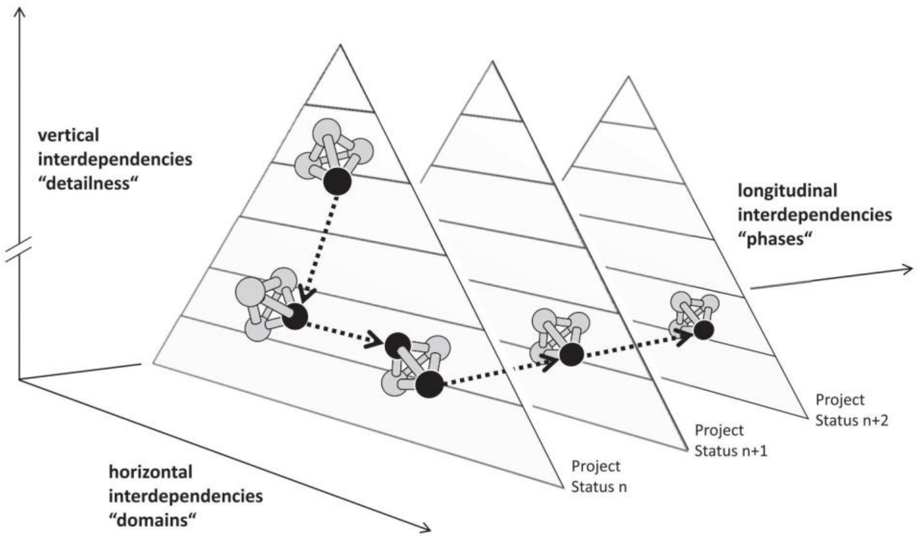


Figure 17: The interdependencies of application models (Scherer & Schapke, 2011, p. 587)

The detail levels are an integral part for the description of a BIM-model regarding the design and planning process. The specification concerning the detail level of a BIM-model can be described by several terms, which are based on the standards and guidelines in the respective country. In the year 2013 the British standard PAS1192-2 was published and the Level of Definition was introduced. The Level of Definition can be subdivided into Level of Model Detail, which refer to graphic content, and level of information, which refer to non-graphic content. These definitions were continued and further developed by NBS BIM Toolkit and the AEC(UK) BIM Technology Protocol. In Germany the Level of Development was suggested and published (BIMForum). In addition, in Australia the Level of Accuracy and the level of coordination were introduced. An overview of the developments concerning these BIM-based specifications are provided by Bolpagni and Ciribini (2016).

The models concerning the detail level of a BIM-model (e.g. level of development) are both generalizations and abstractions Figure 18: LOD model as generalized and abstracted model and its informational distance to BIM-model in terms of additional information of the BIM model. Comparable to the domain model, the LOD-model provide potential descriptions of a variety of models and contain rather a framework for the description of semantic and geometric models than a specific description of geometry and semantic. Thus, a LOD-model can be seen as generalization. Additionally, the LOD-models are abstractions of the original, since the LOD models is an informal reduction of the original model and reflects only a relevant selection of the original semantic and geometry. Due to the abstracted character of the LOD-model, the external

BIM-model can contain more information than the required LOD-model. The result is an informational distance in terms of additional information between the BIM-model and the required LOD-model.

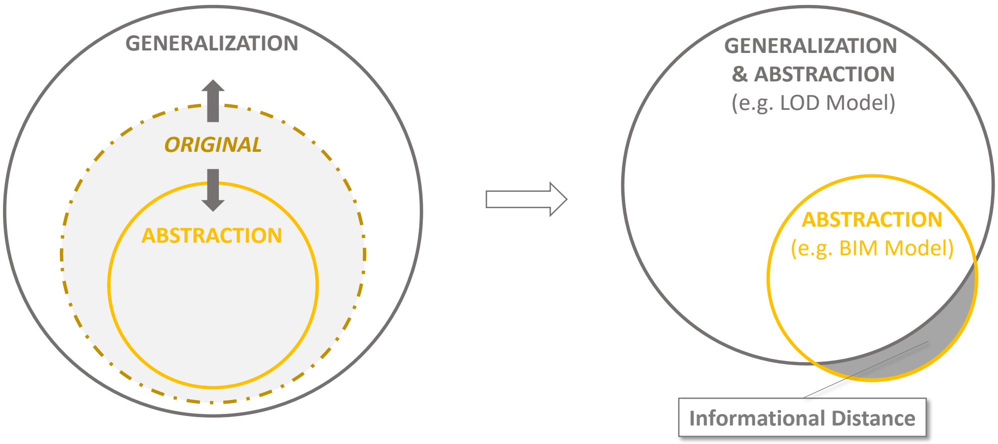


Figure 18: LOD model as generalized and abstracted model and its informational distance to BIM-model in terms of additional information of the BIM model

3.1.4 Procedure models

A definition of procedure models is provided by Lindemann (2009, p. 49), who discuss the procedure models regarding product development: Procedure models are models which illustrate important elements of operation sequences and can be used for the support of planning and controlling of processes. The user has an assistance to realize at which step of the process he is operating and which steps are next. The distinction between procedural models and methods is often omitted, but significant for the prevention of misunderstandings. According to Lindemann (2009, p. 58), the procedural model address the question „What to do?“ and are formulized more general and problem independent. The procedural models describe which steps have to be done. In contrast to that, methods describe “How to do?” and are problem-oriented. Methods address often a specific application and describe in which way the steps have to be carried out. However, the boundaries of the distinction between procedural models and methods are not defined exactly.

A model is an abstract or generalized representation of the original with respect to a specific purpose. Concerning procedural models, the particular purpose differs concerning the period under preview. For instance, procedure model can represent sequences of elementary thinking or operation processes in a fraction of seconds (micro-logic). In contrast to that, procedural models can represent the coarse processes of a whole project to create an overview of the undertakings (macro-logic). In between of macro- and micro-logic models, are procedure models which address operative working sequences and coarser working phases (Lindemann, 2009, p. 38). The selection of the adequate granularity of the procedural model depends on the user's intension. Common procedural models in the BIM-based planning process address in general rather on macro- than on micro-logic. For instance, the proposed VDI definitions assign level of details to the coarse planning phases according to the *Honorarordnung für Architekten und Ingenieure* (HOAI). Another example are the Business Process Model and Notation maps to represent the information flow within the BIM-based planning process. However, a model respective to the operative steps within the BIM-based design or planning process could not be found (Figure 19).

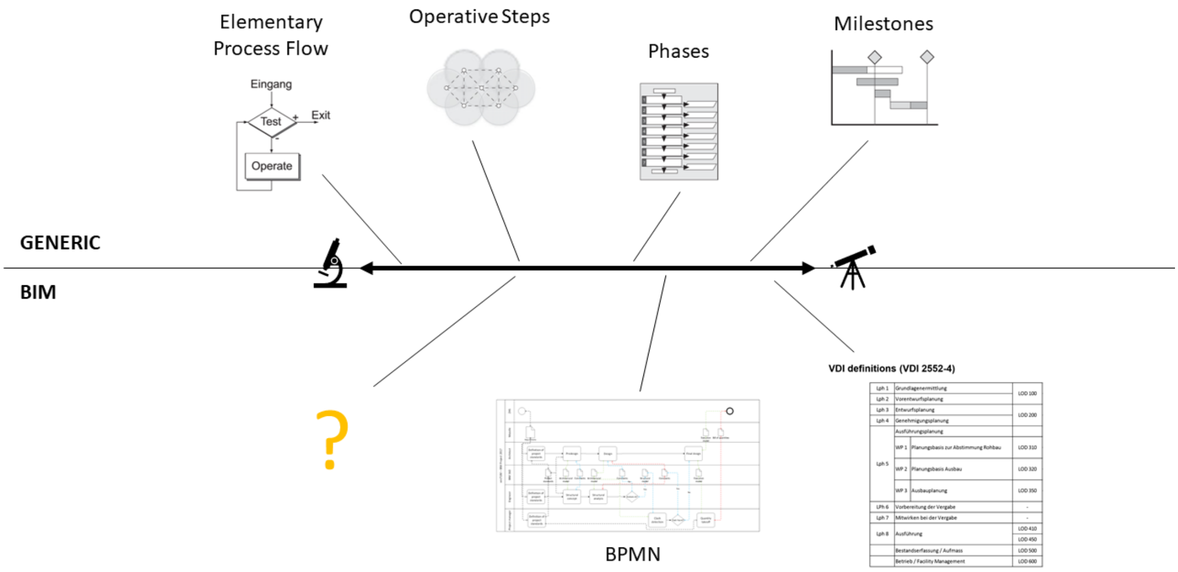


Figure 19: Micro- and macro-logical procedure models of the BIM-based design- and planning process adapted and extended from Lindemann (2009, p. 51)

3.2 Design- and planning theory

The design theorist Rittel (1972, p. 392 et. seqq.) distinguish between the first and second planning generation**.** The basic assumption of the first planning theory is a rational and objective acting human. If all necessary information is provided, the optimal alternative can be found due to rational decisions. Additionally, the first generation assumes that the problem formulation and the problem solution are phases, which can be handled separately. However, the requirements for the successful planning process in accordance with the idea of the first planning generation was revealed as unrealistic and criticism raised. While the first planning generation assumes planning problems as well-defined, the second generation address rather ill-defined problems. Well- and ill-defined problems are described in the section below. An underlying statement of the second generation was the assumption that an ill-defined problem is uniqueness and thus a transfer of planning process or models is not possible. The theories from the second generation are considered either as too general or as too specific. Too general because there is a lack of differentiating between subtasks of planning process, e.g. operation or ethic. The theories are too specific for an holistic integration and systematic relation of planning aspects (Schönwandt, 2002, pp. 30–36). Therefore, Schönwandt (2002, pp. 35–36) proposes a third planning generation, which covers the content-related aspects (e.g. spatial, social, economic, ecological aspects) and excludes restrictions concerning the intellectual capacity, perception and possibilities of interventions of the planner. In addition, the third planning generation refers to semiotic, epistemic and ethical components of planning. The systemic theory is primarily based on Claus Heidemann and Jakob Uexküll and was applied successfully as assistant methodology in the planning process. For instance, Schmid (2015) made use of the general system theory to show, “how functional integration as an indication can be used in design and assessment in order to identify stringent solution alternatives early and targeted in the planning process.” (Schmid, 2015, xi)

Every planning process starts with a declarative task- or problem specification. Regarding a task specification, the applied procedures and models are known previously. Concerning a problem specification, the means and methods have to be elaborated (Schmid, 2015, p. 8). The decomposition of problems and the following synthesis of the particular solution does not mean an adequate holistic solution. These circumstances can be illustrated by the concept “Muddling Through” from Lindblom (1959, p. 79 et. seqq.), which indicates that solving successively particular problems does not solve the whole problem. In general, architectural design and planning problems can be categorized into three groups: well-defined problems, ill-defined problems and wicked-defined problems (Rowe, 1991). Comparable to that, Chandrasekaran (1990) uses the terms Class3-, Class2- and Class-1 Designs and Karbach and Linster (1990) discusses Routine-, Innovative- and Creative-Design. The well-defined problems were the subject of the first planning generation, where the assumption was made that the rational, objective human can solve all problems, given all information are available. The goal of the problem-solving process is clearly defined, the problem itself is accurately determined and the approaches to achieve the goal are known. An example for well-defined problems are board games or linear equations. These kinds of problems provide the potential to automate the problem-solving process. Ill-defined problems occur, when the solution procedure and goals of the problem-solving process are not determined previously. Depending on the analyzation of the problem, the problem goal can be defined and, subsequently, problems solutions are created. These solutions refer directly to the current problem and not to the initial problem, what leads to solution revisions and the iterative character of the planning process. For instance, ill-defined problems in the design process appear, when the design result is not sufficiently determined by the provided instructions. Wicked problems cover problems, which are less precise determined than ill-defined problems. The specifications of wicked problems according to Rittel are listed in Table 6.

Planning is influenced by biological and psychological properties, the social and cultural environment and organization and cooperation's of the planner. Furthermore, the planner is restricted by the selective and section-based perception and cognition. There are also limitations for our capability to think and to act. The latter one means that we are not able to modify everything we want to modify. These restrictions are often not considered in planning models of the second generation. (Schönwandt, 2002, pp. 36–37) Design- and planning models as procedure models have the purpose to assist the planning individual by the representation of the basic process steps. An operative procedure model shows the operational steps and serves rather as orientation than as obligate procedure for the designer or planner. In the chapter 1.6.2, the analysis, synthesis and evaluation step were determined as three common steps of several operative procedure models. In accordance to these steps, Grunwald (2006) mentions three planning problems: Information-, synthesis- and evaluation-/ decision problem. A lack of information and knowledge exists from the beginning to the end and is called information problem. This problem can be reduced by the application of several analysis. By the combination of tacit and explicit knowledge the requirements of the creation of objective-oriented variants and alternatives can be provided. Comparable to the rule no. six from the characteristics of wicked problems, there are an uncountable number of different variants and alternatives, what results in the synthesis problem. Within the synthesis process, the most objective-oriented possibility has to be chosen from an uncountable variety of different possibilities. As a result, the selection of the most object-oriented variant or alternative is difficult to achieve. After the creation of potential solution, the most objective-oriented ones have to be compared based on several criteria. These criteria can be in conflict, what results in difficulties to evaluate and decide for an adequate potential solution. Additionally, subjective criteria are often significant for the decision-making, what is not desirable. Thus, in the last step, the evaluation- and decision problem is relevant.

Table 6: Specifications of wicked problems according to Rittel and Webber (1973, pp. 161–167)

1	There is no definite formulation of wicked problem
2	Wicked problems have no stopping rule
3	Solution to wicked problems are not true or false, but good or bad
4	There is no immediate and no ultimate test to a solution to a wicked problem
5	Every solution to a wicked problem is a ‘one-shot operation’
6	Wicked problems do not have an enumerable set of potential solutions
7	Every wicked problem is essentially unique
8	Every wicked problem can be considered to be a symptom of another problem
9	The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problems resolution.
10	The planner has no right to be wrong

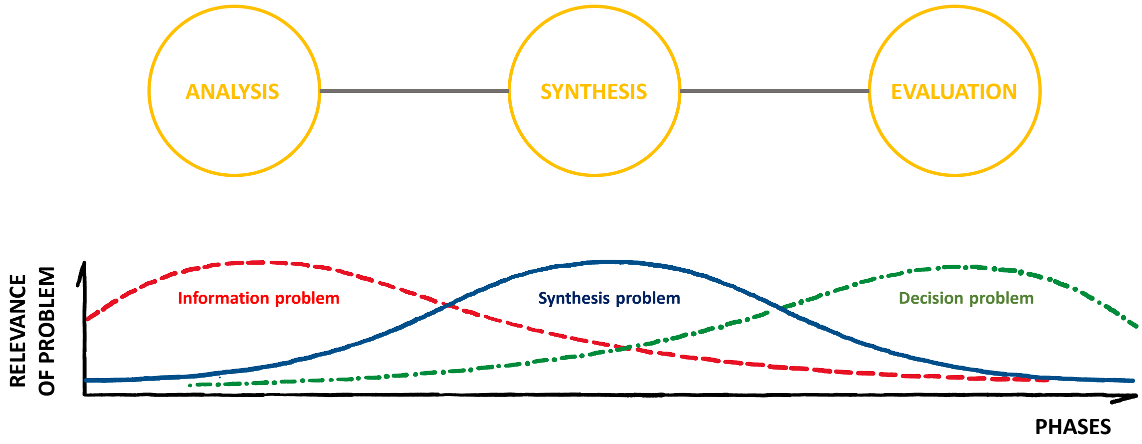


Figure 20: Relevance of problems during the operative planning process adapted from Schmid (2015, p. 9)

3.3 Communication theory

Riklef Rambow (2012) describes Architecture among others as a social process, which take place between many different involved actors. The result depends on the quality of communication between these actors (Hahn, 2012, p. 103). In a building project the architect creates a mental image of a future building in his mind. The architect communicates this mental image to several other involved persons from different disciplines with the use of media like plans or models. The demands for useful information differ from person to person. Furthermore, the different involved persons have different perspective concerning the building itself: For “a bricklayer it is the result of stacking quantities of bricks upon each other. The energy consultant sees a house as a shell around comfortable climatic zones and the owner defines it as the source of monthly revenue from renting it out.” (Beetz, 2009, pp. 13–15)

One important contribution to the field of communication research was Shannon and Weaver’s Mathematical Theory of Communication (Weaver, 1953). Further communication models were established, e.g. the models from Gerbner (1956), Lasswell (1948), Newcomb (1953), Westley and MacLean (1955), Jakobson (1960), which focus on the process of communication. The number of different models mentioned here indicates to the complexity of communication research. The following section focus on the model of Shannon and Weaver since their model is easy to understand and was the basis for further elaborations in the field of communication theory. The research of Shannon and Weaver was done in the Bell Telephone Laboratories during the second

World War, with the aim to send a maximum amount of information along a given channel. The model they have developed is depicted in Figure 21. During their study Shannon and Weaver have identified three levels of problems: The *technical problem* concerns the issue about how accurately the symbols of communication can be transmitted. The issue how precisely the transmitted symbols convey the desired meaning are called *semantic problems*. And the *effectiveness problems* address the question how efficiently conduct the received meaning affect in the desired way. The model of Shannon and Weaver take account of encoding the meaning in the message but does not consider that the culture plays an important role concerning the correct interpretation of the message (Fiske, 1990, pp. 6–7).

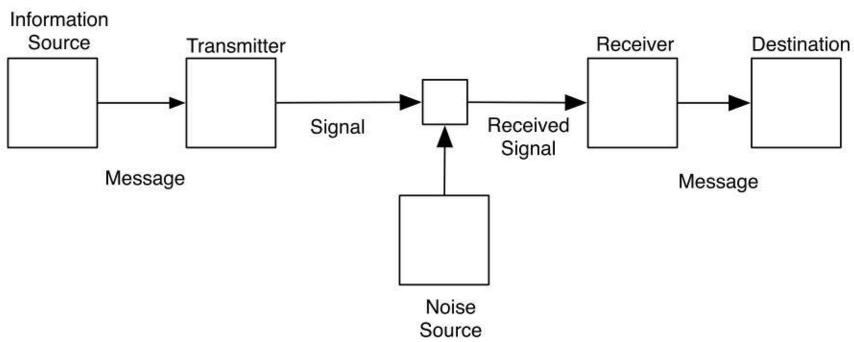


Figure 21: The communication model by Shannon and Weaver (1953)

The models mentioned in the section before consider communication as a process. Additionality, communication can be handled as the generation of meaning with the use of symbols. In contrast to the previous models, the models with focus on that generation are not linear but structural. That means they don't deal with a series of steps a message has to pass. The most influential models are the models from C.S. Pierce (1931-58), Ogden and Richards (1923) and Ferdinand des Saussure (1915/2011). The models of Peirce and Ogden and Richards (which are very similar) are based on a triangle structure, which consists of the three points: the symbol, the object to which it refers and its users. This triangle is also known as semiotic triangle and the one from Ogden and Richards is depicted in Figure 22. Each point of the triangle "is closely related to the other two and can be understood only in terms of the others." (Fiske, 1990, p. 41) In contrast to Peirce and Ogden and Richards says Saussure that "the sign consists of its physical form plus an associated mental concept, and that this concept is in its turn an apprehension of external reality." (Fiske, 1990, p. 41) The model of the semiotic triangle consists of 1:1 relation between signs, concepts and objects.

But in the real world, there can exist for one symbol more than one concepts and objects. Thus, a more realistic model would represent m:n:o relationships (Dengel, 2012, p. 13). Therefore, each edge of the triangle is prone to be the source of ambiguities and misunderstandings. For instance, depending on the mood or the environment of the receiver, the interpretation of symbols can be different (Dengel, 2012, p. 13). In communication theory, the amount of information in a document would be quantified by the number of possible messages or meanings that the document can be shown to contain (Lobel, 2008, p. 21). Concerning the impact of semiotic in the architecture, there exists several researches. For example, Umberto Eco (1972) transfers the studies of semiotic to the field of architecture. And a connection between semiotic and aesthetic was established by Bense (1965).

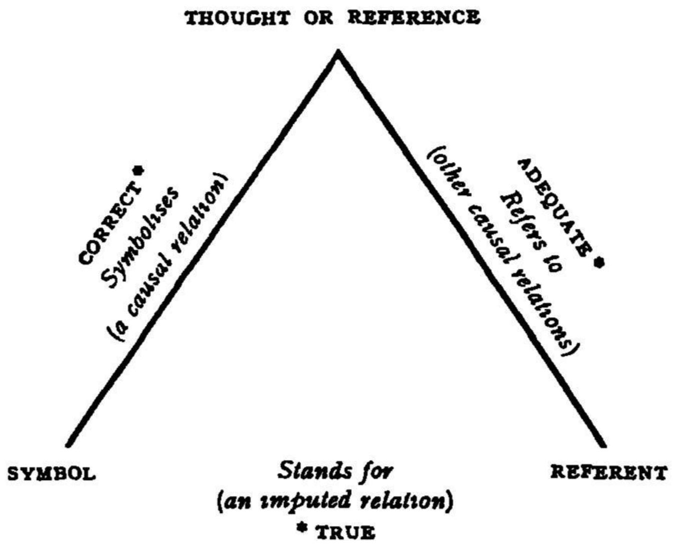


Figure 22: The semiotic triangle by Ogden and Richards (Ogden & Richards, 1923, p. 11)

For the term *Thought of reference* from the semiotic triangle according to Ogden and Richards (Figure 22) exists several synonyms. One of them is the term *construct*, which will be used in the further thesis. As explanation of constructs serves Figure 23, where different symbols are depicted. We have learned in our childhood that these symbols represent the number seven. The number seven is the construct, since the number exists only in our mind. Constructs are limited, preliminary, variable and depend on the context. During the time there are sometimes changes regarding the meaning of constructs. For example, a “train station” was earlier only associated with the arrival and leaving of trains and their travelers. Today a train station involves also supermarkets, bakeries, etc. Similar developments exists for further constructs in building sector (Schönwandt, 2002, p. 134). An important property of concepts (in German: “Begriffe”) like train station, is that they cannot be tested for truth, because they neither assert nor deny anything. “Concepts can only be exact or fuzzy, applicable or inapplicable, fruitful or barren.” (Bunge 1996, p. 49) Among others these properties of constructs and concepts result in several errors in the communication in a collaborative planning process among different disciplines (Schönwandt, 2002, p. 134).

Figure 23: Several symbols for one construct according to the example from Schönwandt (2002, pp. 63-64)

The transfer of Information is always combined with a certain purpose. One requirement for a successful communication is a shared knowledge base, which Rambow (2012) calls “common ground” (Figure 24). The actors must see very fast what the communication partner knows (previous knowledge) and how his or her perspective looks like. These assumptions are often made with uncertain information. As result the previous knowledge is sometimes underestimated, which leads to redundancy and tediousness. On the other hand, the consequences of an overestimated previous knowledge are misunderstanding and frustrations. There are two possibilities for having a positive influence on a change of perspective: Either the “common ground” can be extended or the willingness for a change of perspective can be improved. The sentence “you only see what you know” is an exemplary expression for that issue (Rambow, 2012, pp. 111–113). For illustration of the huge effort, which is to spend for communication due to a missing “common ground” and ambiguous information, the Toolmakers Paradigm from Reddy (1979/1993) can be used (Figure 25). In each sector of the circle exists a slightly different environment and one inhabitant. They can only communicate to each other by delivering sheets of paper using the hub in the middle of the sectors. The inhabitants use it to make tools which are useful for their survival. Without the knowledge about the other sector, effort is needed to overcome the failure of communication. Lobel compares the toolmakers paradigm to the interoperability within the AEC industry with respect to BIM and points out the analogy to common building information modelling representations (Figure 26) (Lobel, 2008, pp. 57–60).

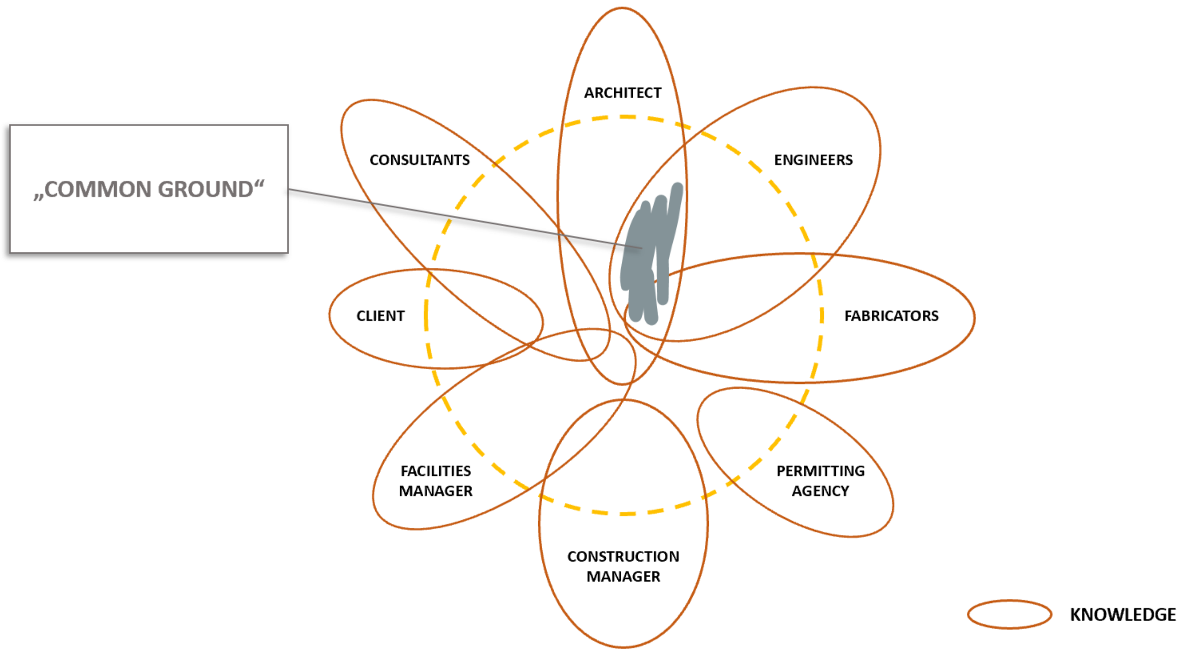


Figure 24: Illustration of the "common ground" between AEC-project participants

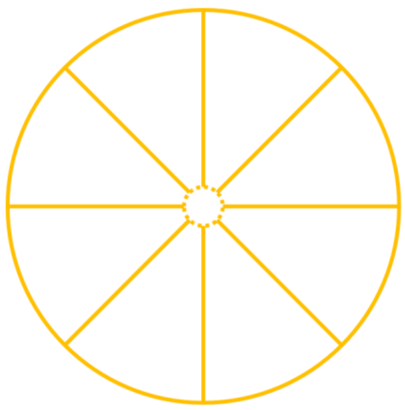


Figure 25: The Toolmakers Paradigm according to Reddy (1979/1993)

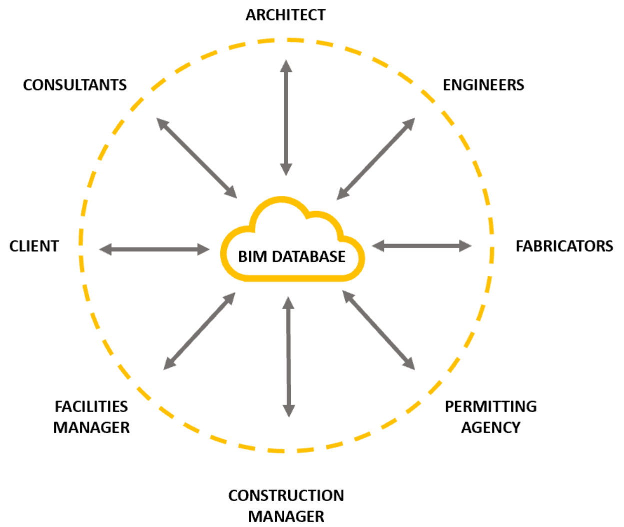


Figure 26: Simplified and common representation of BIM-based collaboration

4 Nature of fuzziness

The following chapter provides a literature review concerning conceptualization of fuzziness, fuzziness in scientific visualization, fuzziness in CAD-based design process and fuzziness as part of models describing the level of detail regarding BIM-models. The literature review is used to derive assumptions concerning the categorization and characterization of fuzziness. Besides the research regarding visualization approaches, the fuzziness categorization and characterization is an integral part for the development of an adequate fuzziness visualization.

4.1 Conceptualization of fuzziness

Since a general conceptualization does not exist, the terms fuzziness and uncertainty were conceptualized for the scope and context of the thesis (see chapter 1.6.3). With respect to the previous conceptualizations, uncertainty refers to future events and fuzziness refers to objects like models. However, in the literature this distinction is in general not available. Thus, the literature review of that chapter covers both fuzziness and uncertainty.

The terms uncertainty and fuzziness are often conceptualized as missing or incomplete knowledge. However, the designation *incomplete knowledge* is prone for misunderstandings, because only available knowledge can be used for the solution finding process. Thus, the term fuzziness involves rather incomplete data or information than incomplete knowledge (Steinmann, 1997, p. 99). Additionally, for conceptualization in terms of incomplete knowledge, there must be distinguish between the facts that somebody knows that he doesn’t know, that somebody doesn’t knows that he doesn’t know and that somebody doesn’t know that he knows.

The discussion of the term uncertainty is significant for all kinds of scientific fields. In the field of informatics, the uncertainty is important for learning and decision-supporting systems. Logic and Mathematic are confronted with uncertainty when they calculated with formal logic systems, which shall be complete and consistent. In the psychology the term uncertainty is used when a human is in new and unfamiliar situations and, based on this, behavior patterns are deduced. A decision under uncertainty is a major phrase in the field of decision theory, which is applied in several subject areas. The decision theory is mainly used in economic and business science, which develop stable management-models for the increasing complex environment to achieve better predictions. The social science and humanities use uncertainty with respect to types of discourse and value systems. Thus, a conceptualization, modelling and analysis of the term uncertainty is based on the subject areas and interests. The answer to the question *how a conceptualization and modelling across the disciplines could be achieved* and *how "patterns of uncertainty" across disciplines could be described* are major research fields (Jeschke, Jakobs, & Dröge, 2013, pp. 7–8).

In addition to the conceptualization of fuzziness in chapter 1.6.3, a further subdivision of that umbrella-term is useful to prevent misunderstandings. In the literature, a variety of further categorizations of fuzziness can be found: According to Forte (2002) three concepts respective to fuzziness can be distinguished and are descriptively represented in Table 7. Fuzzy data means that a set of data is inexact. For instance, when that set of data differs from reality. Fuzzy parameter is one single value that is inexact, i.e. differs from reality. Fuzzy linguistic variable means that a symbol, term or group of words can be interpreted differently (ambiguity) or that a state is not sufficiently differentiated from other (vagueness). According to Hawer et al. (2018, p. 53) fuzziness can be attributed to both quantitative and qualitative reference objects (Table 8). Quantitative means that the reference objects are measurable (e.g. heat, etc.) and qualitative refers to non-measurable reference objects (e.g. aesthetics, etc.). Reder (1995, pp. 12–13) concludes from Kruse (1993), Kudraß (1991) and Altrock and Zimmermann (1993) that fuzziness can be classified in imprecision, vagueness and uncertainty (Table 9). The concept imprecision is used in terms of the perception of the environment. A synonym for imprecision is sensorial fuzziness. The concept vagueness means the reduction of information to its essential basics to facilitate the communication. This can address both content-related fuzziness (e.g. "fast" car) and informational fuzziness (e.g. "creditworthiness"). The purpose of the latter one is to reduce a complex concept to one word. The purpose of content-related fuzziness is to avoid exact specifications. The categorization of fuzziness in the design process according to Steinmann (1997, p. 96 et. seqq.) is reviewed in chapter 4.3.

Table 7: Distinction between fuzzy data, -parameter and -linguistic variable according to Forte (2002)

Concept	Description	Example
Fuzzy data	*Set of data that is inexact*	Differs from reality
Fuzzy parameter	*One single value is inexact*	Differs from reality
Fuzzy linguistic variable	*a) Varying perceptions regarding the meaning of symbol, term or group of words* *b) state which cannot sharply differentiated from other states*	a) Ambiguity b) Vagueness

Table 8: Distinction between qualitative and quantitative reference objects according to Hawer et. al. (2018, p. 53)

Fuzziness	Description	Example
Qualitative	*Non-measureable reference objects*	aesthetics
Quantitative	*Measureable reference objects*	heat

Table 9: Subdivision of fuzziness into imprecision, vagueness and uncertainty according to Reder (1995, pp. 12–13)

Fuzziness	Description	Example
Imprecision	perception of the environment	Sensorial errors
Vagueness (linguistic)	the reduction of information on essentials to facilitate the communication	Content-related (e.g. fast car); informational (e.g. creditworthiness)
Uncertainty	*(not covered)*	(not covered)

4.2 Fuzziness in scientific visualization

The field of scientific visualization address rather the representation of physical data than the representation of abstract data. Pang et al. (1997, p. 372) illustrates by the visualization pipeline (Figure 27) the accumulation of uncertainty over the stages acquisition, transformation and visualization. Pang et al. (1997, p. 371) define uncertainty as statistical variations or spread, errors and differences, minimum maximum range values, and noisy or missing data”. This broad definition intersects with the definition of fuzziness made in chapter 1.6.3.

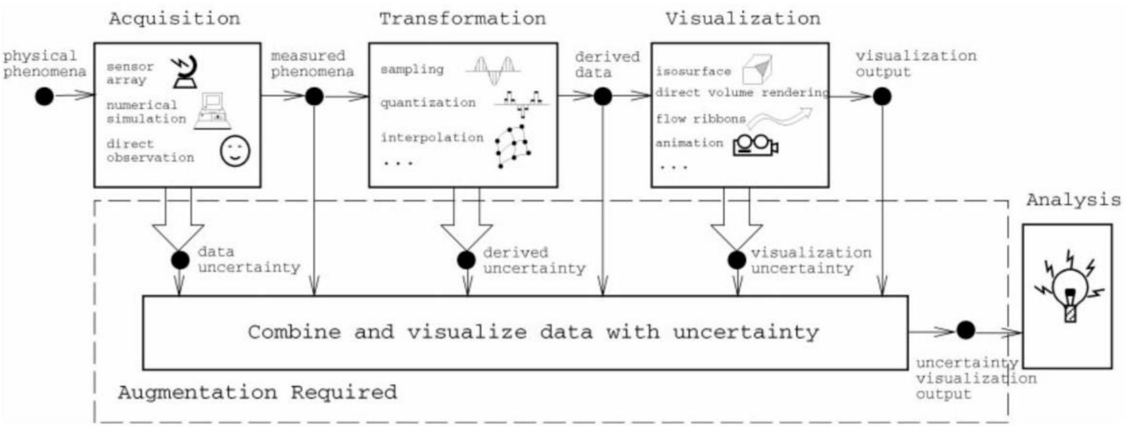


Figure 27: Visualization Pipeline for illustration of uncertainty (Pang et al., 1997, p. 372)

Respective to the acquisition of data in the field of scientific visualization there is a variation of data sets from instrumental measurements, numerical methods and statistical variation of data entry (Chatfield, 1983/2018). When measurements are taken by a machine or person there exists experimental variability. This variability is based on statistical variation and the number of taken measurements. In numerical modeling “the model and its parameters have been decided by a domain specialist, and they are inherently a simplification (e.g., linearization of a nonlinear system) of the system being modeled. [..] there is variability in human observations, in terms of both difference in perception among individuals and slight differences in performing a task repeatedly” (Pang et al., 1997, pp. 371–372). Bonneau et al. (2014, pp. 5–6) describes the uncertainty in data as the accumulated data through a sampling process, which might give the appearance of too little information, too much information, or information that just cannot be trusted. The sources of these derivation can be “noisy data, noisy instruments, human error in the data gathering process, or sampling at a scale different that natural to the phenome” (Hansen, Chen, Johnson, Kaufman, & Hagen, 2014, pp. 5–6). Another reason for data uncertainty can be contradictory values or metadata about a data source. Examples for fuzziness as consequence from a data source are old data sources, untrusted sources or a non-standardized process as a source (Bonneau et al., 2014, pp. 5–6). After the acquisition of data, the data will be transformed instead of rendering directly. These data transformations alter the original form of data and could involve the conversion from one unit of measure to another unit of measure or more complex tasks like the application of algorithms. Altering data can occur in different stages of the visualization pipeline (Pang et al., 1997, p. 372). An example for uncertainty in the visualization process is the global illumination of 3D scenes, which is based on radiosity algorithms. The rendering process contains uncertainty concerning data collection, algorithmic errors and computational accuracy. Another example for uncertainty in the visualization process is the volume rendering of 3D data sets. Depending on the approach for the rendering process the results differ slightly from each other. Further examples are the surface approximation dealing with scattered data sets, interpolation in taking slices through data sets (Pang et al., 1997, pp. 372–373).

4.3 Fuzziness in CAD-based design

Steinmann (1997) discuss in his doctoral thesis the modelling process in Computer Aided Design (CAD) and covers (not exhaustive) fuzziness respective to the process of modelling and models. Here, the term fuzziness is defined as the "informal distance to the degree of the complete and accurate description, which can be achieved in a particular model world"[6] [Translated by the author] (Steinmann, 1997, p. 96). Fuzziness can be categorized in three main classes: operation-oriented, goal-oriented and model-oriented fuzziness (Steinmann, 1997, p. 96). The model-oriented fuzziness can be further subdivided into several classes (Figure 28). In the doctoral thesis from Reder (1995) the attributive fuzziness respective to CAD-models is discussed. The fact that this dissertation covers one subcategory of fuzziness in the design process, indicates to the complexity of fuzziness in the CAD-based design process.

The operation-oriented fuzziness is related to the organization of the design process. The organization of the design process does not cover modifications of the model and are not depicted in formal-logic models, since the outcome of the design is independent from the sequence of design actions. The organization of design processes contains,

[6] *Original*: „Unschärfe ist der informationelle Abstand zum Grad der vollständigen, exakten Beschreibung, der in einer bestimmten Modellwelt erzielt werden kann.“ Steinmann (1997, p. 96)

among others, technical resources, working hours or time constraints. An example for operation-oriented fuzziness is the submission of an incomplete design due to time limitation and pressure. However, researches respective to the operation-oriented fuzziness is rarely available (Steinmann, 1997, p. 62 and 95). Due to contractionary criteria, the evaluation and selection of one variant or alternative in the design process is problematic and results in goal-oriented fuzziness (Steinmann, 1997, p. 95). The model-oriented fuzziness refers to the model itself and can be subdivided into syntactical and semantical fuzziness. Syntactical fuzziness is model-information, which cannot be formulized, or their formulization is too complex. The syntactical fuzziness is based on the character of the model itself. These information can be included in the model by the description in terms of textual communication approaches (Steinmann, 1997, pp. 95–96). In contrast to syntactical fuzziness, semantical fuzziness does not depend on the character of the model itself and can be represented in the external model (Steinmann, 1997, pp. 95–96).

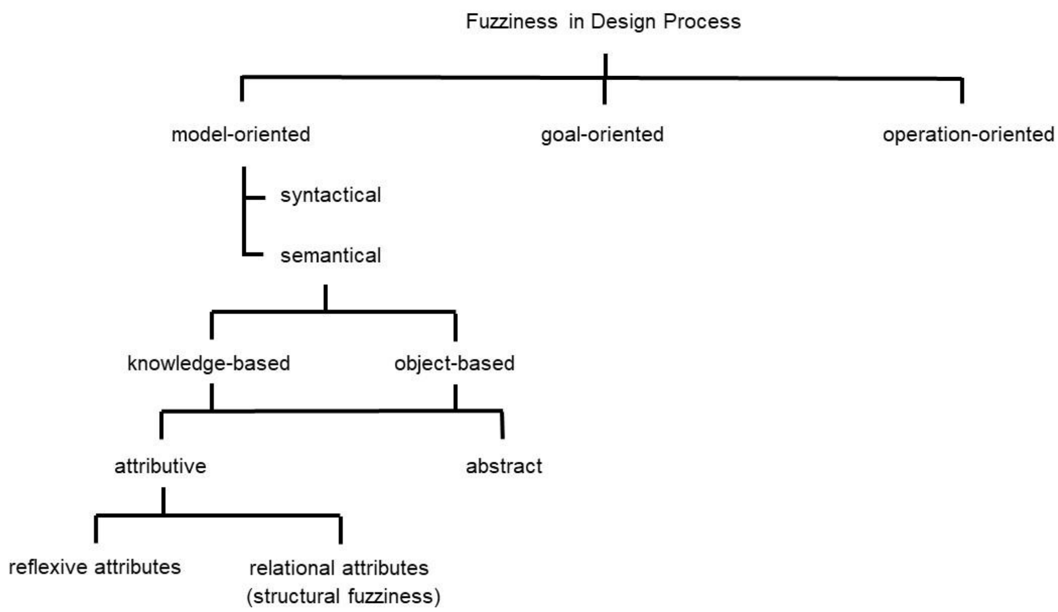


Figure 28: Categorization of fuzziness in design adapted from Steinmann (1997, p. 96) [translated by the author]

Semantical fuzziness can be further subdivided into knowledge-based and object-based fuzziness. The origin of knowledge-based fuzziness is the lack of knowledge or information, which is especially available in early design phases. The information problem within an operative planning process exists during the whole procedure and can be reduced by several analysis and reviews. The object-based fuzziness results from the characteristics of the available objects or the object-based programming paradigm itself. Further classification of both knowledge-based and object-based fuzziness can be achieved by use of attributive and abstract fuzziness. Attributive fuzziness arises by defining a property of an object in an application model. For instance, an object can have one exact attribute for a property, an attribute out of a set of attributes or no attribute. The abstract fuzziness is based on the concretization of abstract classes during the design process, since a design process goes in general from the abstract to the detail. Thus, an abstract class does not contain the same amount of information like detailed class and are fuzzier than such classes which are created in later design phases (Steinmann, 1997, p. 100) (Figure 29). Structural fuzziness refers to relations between objects. One object could be assigned to a variety of different objects. For instance, the roof could be related to one of a set of floors (ground-, first- or second floor) (Figure 30). When the set of reference objects is missing, then the relation is incomplete (Figure 31).

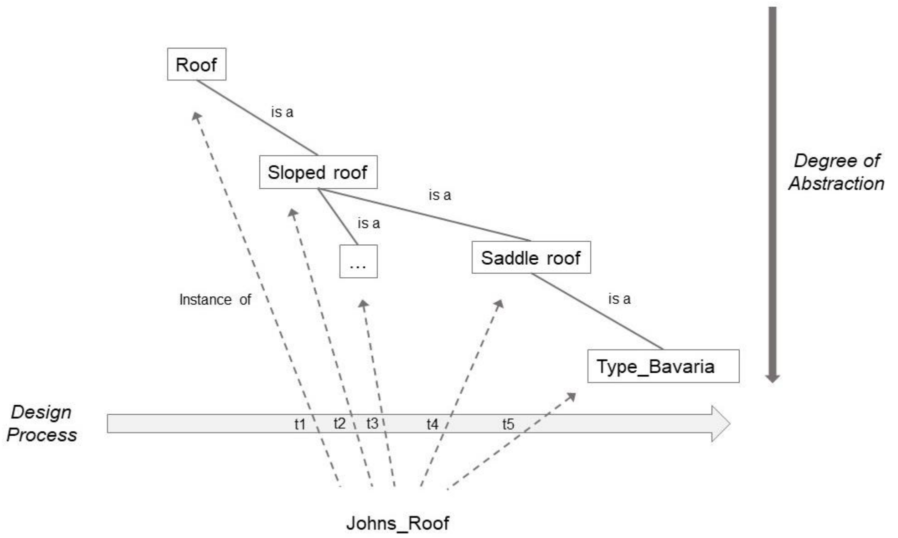


Figure 29: Classification as abstraction fuzziness according to Steinmann (1997, p. 100)

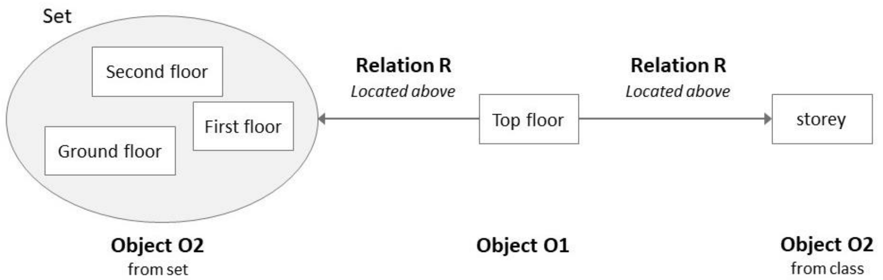


Figure 30: Structural fuzziness (Steinmann, 1997, p. 99)

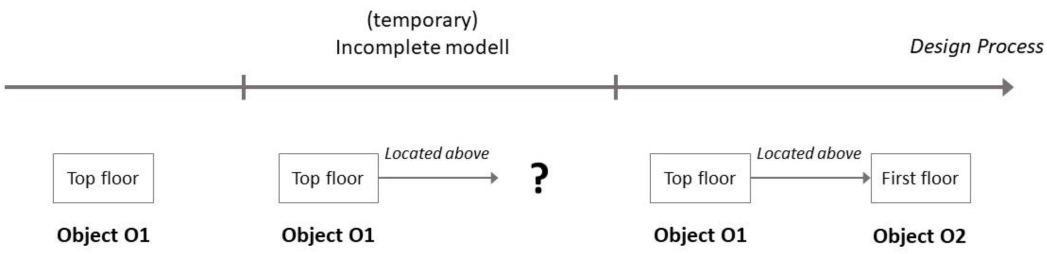


Figure 31: Structural incompleteness (Steinmann, 1997, p. 99)

4.4 Conclusion and further assumptions

Based on the literature review concerning the basic theories and fuzziness, assumptions for the categorization and characterization of fuzziness in the design process were made to accomplish a suitable fuzziness visualization. These assumptions are rather first ideas and attempts, than proposals for the categorization of fuzziness regarding a generic purpose. Thus, referencing this chapter should be done carefully.

4.4.1 Categorization

During the planning process the task- and problem formulation is analyzed, alternatives and variants are developed, and different alternatives and variants are evaluated to come to a decision for a potential solution. Since planning problems are wicked problems and the solving process is influenced by several characteristics (e.g. social and cultural environment, selective perception, selective cognition, etc.), the operative planning process is an iterative and complex procedure. Due to explanation purposes, the operative planning process is represented in Figure 32 as linear procedure, where the development of alternatives and variants is depicted as integral part of the planning process. For the further thesis, the chosen alternative or variant will be called *current solution*, since the term indicates to the temporary characteristic and the vagueness. Based on the current solution, alternatives and variants on a higher granularity level can be created to get to an exact and complete description. This is not part of the solution finding process regarding the original problem- or task formulation and is called *residual*. In Figure 32, two procedures are illustrated which differ concerning the potential variants but get to the same current solution.

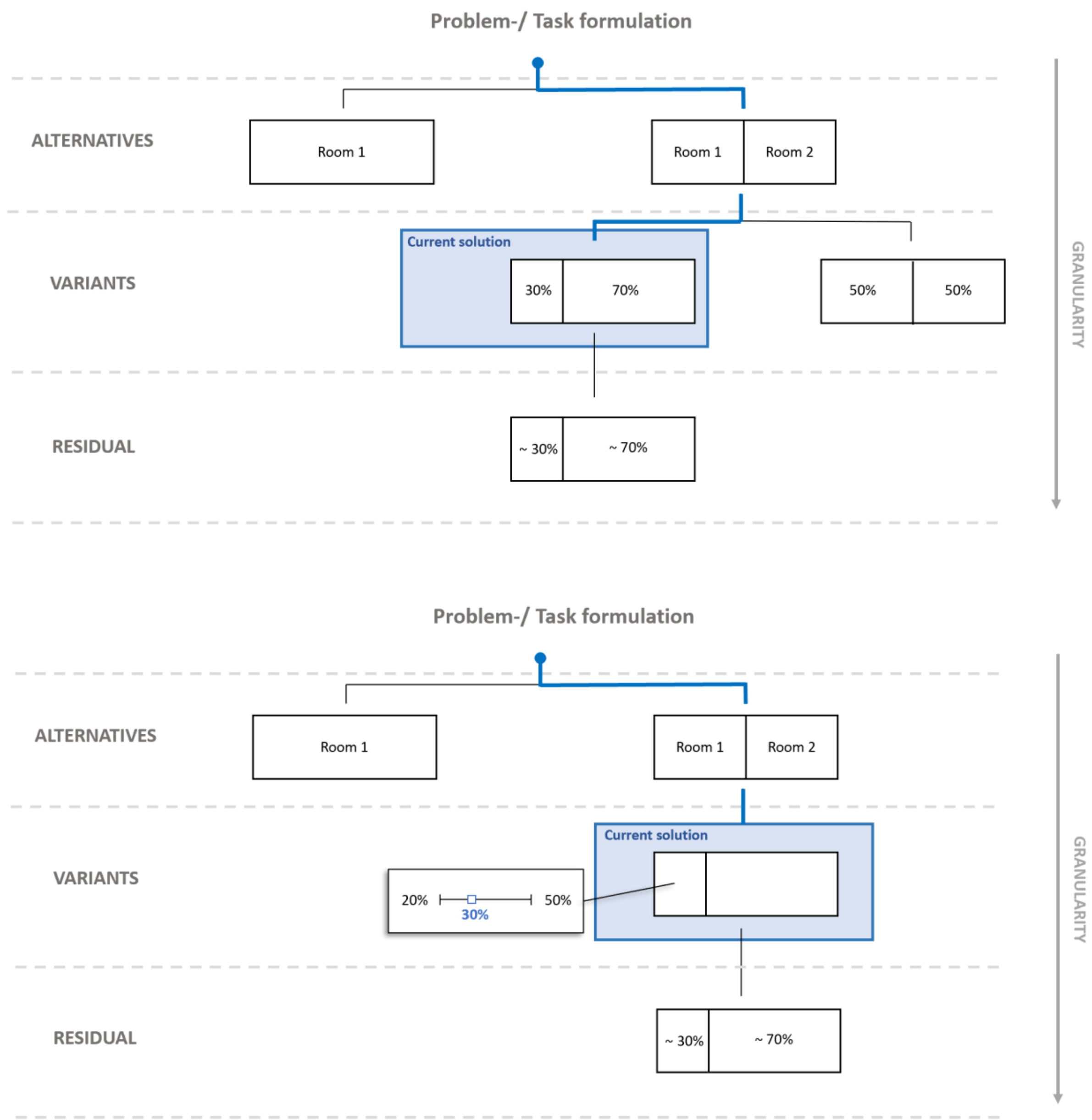


Figure 32: Representation of two different mental models concerning the design process with the same current solution but different characteristics of the respective variants

For the scope of the thesis, the mental model within an architectural design process covers several alternatives and variants of semantic and geometric building information (Figure 33). Other definition of the mental model could include further aspects, e.g. social and cultural aspects which are associated with the model. The information and knowledge within the mental model is tacit or explicit available and is either syntactical or can be externalized and formalized as an abstracted model. Regarding the context of the thesis, the abstracted model is a CAD-model and reflects only a relevant selection of the mental model. This relevant selection is based on the purpose of the reduced model and is restricted by environmental frameworks like the capabilities of the CAD-tool. Another restriction are the capabilities of the modeller to externalise the mental model. For instance, the purpose of the CAD-model could be the representation of the current solution (Figure 33). Thus, the objective of the thesis can be described as the reduction of the horizontal informational distance between the CAD-model and the mental model by extending the scope of the CAD-model using adequate visualizations.

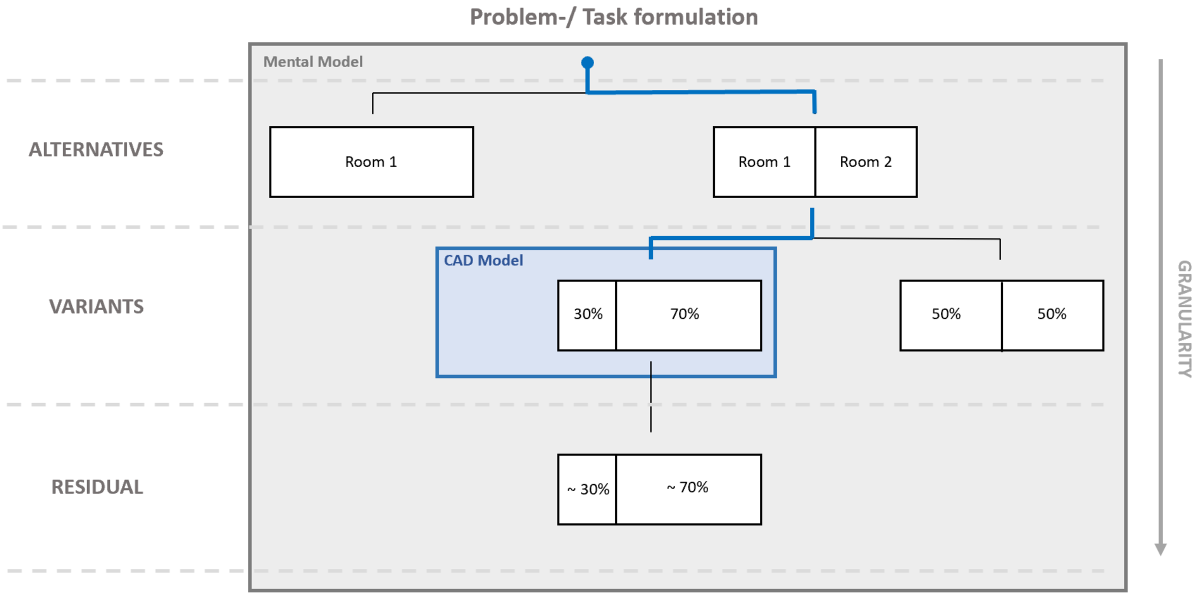


Figure 33: Model-theoretical concept for the representation of fuzziness in the design process

Fuzziness is defined as the informational distance to an accurate, complete description within a particular model world. Since the mental model (particular model world) contains a variety of potential alternatives and variants on different granularity levels, there is fuzziness within the design process concerning *alternatives*, *variants* and the *residual*. Consequently, there is the assumption that the temporary current solution within an iterative design process contains fuzziness based on three categories (Figure 35):

- *Fuzziness of alternatives*: The nature of potential solutions is different.
- *Fuzziness of variants*: The nature of potential solutions is similar, however some characteristics of the elements are different
- *Residual fuzziness*: Fuzziness of alternatives and variants on a higher granularity level, which is not relevant for the current problem- or task-formulation

The fuzziness of alternatives refers to the nature of the potential solution, what is called for the further thesis *solution-specific*. The fuzziness of variants refers to specific elements, what is called *element-specific*. The residual fuzziness can contain both solution-specific and element-specific fuzziness, since it is based on alternatives and variants on a higher granularity level.

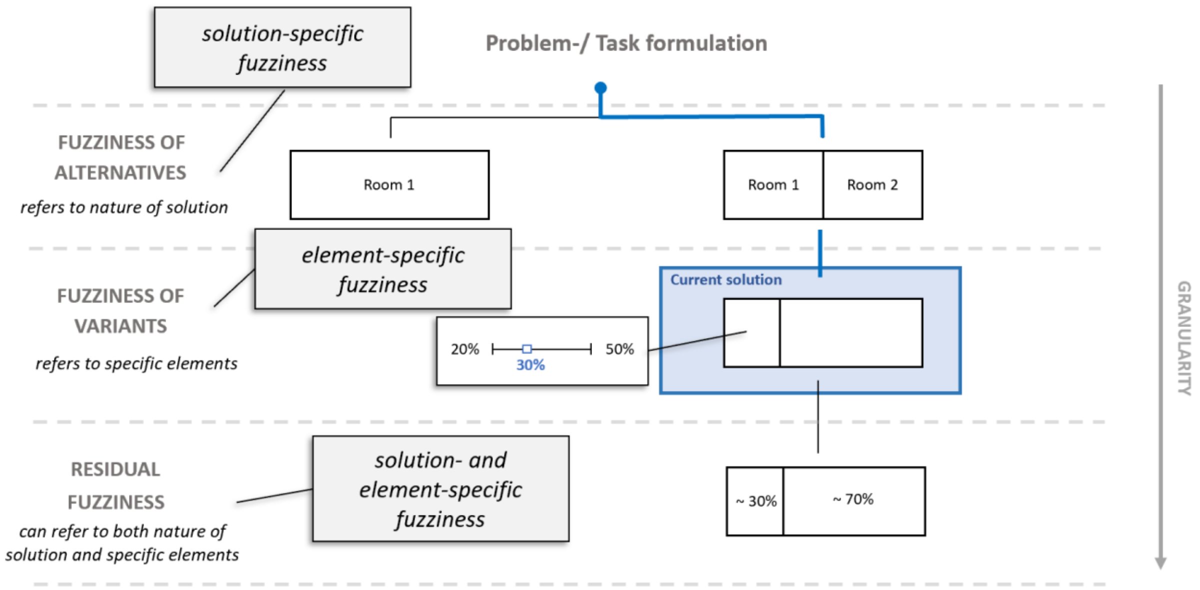


Figure 34: Categorization of fuzziness with respect to the design process

4.4.2 Fuzziness characteristics

Several definitions and conceptualization were reviewed to create a basis for the development of a potential visualization. An overview concerning the assumed characteristics of fuzziness is provided in Figure 35. For the further thesis, the assumption was made, that there are four kinds concerning the nature of fuzziness: Incompleteness, Imprecision, Vagueness and Ambiguity. These characteristics address the question “How is the information affected?” and are described in Table 10. An informational distance between two models within a particular model world in terms of incompleteness occurs, when one model contains information, which is not contained by the other model. The concept imprecision means the deviation of information in terms of inexactness. Vagueness occurs, when one value or alternatives has to be selected out of a set or range of potential values or alternatives. Using the planning procedure in Figure 32 as illustration, a set of alternatives concerning a space concept could contain Alternative A (one room) or Alternative B (two rooms). A range of values could describe the potential values for an area: one out of 20% to 50%. The informational distance in terms of ambiguity refers to n:m:r relationships within the semiotic triangle. Examples are differences in interpretations of symbols or the expression of one concept by different symbols. This kind of informational distance exists primarily between two mental models and can be both horizontal and vertical. Due to limitation purposes, the ambiguity is not considered for the further thesis.

Table 10: Nature of fuzziness in terms of informational distance within a particular model world

Incompleteness		Missing information
Imprecision		Inexact information
Vagueness	*Set*	Set of potential information: e.g. one out of {A;B;C}
	Range	Range of potential information: e.g. one out of [0;5]
Ambiguity		Different interpretation of symbols; Several symbols for one concept

To provide an exact description of fuzziness, it has to be clarified how the informational distance is related to the models. These characteristics are called *properties of fuzziness* for the further thesis and address the question “Which information is fuzzy?”. The major differentiation is based on solution-specific, element-specific and syntactic fuzziness. The solution-specific fuzziness refers to the different nature of solutions. In general, the respective nature of fuzziness for the solution-specific fuzziness is the vagueness set. The element-specific fuzziness refers to a specific element and can be further subdivided into geometric and semantic characteristics. The semantic fuzziness refers to semantic information and can be further subdivided into attributive (reflexive), attributive (relational) and abstract information. The fuzziness concerning the reflexive attributes refers to information associated with the object itself (e.g. color, material, etc.). The fuzziness concerning relational attributes describes the vertical informational distance associated with the relation between the objects. And the vertical informational distance in terms of abstract information is related to the character of the object itself. (see Table 11) The syntactical fuzziness consists of model information, which cannot be formalized in a CAD-Model. The syntactical fuzziness is not covered within the further thesis.

Table 11: Element specific properties of model-oriented fuzziness

Syntactical		Model information which cannot be formalized
Geometrical	*Attributive (reflexive)*	Attributes describing geometric information
Semantical	*Attributive (reflexive)*	Attributes describing semantic information
	Attributive (relational)	Attributes describing the relation to other objects
	Abstract	Information about the object itself

The *value of fuzziness* relates the fuzzy information to a numerical value. For instance, this numerical value could be a probability concerning the selection of an individual from a set of alternatives or a range of values. The probability for the selection of alternative A could be higher than the probability for the selection of alternative B. However, it is questionable if the value of fuzziness can be quantified during the design process. In terms of ambiguity the value of fuzziness could refer to the fuzzy logic theories to access the information numerical.

Additionally, the source of fuzziness is a necessary characteristic to describe the vertical informational distance in a holistic manner. Examples for potential sources of fuzziness, which were deduced from previous literature review, are depicted in Table 12: For instance, fuzziness can be caused by missing knowledge (knowledge-oriented), insufficient supply of objects in the domain model (object-oriented), time pressure (operation-oriented), creation of alternatives to satisfy declarative task specifications (goal-oriented), different interpretation of the same symbols (communication-oriented), errors in gathering data (computational visualization-oriented), etc. This enumeration of potential sources of fuzziness is not exhaustive but indicates to the great amount of different origins of informational distances to the degree of an accurate, complete description within a particular model world.

Table 12: Examples for sources of fuzziness

Knowledge-oriented	Caused by lack of knowledge
Object-oriented	Caused by inadequate objects
Operation-oriented	Caused by the organization of the design process
Goal-oriented	Caused by the characteristics of the design process and task
Communication-oriented	Caused by lack in communication
Computational Visualization-oriented	*Acquisition*: e.g. unreliable data
	Transformation: e.g. computational approximation of curves
	Visualization: e.g. rendering

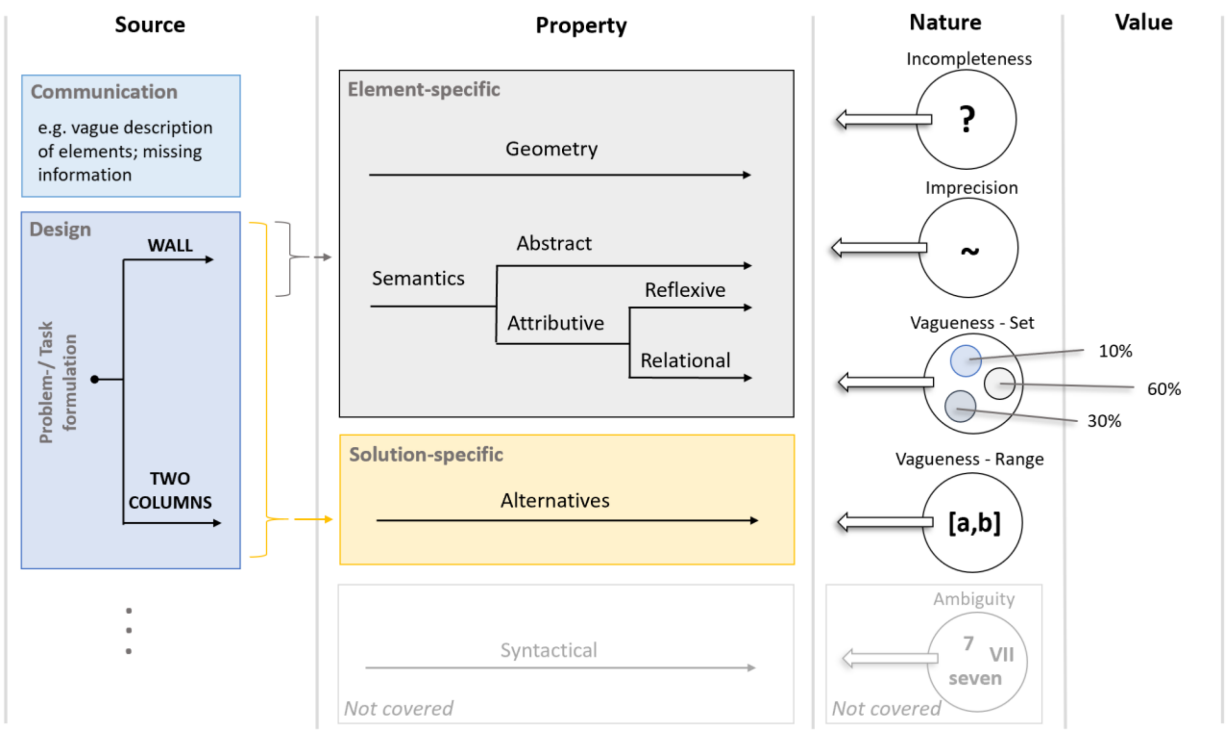


Figure 35: Overview about the characterization of model-oriented fuzziness

5 Visualization of fuzziness

In this chapter the basic theories regarding visualization, perception and interaction are reviewed. After that, a closer look on methods for fuzziness visualization in Computer Aided Design and other domains is provided. Based on this literature review, conclusions are made concerning potential visualization methods for the development of an adequate fuzziness visualization.

5.1 Visualization

Visualizations can represent both physical and abstract data. According to Card et al. (2007, p. 6) the visualization of physical data refers rather to the field of scientific visualizations, while abstract data refer rather to the field information visualization. However, the boundaries between these areas are not always clear, since physical data is often related to abstract data. A definition concerning information visualization is provided by Card et. al (2007, p. 6), who defines information visualization as “the use of computer-supported, interactive, visual representations of data to amplify cognition”. Here, cognition is further proposed as “acquisition or use of knowledge”. Another definition is provided by Munzner (2015, p. 1), who states that “computer-based visualization systems provide visual representations of datasets designed to help people carry out tasks more effectively”. Conclusively, for the further thesis the term scientific visualization refers to physical data and information visualization refers to abstract data. Both concepts have the purpose to amplify cognition and to carry out task more efficiently (Table 13).

Table 13: Conceptualization of scientific- and information visualization

Visualization	Reference	Purpose
Scientific visualization	Physical data	Amplification of cognition/ Carrying out task efficiently
Information visualization	Abstract data	Amplification of cognition/ Carrying out task efficiently

The need for visualization is present, when human capabilities have to be augmented rather than replaced with computational decision-making methods (Munzner, 2015,

p. 1). The solving process of planning problems is a cognitive process, which needs the iteration of seeing, thinking and acting. The value of visualizations for the amplification of cognition is illustrated by Ware (1999/2013, p. 2), who states following:

> "As Hutchins (1995) so effectively pointed out, thinking is not something that goes on entirely, or even mostly, inside people’s head. Little intellectual work is accomplished with our eyes and ears closed. Most cognition is done as a kind of interaction with cognitive tools, pencils and information systems. Neither is cognition mostly done with a computer. It occurs as a process in systems containing many people and many cognitive tools."

Thus, the need for visualizations is integral part for an efficient planning process. This fact is pointed by Norman, who says that the “power of the unaided mind is highly overrated. […] The real powers come from devising external aids: it is things that make us smart” (Norman, 1993, p.43). Furthermore, the cognitive tools are an essential part of the communication process, which is indicated by Hansen et. al. (2014, pp. 3–4), who writes that the “goal of visualization is to effectively and accurately communicate data.” Thus, the purpose of cognitive tools can be seen as the efficient communication of data and the support of thinking processes to amplify cognition. The computer scientist Shneiderman (2007, p. 6) illustrates these circumstances by saying that the “purpose of visualization is insight, not pictures” and that the “main goals of this insight are discovery, decision making and explanation.” This statement could be transferred to the AEC-industry by saying that the purpose of visualization is rather the extraction of a deeper understanding of the building or building project, than the pure representation of geometry and semantic information.

The visualization and cognitive processing of information is based on a cognitive system. According to Ware (1999/2013, p. 2), the cognitive system is an individual working with a computer-based visual thinking tool and consists of both the human visual system (a flexible pattern finder combined with an adaptive decision-making system) and the computational power with vast information resources coupled to the World Wide Web. A model of the cognitive system is the visualization pipeline, which represents the steps from the data acquisition to the visual cognitive processing and the potential interactions within these steps. The first step describes the acquisition of data by data gathering. This step includes for example the accumulation of data from sensorial input or the information from test files. The second step refers to the transformation of the data as preparation for the visualization. This could be simple conversion of units (e.g. the sensorial input is measured in miles, but meters are needed for the visualization) or more complex algorithms (e.g. the conversion of measured geometrical data into boundary representations). The third step is the visual mapping of the prepared data and can be modified by view manipulation, what represents the most common understanding of "interaction". Respective to the intension of the user, the data is displayed in an adequate manner by the visual mapping. This information can be explored by interacting with the user interface to gain insights. Originally, the social environment is part of the visualization pipeline to illustrate the influence of surroundings on the cognitive system. However, these aspects are neglected in the Figure 36 for simplification of the visualization process regarding the scope of the thesis.

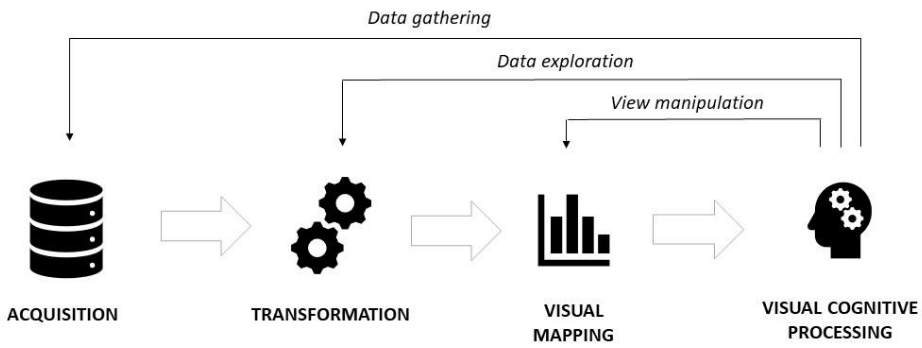


Figure 36: The visualization pipeline according to Ware (1999/2013)

The cartograph Bertin (1983/2007) proposes in his framework, called the "Properties of the Graphic System", eight visual variables. Bertin has developed the framework for the printed page, but several researchers have verified that the framework is applicable to digital displays by making some adjustments (see for instance Ware, 1999/2013). Following Bertin, the eight visual variables are the dimension x, dimension y, size, color value, texture, color hue, orientation and shape and can described a random mark on a map. These visual variables can be extended by the visual variables color saturation, arrangement, crispness, resolution, transparency (Roth, 2016, p. 3) (Figure 37). However, direct translated the visual variables are rather called retinal variables. That indicates to the circumstances that the variables are processed pre-attentively or in an immediate and preconceptual manner. Or in other words: the visual variables are "seen" perceptually instead of "understood" cognitively (Roth, 2016, p. 6).

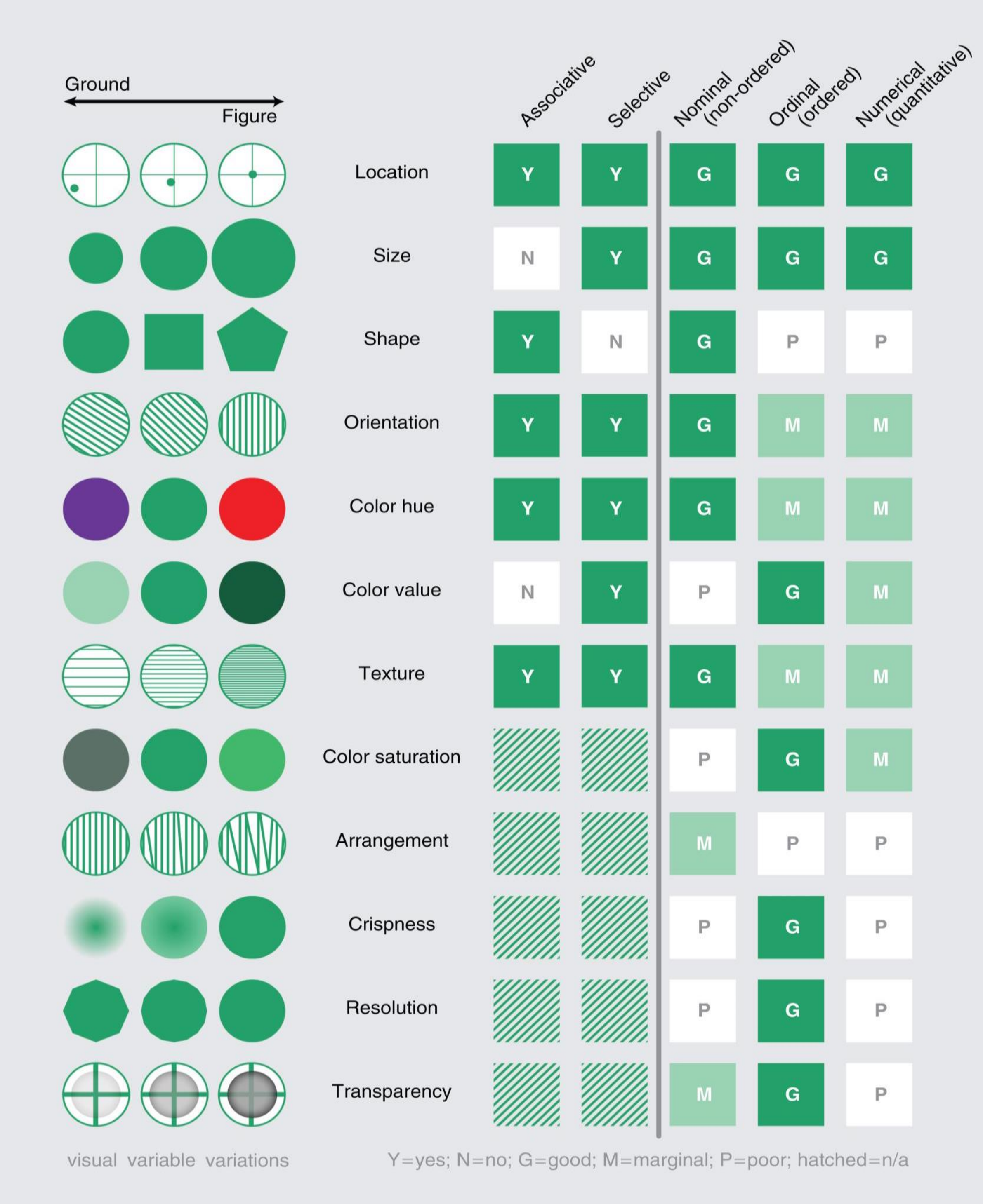


Figure 37: Visual variables and their syntactics (Roth, 2016, p. 3) derived from derived from Bertin (1967/1983), MacEachren (2008), and MacEachren et al. (2012).

Tufte (2015) has published the principles for graphic excellence and integrity, which address the creation of adequate visualizations. One major principle, graphical excellence, is defined as that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space. For the creation of graphical clarity, precision and efficiency with respect to *graphical excellence*, Tufte (2015) concludes following basic courses: Avoid distorting what the data shows; Encourage the eye to compare the data; Present a large amount of data in a small space; Reveal multiple levels of detail in the data; Closely integrate statistical and text description with the data. The intension of the *data-ink maximation* principle is the representation of the largest amount of data with the least amount of ink, since the visualization of unnecessary data could lead to distraction and unclearness. Another principle is called *data density*. This principle describes the amount of data elements divided by the area of the graphic. When the data density is very low, then the size of the graphic must be reduced, the model must be abstracted or another source system for the model could be more adequate (e.g. table). The principle of *small multiplies* provides that for a comparison of data, only the data itself should change and not the design of the graphic.

5.2 Perception

Perception is a complex part in the information visualization pipeline (see Figure 38), which address the gain of sensorics raw material and process of this material by cognitive elements. While the field of perception research contains the acquisition of all senses available, the visual perception focuses on the perception of light. The relevance of the perception research can be demonstrated by the assumption that all knowledge and insights are based on sensorial experiences. Due to the complex nature of perception research, the topic cannot be described exhaustive in the thesis. Thus, in the following section, a simplified model for the perception is described and the four major perception theories are explained roughly.

A model of the complex process of perception can be reduced on basic steps between a visual stimulus in the physical world and the visual perception. For instance, Wolfe (1988, p. 93) states three basic steps: In the first step, a stimulus is formed on the retina and received by the neural tissue at the back of the eye. The data is converted to electrochemical signals and processed by the nervous system. In the second step, visual variables like size or color are extracted. In the third step inferences about the nature of the real-world stimulus based on the processed input and the observers knowledge about the visual about the visual world are made. Another simplified model was published by Ware (1999/2013, pp. 21–22) and depicts subsystems within the human perception system. The stage one describes that the features from every part of the visual field are extract simultaneously by parallel processing of billions of neurons in our eyes and brain. The processing takes places independently of the attention. Regions and simple patterns (e.g. continuous contours, regions of the same color or texture, patterns of motion, etc.) are extracted within the second stage of visual analysis. The second stage is mainly influenced by the information available form stage one and by the top-down action of attention driven by visual queries. The third stage is called visual working memory and provides the objects by the demands of active attention. The available patterns for the answer of visual queries and the information, which is stored in the long-term memory related to the task construct these objects. A simplified model is represented in the Figure 39, which is based on the three major steps from Wolfe and extended by the step "Recognize patterns" from Ware.

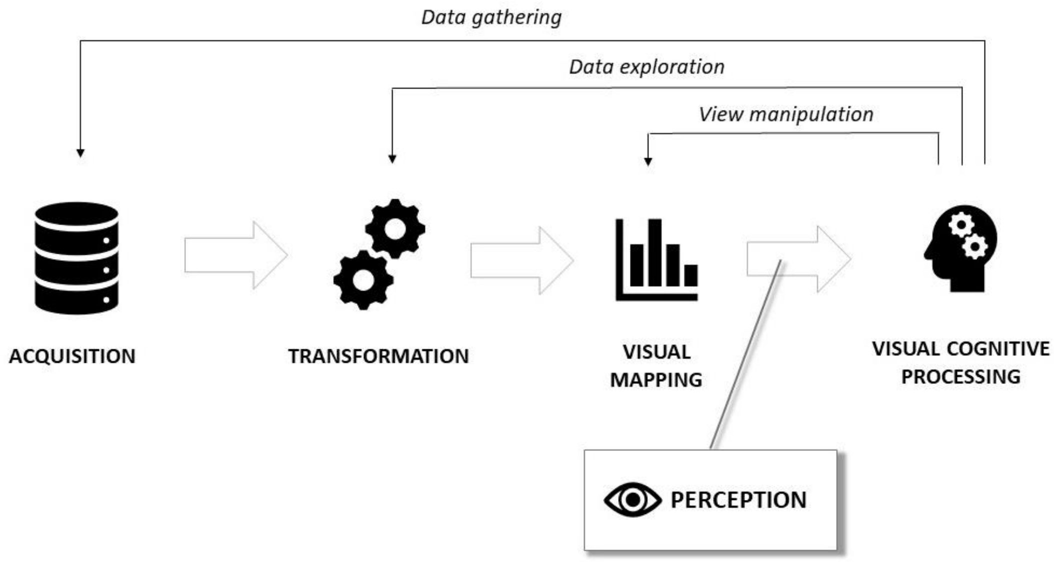


Figure 38: Perception in visualization pipeline adapted and enhanced from Ware (1999/2013, p. 4)

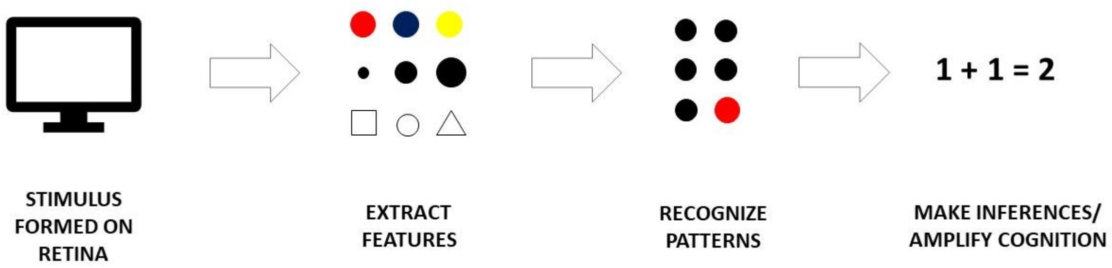


Figure 39: Major steps of perception process based on Wolfe (1988, p. 93) and Ware (1999/2013, pp. 21–22)

The four most influential theories in the field of perception theory are classical psychophysics, gestalt psychology, perception psychological approach from Gibson (1979/2015) and the computational approach from Marr (2000). The classical psychophysics covers the determination of quantitative transformation equations between physical input and a psychological output. The Gestalt psychology, which is originated in German Schools, is a contractionary movement to the Element psychology. In contrast to the element psychology, the Gestalt psychology says that the perceptions and emotions are more than the sum of its parts. Furthermore, the Gestalt psychologists examined how perception is organized and conducted the gestalt laws. The gestalt laws states when we perceive lines or symbols as a group. The gestalt laws are subordinated to the “Prägnanzprinzip”, which says that there is the tendency to perceive the simplest, most stable and best gestalt. A selection of four gestalt laws is depicted in Figure 40.

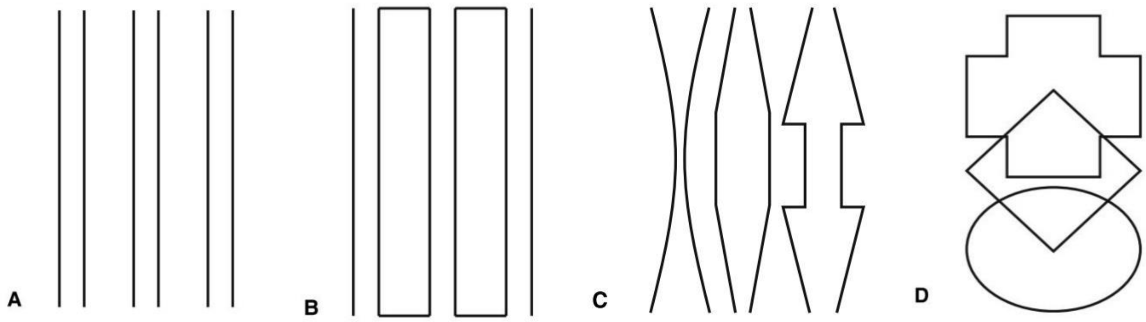


Figure 40: Four Gestalt laws for object recognition: A) law of proximity B) law of unity C) law of similarity D) law of continuous lines

Another fundamental theory was published by Gibson, who refuse the retinal picture as basis for the perception. Instead, Gibson says that the optic arrangement (optic arrays) of the surfaces and their characterized alterations are fundamental to perceive the events and layout of the environment. For instance, the information of the distance to an object is available, independently of the position of the observer. In contrast to several theorist, Gibson sees perception as direct and not as active process. Active process means that, based on the available sensory evidence, the brain deduces certain things about the environment. In a direct perception process, the information of the optic array is captured directly and doesn’t have to be processed. Additionally, Gibson has published the affordance theory, which is probably influenced by the theory from Koffka (1935/2014). Koffka states that the observer does perceive the invitations of the objects. For instance, the invitation of a chair is the option to sit down. Gibson states in the affordance theory, that these invitations can be extracted directly from the optic arrangements. Due to the missing empirical verification of Gibson's theories, the radical thinking of Gibson is not fully accepted in field of perception research.

The fourth theory is the computational approach from Marr (2000), which connects psychological and neurophysiological knowledge with thoughts from the field of artificial intelligence. In contrast to Gibson, Marr focus on the stages of information process, which occurs between the retinal representation and the subjective perception impression. For that, following major question must be solved: How can the information about the form of object extracted from the retinal display? How are the information processed, such that the perception impression is a description of the real world? The stages of information processing shall be determined by algorithmic approaches, what is different to classical perception theories.

5.3 Interaction

The interface between the individual human and the computer-based visual thinking tool is called interactive visualization and is important for the performance of the cognitive system (Ware, 1999/2013, p. 2). Interactive visualization is a process, which is based on three kinds of interlocking feedback loops: Data manipulation loop, which covers the eye-hand coordination and is used to select and move objects. The exploration and navigation loop, which is intended to analyze the data for orientation purposes. The problem-solving loop is based on the iterative character of the problem-solving process. That means for solving the reformulated problem, new data is added, and problems solutions are identified. The gained insight leads again to a reformulation of the problem (Ware, 1999/2013, p. 346).

The Data Selection and Manipulation Loop covers numerous types of interactions and an rough accumulation of these types is provided Ware (1999/2013, pp. 346–353): The time which is needed for the reaction to a signal can take place in about 130 msec (Kohfeld, 1971). The reaction to a signal can be extended by a choice, which has to be made for the subsequent reaction. The so called choice reaction time can be modelled by the Hick-Hyman law (Hyman, 1953). Another kind of epistemic interaction are the hover queries. These queries occur, when the cursor is placed on an object and, if necessary, a mouse button is clicked. Furthermore, the two-handed interaction focusses on a better epistemic interaction with the computer interfaces. The exploration of the user interface by using one hand, which moves the cursor, while the other hand remains still, seems to be a lack of productivity (Buxton & Myers, 1986). One well-known principle is the kinematic chain theory (Guiard, 1987), which says that the left hand and the right hand form a kinematic chain. The non-dominant hand covers a frame of reference for movements with the dominant hand. While the non-dominant hand controls the object of reference, the dominant hand should be used to select the details or manipulate data. For the learning progress of the operation of the user interface the stimulus-stimulus response compatibility is an important aspect. This aspect means that the control movements on the user interface should be similar or compatible with everyday experiences: The movement of the mouse to the right should cause a movement of the displayed object to the right (and not to the left).

5.4 CAD-based fuzziness visualization

Concerning the visualization of attributes in a CAD-Model, it must be distinguished between direct and indirect attributes. While direct attributes can be visualized directly in the model (e.g. geometry, color), indirect attributes must be visualized by a transformation respective to the representation (e.g. temperature). For instance, the indirect attribute temperature can be visualized by colors which are associated with the respective temperature or single values can be compared by modifying the seize of geometrical figures respective to the temperature value. Furthermore, these attributes can be categorized into four types: nominal-, ordinal-, interval-, ratio-scale (Rittel & Reuter, 1992). The nominal scale refers to a set of attributes, which consist of discrete values without an order. An example of nominal scale is a set of materials: material = {concrete, timber, masonry}. The ordinal-scale is based on sets of elements, which can be ordered by their weight, e.g. height = {low, intermediate, height}. The interval-scale refers to sequences of elements with real numbers, which can be compared due to their differences. Here, the zero point and measure units are arbitrary: e.g. temperature differences of Celsius temperature scale. In contrast to interval-scale, in the ratio-scale zero point and normalization is available. Thus, arithmetical operations can be carried out. An example for ratio-scales are the temperature-scale respective to Kelvin and the length of building elements (Reder, 1995, pp. 45–46). Indirect attributes can be associated with direct attributes (e.g. material with color and texture).

The fuzziness in a CAD-Model model can be visualized in a general view or in a modified view to represent the fuzziness after demand. The visualization can be based on both the exact representation (e.g. the visualization of alternatives concerning geometrical attributes) or the indication of the availability of fuzziness. For instance, the representation of all alternatives concerning the vagueness of a direct attribute seems to be easier than the representation of a range of alternatives of indirect attributes or the representation of incomplete descriptions of an element. According to Reder (1995, pp. 46–47) the fuzziness can be represented in a fuzzy view on the respective element. In a fuzzy view can be visualized both the element itself and the fuzziness. However, only the element is visualized in the original project representation and serves as a connection between the project representation and the fuzzy view.

Table 14: Different types of indirect attributes (for instance Rittel & Reuter, 1992).

Nominal-scale	set of elements, which consist of discrete values without an order
Ordinal-scale	sets of elements, which can be ordered by their weight
Interval-scale	sequences of elements with real numbers, which can be compared due to their differences
Ratio-scale	sequences of elements with real numbers with zero point and normalization

5.5 Current visualization techniques

Due to difficulties in applying pre-existing methods, escalating visual complexity and the lack of obvious visualization techniques, the visualization of fuzziness and uncertainty remains an unsolved problem (Hansen et al., 2014, p. 4). There are visualization techniques, which are based on both indirect and direct approach. Within the indirect approach the uncertainty “is not explicitly displayed, but used to parameterize the visualization process instead.” (Griethe & Schumann, 2006, p. 8) The comparison of current visualization techniques and their evaluations is complex, due to the fact that there is no common definition of fuzziness. In the literature, there are different categorizations of visualization techniques. For instance, in the field of Geospatial Information Systems (GIS) an often-used categorization is the distinction between intrinsic and extrinsic indicators. Intrinsic techniques are used to visualize some uncertainty without attention to the magnitude of the uncertainty. Some examples for intrinsic techniques are the use of shape, color or transparency. Cain (2015, pp. 15–25) concludes three intrinsic methods for depicting point data uncertainty (Table 15 and Table 16). Griethe and Schumann (2006, pp. 8–11) provide another classification by the distinction of the classes utilization of free graphical variables, additional objects, animation, interactive representation, sonification and psycho-visual (Table 17). Hansen et. al. (2014, p. 18) distinguish between comparison, mapping, glyphs and image discontinuities. Using the visualization technique comparison, the difference of animation can highlight the regions of distortion or blur or highlight differences in visualization parameters. Such techniques have been applied to multivariate data displayed through scatter plots or parallel coordinates.

Table 15: Intrinsic and extrinsic visualization techniques according to the literature review from Cain (2015, pp. 15–25)

Visualization techniques	Description	Examples
Intrinsic	- data icon changed - Without magnitude of uncertainty	shape, color, transparency
Extrinsic	- primary data icon unchanged - add composite image - with magnitude of uncertainty	thermometers, arrows, bars, pie charts, graphs, complex objects, glyphs

Table 16: Intrinsic visualization techniques according to the literature review from Cain (2015, pp. 15–25)

Visualization techniques	Description
Color saturation	reducing the saturation level of the symbol fill, achieved by increasing the grey content of the symbol fill color
Contour crispness	reducing the crispness of the symbol boundary
Opaqueness	increasing opaqueness of the symbol corresponds to greater uncertainty

Table 17: Visualization Techniques according to Griethe and Schumann (2006, pp. 8–11)

Visualization Techniques	Description
Utilization of free graphical variables	color, size, position, focus, clarity, fuzziness, saturation, transparency and edge crispness
Additional objects	labels, images or glyphs
Animation	uncertainty is mapped to animation parameters such as speed or duration, motion blur, range or extent of motion
Interactive representation	uncertainty can be discovered by mouse interaction
Sonification and psycho-visual	incorporation of acoustics, changes in pitch, volume, rhythm, vibration, or flashing textual messages

Table 18: Visualization techniques according to Hansen et. al. (2014, S. 18)

Visualization Techniques	Description
Comparison	- Representation of difference between e.g. surfaces - Side-by-side comparison of data sets
Mapping	- Free variables in rendering equation - Modifying visual attributes e.g. change surface reflectance, color, opacity
Glyphs	- Symbols used to signify data through parameters e.g. location, size, shape, orientation, color
Image Discontinuities	- Discontinuities as areas with distinct data characteristics e.g. surface roughness, blurring, oscillations, depth shaded holes, noise, texture or e.g. translation, scaling, rotation, warping and distortion of geometry

5.6 Possible visualization techniques

Based on the literature review concerning visualization techniques and on experiences with modelling tools regarding BIM, the following visualization approaches were deduced:

- Filter approach
- Symbol approach
- Animation approach.

These visualization approaches can be combined with each other and can be assigned to the respective characteristics of fuzziness, which shall be displayed. The filter-approach means the modification of visual variables by applying filters on the CAD-Model. The symbol approach is an extrinsic visualization technique using additional symbols to the initial representation to depict the respective information. The animation approach depicts time dependent changes to the initial representation. The visualization approaches will be explained more detailed in chapter 6. Furthermore, these approaches can be applied in different views, e.g.:

- 2D-plan-view,
- normal 2½D -view
- walkthrough 2½D-view

The 2D-plan view means the representation of the dimension reduced model like it is known from floor plans. The normal 2½D -view is the standard representation of three-dimensional model by a two-dimensional display. The 2½D -view as walkthrough means the adaption of the sizes of the model and the controller to navigate and explore the model related to the real life. In the different approaches with respect to the possible application are depicted. Within the table the circle symbol is used when it does not seem to be clear if the approach can be applied. Since the purpose of visual representations is to help people carry out tasks more effectively, the adequate visualization approach depends on the respective task. For instance, when the users intend to identify the fuzzy elements as fast as possible, then the filter approach seem to be rather suitable than the symbol- or animation-approach. However, when the task requires an identification of the exact description of the fuzzy values, then the symbol approach or a combination of the approaches could be the adequate visualization. Thus, there is not the best visualization for all tasks as a whole, but more or less adequate visualizations for the respective tasks to carry out.

6 Fuzziness visualization proposal

In this chapter, a fuzziness visualization was developed based on the literature review and assumptions from the previous chapters. The developed visualizations aim to depict fuzziness in a general manner regardless of the task to carry out.

6.1 Visualization approaches

Based on the assumption regarding the categorization and characterization of fuzziness (chapter 4.4) and on the deduced visualization approaches (chapter 6.4), adequate visualization approaches were developed for the reduction of the horizontal informational distance across two model worlds. Since the depiction of the variety of information regarding a holistic representation of fuzziness within the design process could be too complex, only a section of the fuzziness characteristics shall be displayed by an adequate fuzziness visualization. Two different visualizations were developed to visualize fuzziness in an adequate manner. Only the reflexive attributes are considered within these visualizations regarding the representation of semantic fuzziness.

Visualization A

The different approaches with respect to their application regarding Visualization A are depicted in Table 19. The green colors in the tables indicates the chosen approaches for the respective kind of fuzziness and fuzziness characteristics. For the 2-D plan and the normal 2 ½ D view the filter- and the symbol approach were used for visualizing fuzziness. The property and value of solution-specific fuzziness are visualized using the filter approach. (see Table 20) In that case, the fuzziness visualization is limited to the value of the current solution. For instance, the probability of the current solution could be displayed using different color value for semantics and different border style for the geometry. The applications of the three visualization approaches concerning the representation of the characteristics of element-specific fuzziness is depicted in Table 21. Since the filter approach lacks in terms of displaying the exact values of the respective element-specific fuzziness, the symbol approach was chosen for the adequate visualization. For instance, the potential change in length of a building element cannot be represented by the filter approach. Thus, the nature and property of fuzziness can be communicated, when the specific values concerning the change of length are available.

Table 19: Applied visualization approaches respective to fuzziness and views for Visualization A

	Fuzziness		2D	2½D	
	Solution-specific	Element-specific	Plan	Normal	Walkthrough
Filter					
Symbol					
Animation					

Table 20: Applied visualization approaches respective to the characteristics of solution-specific fuzziness for Visualization A

	Nature (Vagueness Set)	Property (Geometry, Semantic)	Source (e.g. communication, goal-oriented)	Value (Probability)	Details (representation of individual alternatives)
Filter					
Symbol					
Animation					

Table 21: Applied visualization approaches respective to the characteristics of element-specific fuzziness for Visualization A

	Nature (Imprecision, Incompleteness, Vagueness)	Property (Geometry, Semantic)	Source (e.g. communication, goal-oriented)	Value (Probability)	Details (e.g. start and end value of vagueness range)
Filter					
Symbol					
Animation					

<u>Visualization B</u>

The Visualization B is similar to Visualization A but represented in the Walkthrough-view instead of the 2D-plan and 2½D-normal view (see Table 22 and Table 23). Additionally, the characteristic of the element-specific fuzziness is displayed by the animation-approach (see Table 24).

Table 22: Applied visualization approaches respective to fuzziness and views for Visualization B

<table>
<tr><th rowspan="2"></th><th colspan="2">Fuzziness</th><th>2D</th><th colspan="2">2½D</th></tr>
<tr><th>Solution-specific</th><th>Element-specific</th><th>Plan</th><th>Normal</th><th>Walkthrough</th></tr>
<tr><td>Filter</td><td bgcolor="#c4d79b"></td><td></td><td></td><td></td><td bgcolor="#c4d79b"></td></tr>
<tr><td>Symbol</td><td></td><td bgcolor="#c4d79b"></td><td></td><td></td><td bgcolor="#c4d79b"></td></tr>
<tr><td>Animation</td><td></td><td bgcolor="#c4d79b"></td><td></td><td></td><td bgcolor="#c4d79b"></td></tr>
</table>

Table 23: Applied visualization approaches respective to the characteristics of solution-specific fuzziness for Visualization B

<table>
<tr><th></th><th>Nature
(Vagueness Set)</th><th>Property
(Geometry, Semantic)</th><th>Source
(e.g. communication, goal-oriented)</th><th>Value
(Probability)</th><th>Details
(representation of individual alternatives)</th></tr>
<tr><td>Filter</td><td></td><td bgcolor="#c4d79b"></td><td></td><td bgcolor="#c4d79b"></td><td></td></tr>
<tr><td>Symbol</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Animation</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 24: Applied visualization approaches respective to the characteristics of element-specific fuzziness for Visualization B

<table>
<tr><th></th><th>Nature
(Imprecision, Incompleteness, Vagueness)</th><th>Property
(Geometry, Semantic)</th><th>Source
(e.g. communication, goal-oriented)</th><th>Value
(Probability)</th><th>Details
(e.g. start and end value of vagueness range)</th></tr>
<tr><td>Filter</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Symbol</td><td bgcolor="#c4d79b"></td><td bgcolor="#c4d79b"></td><td></td><td></td><td bgcolor="#c4d79b"></td></tr>
<tr><td>Animation</td><td bgcolor="#c4d79b"></td><td bgcolor="#c4d79b"></td><td></td><td></td><td bgcolor="#c4d79b"></td></tr>
</table>

6.2 Software products

The Visualization A was created using the software product Autodesk Revit[7], since it is a common 3D-modelling tool regarding the BIM-based planning process. The Visualization B was created using Unity[8], because the game engine allows simple implementations of animations and walkthrough scenarios. Revit is a BIM-based planning tool for architects, structural engineers and service engineers and supports both 2D- and 3D-modelling. Unity is a cross-platform game engine for the development of interactive 2D and 3D-graphic application and games.

6.3 Development of visualization techniques

The filter-approach means the modification of visual variables by applying filters on the CAD-Model. The different natures of fuzziness could be visualized by assigning different visual variables to the respective characteristics e.g. imprecision is blue, incompleteness is red. For this, nominal attributes could be displayed by nominal visual variables and ordinal attributes could be displayed by ordinal visual variables. For the representation of multiple fuzziness characteristics different visual variables could be used. However, the filter approach lack in displaying specific values of the fuzzy elements. The user can perceive the different characteristics of fuzziness, but the filter approach does not show more detailed information about the fuzziness. In Figure 41 two different filter approaches were applied: In the left picture, the geometric element-specific fuzziness is highlighted by blue color hue. In the right picture, the light blue color shows elements which depends on the fuzziness of the dark blue elements. The filter approach in the Figure 42 was created on the basis of Abualdenien & Borrmann (2019a). Here, the solution-specific fuzziness is represented by different types of border lines and the semantic fuzziness is visualized by green color hue. In addition, the probability of the current solution is subdivided in different levels, which can be visualized by different styles of border lines (geometric fuzziness) and color hue (semantic fuzziness). While the left figure distinguishes between certain and uncertain alternatives, the right picture differentiates between three different probability values for the respective alternatives.

[7] https://www.autodesk.de/products/revit/overview, last accessed 29.03.2019
[8] https://unity.com/de, last accessed 29.03.2019

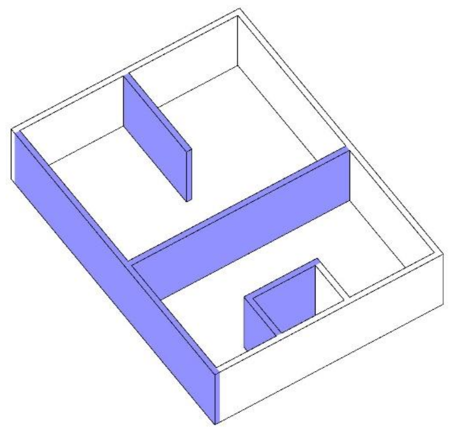


Figure 41: Filter-approach for visualization of geometric element specific fuzziness with color hue. Left picture: without related elements. Right picture: including related elements

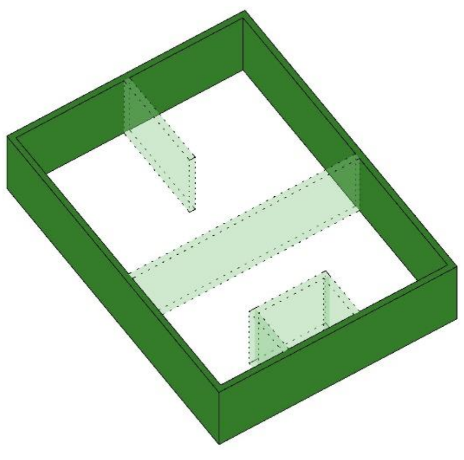


Figure 42: Filter-approach for visualization of solution-specific fuzziness and respective value of fuzziness based on color hue (semantics) and border lines (geometry). Additional filter of probability value with color value and border line style. Left picture: Two probability levels certain and uncertain. Right picture: Three different probability levels (Abualdenien & Borrmann, 2019a)

The flaws concerning the representation of the different nature of fuzziness and specific values in the filter-approach, could be compensated by an extrinsic visualization approach. Thus, symbols were developed to visualize the different natures of fuzziness. While the geometric symbols are embedded within the model, the semantic fuzziness symbols are displayed in an additional information box. For simplification, the target items regarding the fuzziness visualization were walls, which provide an easy geometry. The application of the symbol-approach for more complex geometries is not covered within the thesis and needs to be examined further. The geometric fuzziness symbols are subdivided into two reference groups: position of reference bounding faces and position of the center point of the wall (Table 26). While the position of bounding faces is indicated by a rectangle on the respective surface, the position of the midpoint is indicated by a circle in the middle of the object. These reference symbols can be extended by the symbols regarding the nature of fuzziness (Table 25). The symbols concerning the semantic attributive fuzziness are separated into nominal and ordinal attributes (Table 27). For nominal attributes there is no nature of fuzziness in terms of imprecision and range-based vagueness available. In addition to the representation of the nature of fuzziness, the probability distribution regarding the set-based and range-based vagueness could be expressed by modification of the size or the color of the symbols (Figure 43). While the geometric symbols could be displayed directly at the respective elements, the semantic symbols are visualized within a “info box” sticking to the element. Furthermore, the representation of geometric and semantic fuzziness by symbols could be enhanced with interaction (Figure 45) Clicking on or hovering over the respective symbols could allow modifications concerning the geometric and semantic attributes. However, this interactive modification of geometric attributes could be error prone for complex geometries or multiple dependencies of geometric objects.

Table 25: Symbol-approach for visualization of the nature of element-specific fuzziness

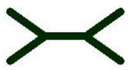
		Geometry	Semantics
Incompleteness			[ ]
Imprecision			~
Vagueness	*Set*		
	Range		

Table 26: Symbol-approach for visualization of geometric reference attributes

Position of center point	Position of reference face
○	□

Table 27: Symbol-approach for nominal and ordinal attributive fuzziness

		Nominal	Ordinal
Incompleteness		[ ]	[ ]
Imprecision		-	~
Vagueness	Set	☑ Non-bearing □ Bearing	□ F90 □ F120
	Range	-	1.60 1.91 2.10

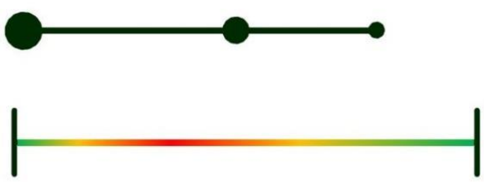


Figure 43: Symbols-approach with representation of probability by symbol size and color value

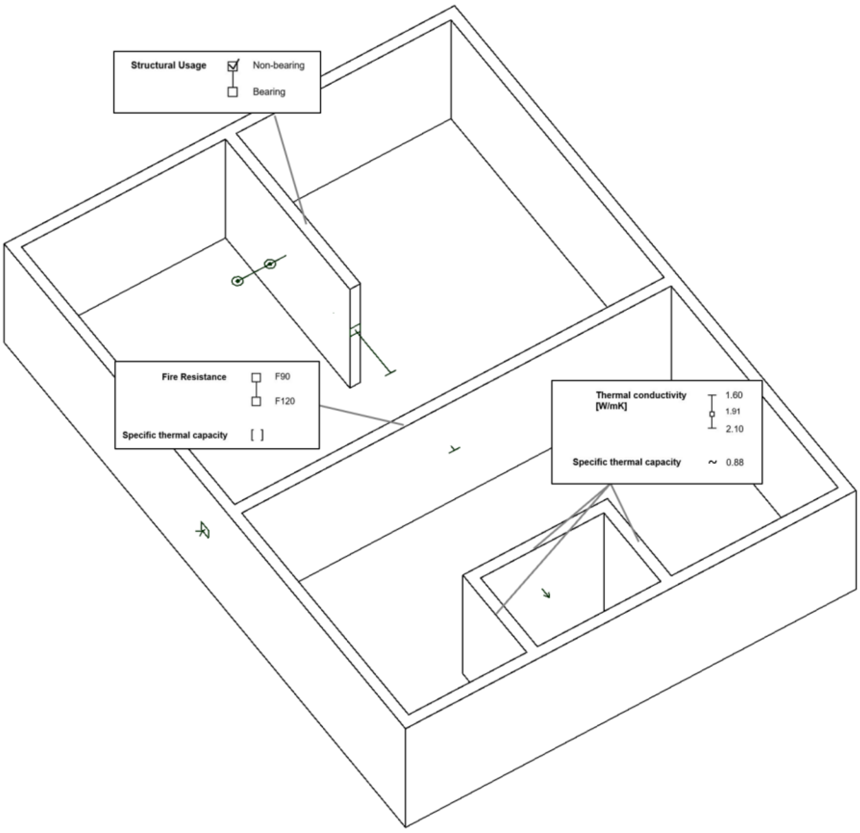


Figure 44: Symbol approached applied in normal view

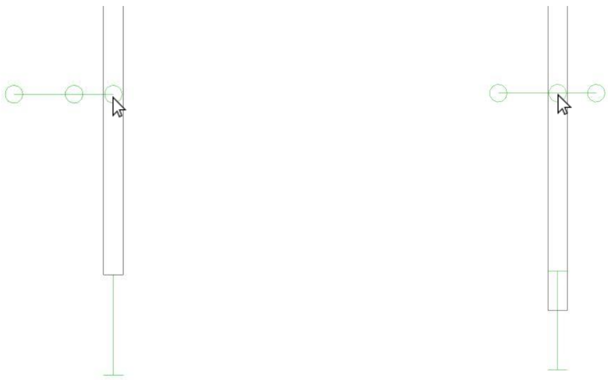


Figure 45: Symbols-approach with interaction

6.4 Proposed visualizations

Due to the different flaws of the filter-, symbol- and animation, a combination of these approach seems to be promising for the efficient communication of fuzziness by a CAD-model. For instance, the filter-approach for semantic and geometric fuzziness can be enhanced by the symbol-approach to identify the fuzzy values and creating a deeper understanding of the vertical informational distances in the CAD-model.

<u>Visualization A</u>

Proposed representation of fuzziness regarding Visualization A is based on the filter-approach for the depiction of solution-specific fuzziness and the symbol-approach for the depiction of element-specific fuzziness using the developed visualization techniques (Figure 46). The combination of the visualization concerning the solution- and element-specific fuzziness is represented in Figure 47.

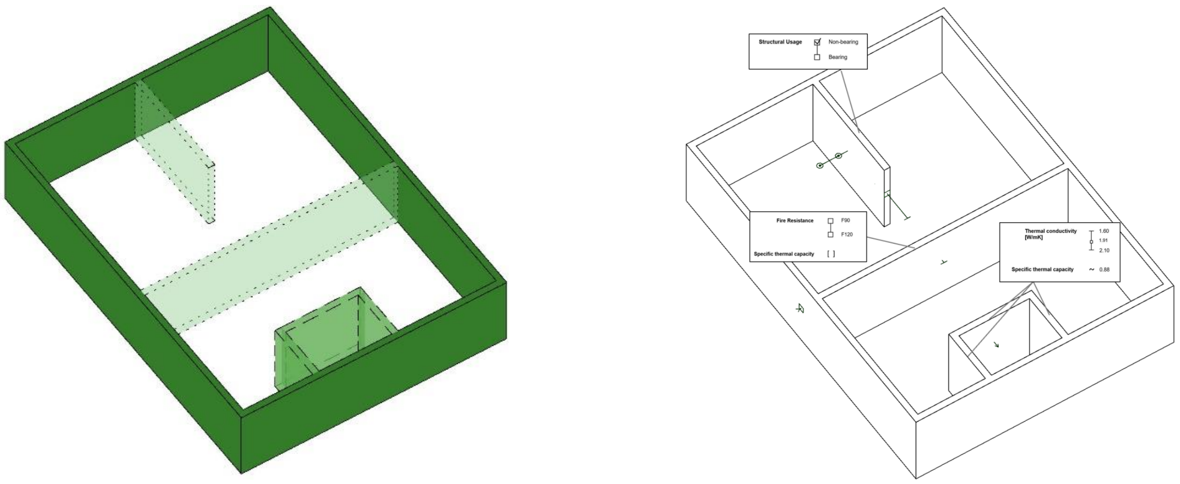


Figure 46: Left picture: Visualization of solution-specific fuzziness using filter approach. Right picture: Visualization of element-specific fuzziness using symbol approach

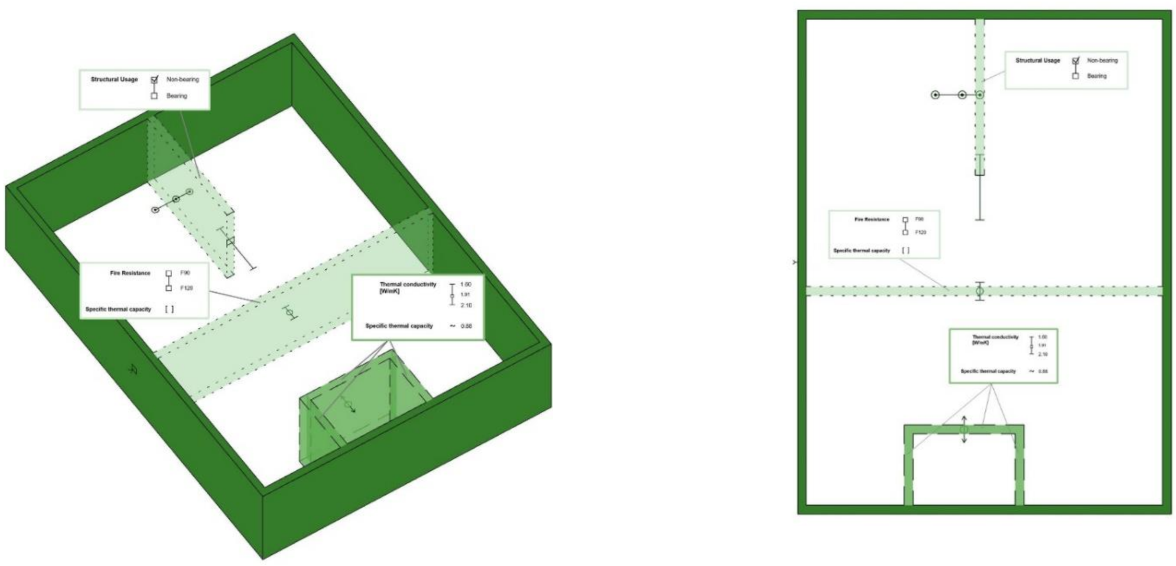


Figure 47: Combined filter- and symbol-approach for visualizing solution- and element-specific fuzziness

Visualization B

The Visualization B is based on the modifications of visual variables regarding the filter-approach and the same symbols comparable to Visualization A (Figure 48). In addition, the visualization provides the representation of element-specific fuzziness using the animation approach and is visualized using the walkthrough-view. The Visualization B was saved as .exe-file and as video[9].

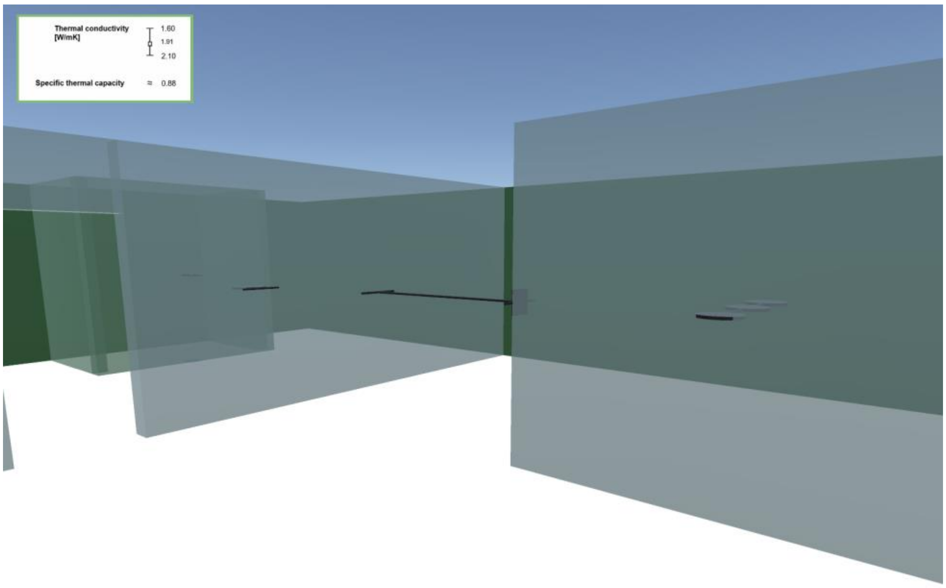


Figure 48: Fuzziness visualization as walkthrough using Unity

[9] The video can be accessed using following link: https://tumde-my.sharepoint.com/:f:/g/personal/fritz_beck_tum_de/Es36dstyjjdHn2Fd8OXHCKBowA78V65ok_hxGWzFZUnNw?e=ptMF74

7 Evaluation

At the begin of this chapter, the research task is repeated. Afterwards, the structure of the evaluation and the used software products are described. Finally, the results of the conducted survey depicted and explained. This chapter serves as documentation of the conducted survey.

7.1 Limitation of research task

The research task was limited to several characteristics of fuzziness, which are represented in previous chapter. Among others, the communication of the source of fuzziness by adequate visualizations won't be part of the evaluation and the visualization of different alternatives and variants is neglected.

7.2 Structure

In the beginning of the evaluation, the test persons have to answer questions concerning their profession and are asked if they are familiar with CAD-drawings. These questions are necessary for the exploration of a connection between the submitted answers and their profession or their previous knowledge.

For the successful evaluation, the mental models of the sender and receiver have to be compared to identify the informational distance between these models. This comparison will be carried out by abstracting the mental model of the sender to CAD-models including the developed fuzziness visualization. Subsequently, the receiver of the message must answer some questions regarding the visualization. The aim of the evaluation is proving if the developed visualization approach is intuitive and usable as basis for further research and development.

To provide an understandable framework for the test persons, a short story delivers some important information: "In the early design stages, the architect has created a building model. However, he is not sure about some information of the model and wants to communicate this uncertainty with you. For that, the architect has developed a visualization approach." Since the linguistic ambiguity of the term "fuzziness" leads to misinterpretations, the term was replaced here with "uncertainty". Among others, the story contains the information that some model information is fuzzy and that the source of fuzziness are uncertainties in the early design stage. This information is relevant for the correct interpretation of the developed visualization approach and, thus, for the reduction of the horizontal informational distance between both sender and receiver.

The original idea for the further evaluation was to provide an incomplete legend explaining the used symbols and colors and the test persons should fill the respective gaps. Multiple potential answers are provided for each gap to reduce the complexity of the task. The provided legend shows the test persons that the visualization approach is structured and contains information that there is a distinction between geometric and semantic attributes. Additionally, the legend contains the information, that the different colors and boundary lines refer to the current solution.

The concluding questions aim to get information about potential improvements and application scenarios from the view of the test persons. Furthermore, the test persons are asked if they like the visualization and if they can imagine using it.

7.3 Software products

For the creation of the survey, the web-based application Google Form was used. Google Forms[10] is a tool for the creation of questions and acquisition of respective answers. The results can be visualized either directly in the web-browser or exported to other formats like .xlsx from Microsoft Excel. In spite of limitation concerning the creation of an adequate layout for the survey, Google Forms was sufficient for the evaluation. The web-based tool was chosen, due to the simple handling.

7.4 Documentation

The documentation of the survey can be accessed using following link: https://goo.gl/forms/Xwbn8oayHtitnBjK2 (last revised at 5th of March 2019). In addition, the questions and their results are documented in Attachment A. The link to the evaluation has been sent to potential participants on the 05th March 2019 using WhatsApp and E-mail. The majority of participants were employees of the structural engineering office Bollinger&Grohmann. Furthermore, the evaluation was sent to fellow students with AEC-background and friends with and without AEC-background. The participants do not have any previous knowledge about the fuzziness visualization and its meaning or deeper knowledge about the content of the thesis. After receiving 24 submissions

[10] https://www.google.de/intl/de/forms/about/

the survey was rated to provide a reliable basis for a valid analysis. Consequently, the evaluation was disabled on 12th of March with a total of 24 submissions.

7.5 Results

There are two ways how the results can be accessed from google forms: the results of individual questions are depicted as diagram within google forms. These diagrams are represented in Attachment A below the respective questions. Additionally, the results of the survey can be downloaded as table[11] (e.g. for Excel). The downloaded table contains more detailed information comparable to the diagrams in google forms. For instance, the table represents the submitted answers for each participant, who are identified based on the submitted time. Using this information an analysis was carried out to identify if there is a relation between the submitted answers and the profession. the conclusion in chapter Since the submitted answers (especially concerning geometric attributes) were rather divers, it is worth mentioning that one person has interpreted (almost) all symbols correct and evaluated all symbols as “clear”.

The diagrams in Figure 49 shows that the major part of the participants are from the domain civil engineering and are working in the industry or studying in the master program. The Figure 50 depicts that the most participants are rather familiar or familiar with floor plans or CAD-drawings.

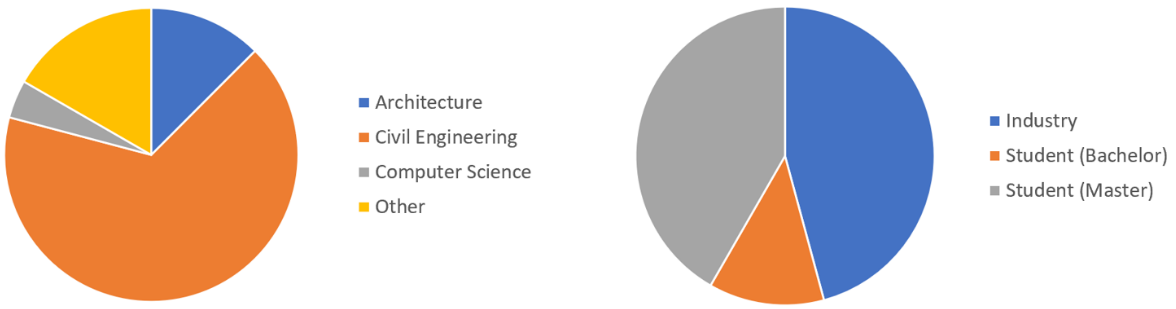


Figure 49: Left: Domain of the participants. Right: Profession of the participants

[11] The results can be accessed using following link: https://tumde-my.sharepoint.com/:f:/g/personal/fritz_beck_tum_de/Ei8YBqsXfWRLlVMjjS2cMSYBaqJGSkX-0TW2kgK6Or7yMw?e=5MbmvV

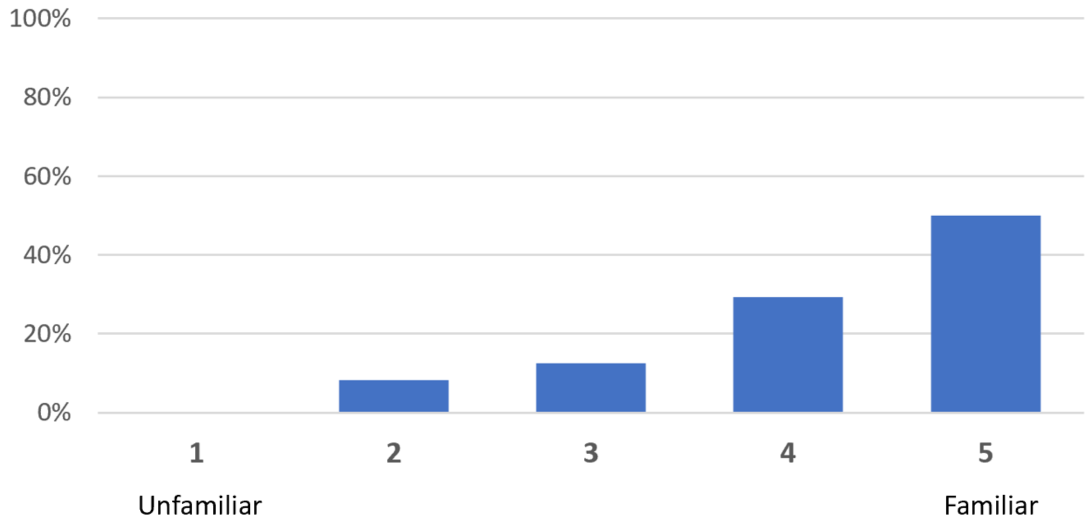


Figure 50: Answers to the question if the participants are familiar with floor plans or CAD-drawings

The transparent walls and the walls with dashed lines were perceived from the major part as uncertain. The walls with “info boxes” and the walls with symbols were interpreted from less than the half of the participants as not certain. Almost all persons recognized the solid filled walls and the walls with solid lines as certain (Figure 51). The different color hues/ values and border line styles of the respective walls were referred by the participants to design stages, vagueness or probability. The distribution between the three answer possibilities is almost equal. Only one person selected “I have no idea” and one person added “load bearing” (Figure 52).

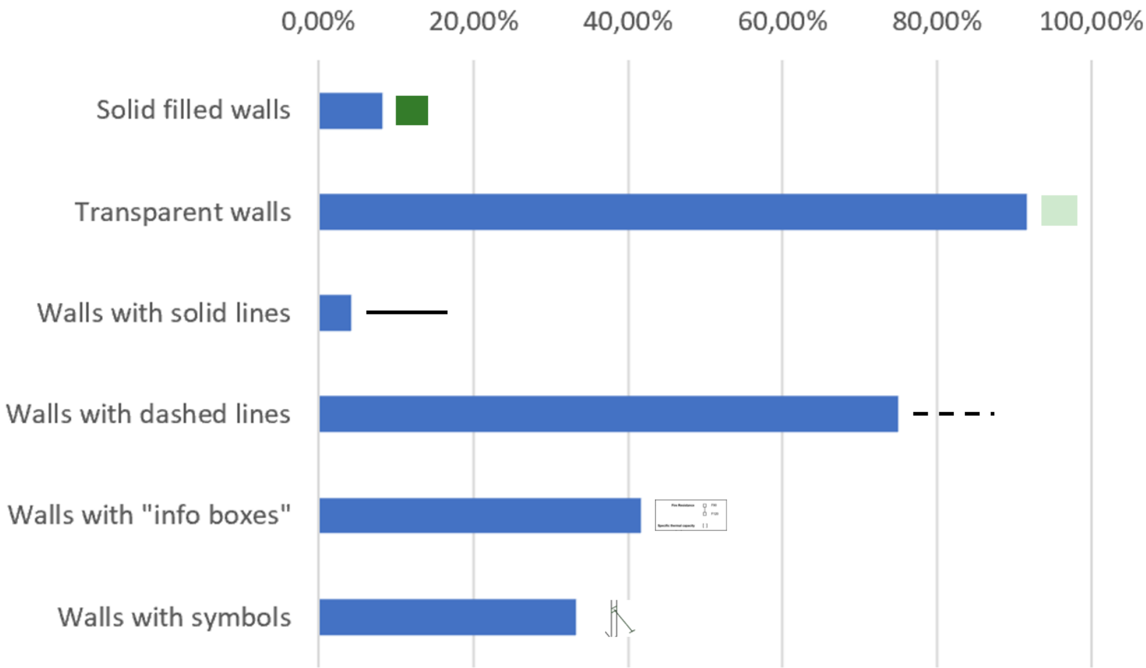


Figure 51: Perception if respective representation of walls refers to certain or uncertain

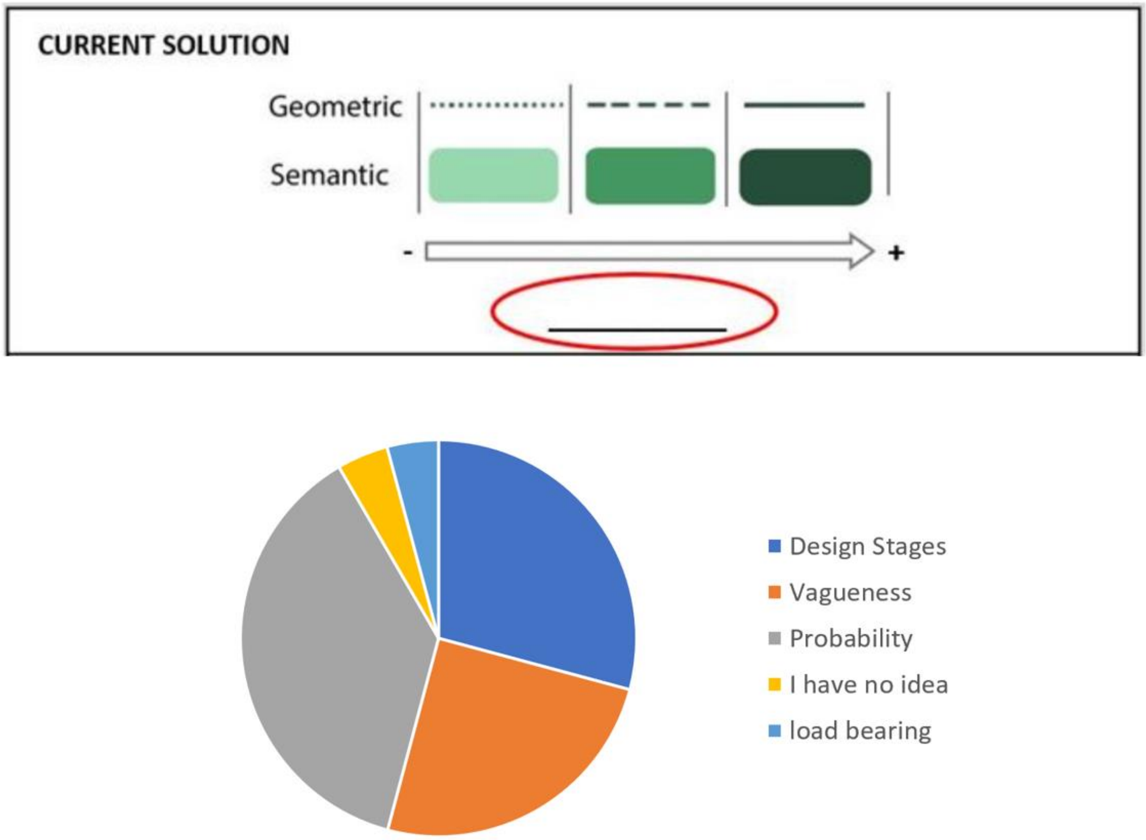


Figure 52:Top: Repetition of the figure from the respective question. Bottom: Interpretation of the color value and hue or border line style by the participants

In Figure 53 the correct answers concerning the questions about the symbols depicting the geometric reference attributes and the semantic and geometric nature of fuzziness are represented. The reference attribute position was recognized by almost 80% and the reference attribute surface position was recognized by almost the half of the participants. None of the individual symbols concerning geometric nature of fuzziness were interpreted correctly by more than 40%. In contrast to that, the symbols concerning the semantic nature of fuzziness were interpreted correctly by a major part. Comparable to the correct interpretation of the geometric and semantic symbols, the respective symbols were rated as *clear* or *rather clear* (Figure 54). The contrary part shows the rating respective to *unclear* or *rather unclear*. It is remarkable that there were more ratings for clear or rather clear than correct interpretations of the respective symbols.

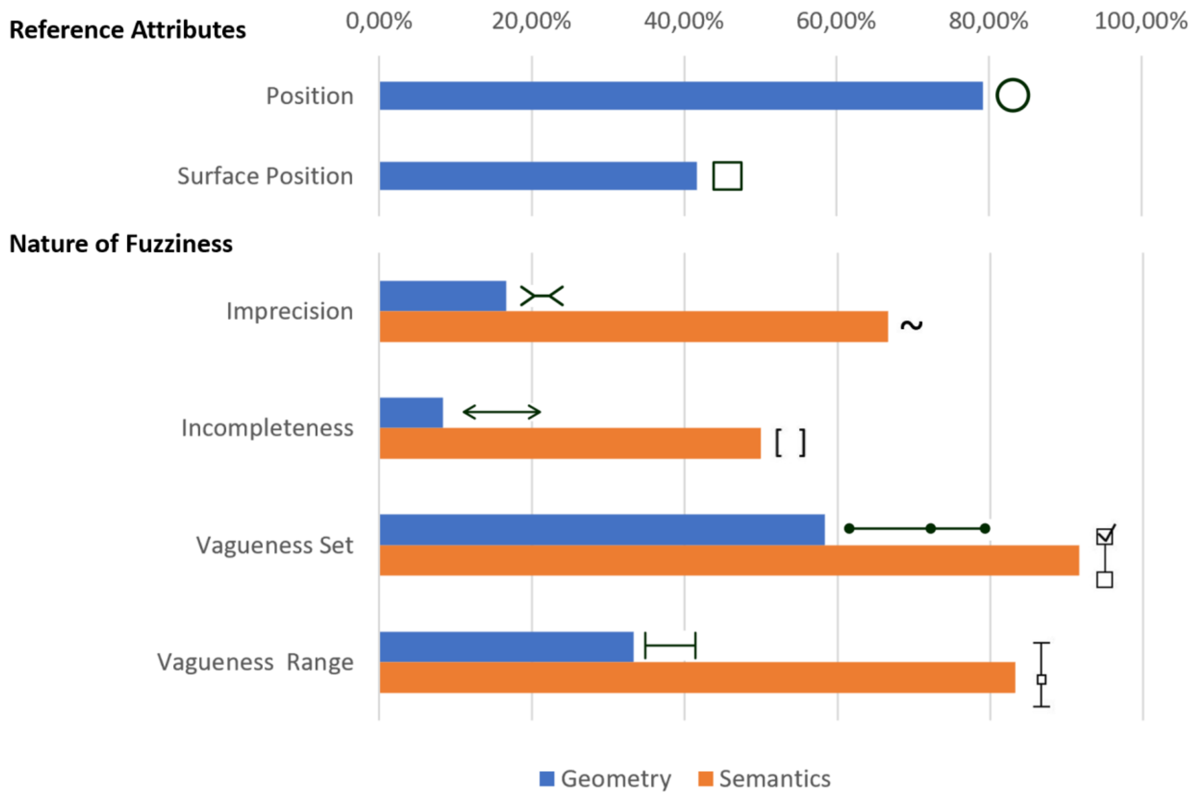


Figure 53: Correct answers concerning the interpretation of the respective symbols in percentage

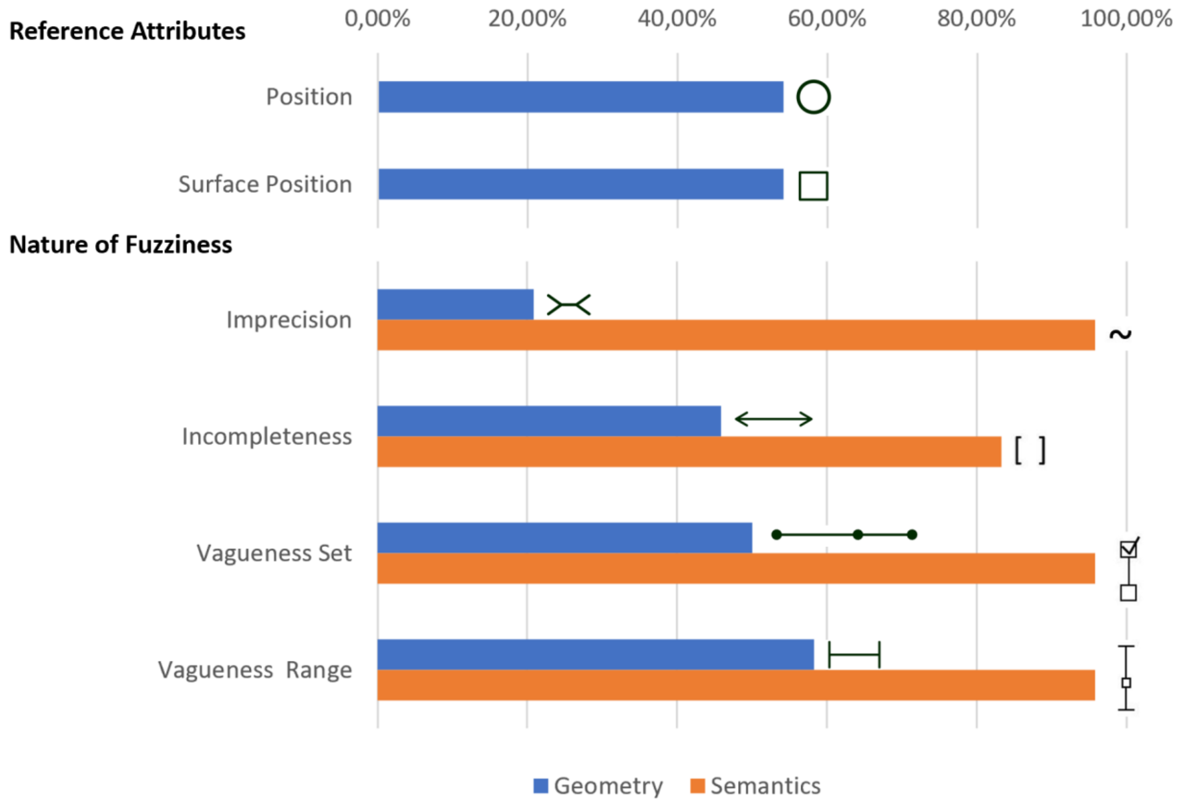


Figure 54: Rating as clear or rather clear concerning the interpretation of the respective symbols in percentage

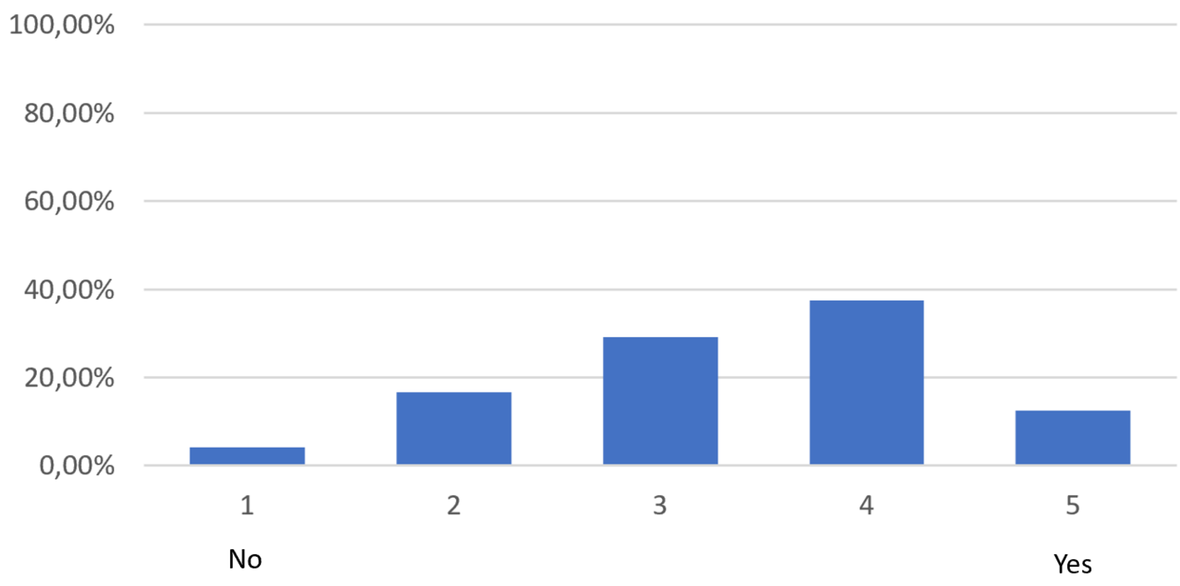


Figure 55: Answers to the questions if the participants like the visualization approach

Answers concerning the question if the participants like the visualization approach are distributed but tending to the answer that the participants like the approach (Figure 55). There are two suggestions concerning the question if the participants have ideas for improvements, which seems to be relevant for the interpretation of the results:

- "For the planning process I would keep it simpler. Probabilities are hard to quantify in the daily planning process. Furthermore, that could be an additional bureaucratic effort in projects. […]" [translated by the author] (civil engineer, industry)

Furthermore, there are two beneficial answers regarding the question, when the participants would use that visualization:

- „During the design phase and subsequent modifications for revised planning and requests from the owner. Thus, also to the end of the project. The visualization is a good measure to represent the confidence to the building." [translated by the author] (civil engineer, industry)
- "If I would use it [the visualization approach], then only to communicate with other Engineers. I don't think a client would be able to understand the symbols if he doesn't have a technical background." (civil engineer, student (master))
- "Yes. I think it would be a good approach in the early design phase. I can imagine that it makes the communication between civil engineers and architects easier. "(architecture, student (master))

8 Discussion

The chapter provides an interpretation of the results from the conducted survey and the conclusion regarding the fuzziness visualization. Furthermore, potential applications of the fuzziness visualization are deduced. These potential applications are based on the conclusion and personal experiences during a job at a structural engineering office. After that, research questions concerning the definition, categorization, visualization and communication of fuzziness are described.

8.1 Interpretation of results

Among others, the result of a survey depends on several characteristics of the survey itself. For instance, an unclear or ambiguous question leads to a high diversity of answers and, thus, is not adequate for a clear interpretation of the result. Another distortion of the result could be based on a lack of motivation of the participants, what leads to random answers regardless the respective question. Furthermore, lack of time could yield to submissions of random answers or insufficient observation of the visualizations. These circumstances concerning a potential distortion of the results have to be considered for their interpretation. Additionally, the informative value of the survey is related to the number of participants. The number of 24 completed submission is considered being sufficient for the results interpretation with respect to the purpose of the survey and the objective of the thesis. However, there were too few submissions to have a reliable basis for a relation between the submitted answers and the profession.

Since the walls with transparency or dashed lines were recognized as uncertain by most participants, these representations could be useful for a quite generic visualization of fuzziness. The walls with symbols and information boxes were less often recognized as uncertain, what could be the result of different interpretation of the symbols or the questions. Since some participants have not recognized the symbols as representation of uncertainties/ fuzziness, an explanation of the visualization is necessary for avoiding misinterpretations of the fuzziness visualization.

There was no major answer which was given concerning the meaning of the different color values and border line styles. Despite of providing the information that it represents uncertainty, the visualization is not clear and, thus, needs an additional explanation. The meaning of the symbol representing the position of the walls were recognized but voted quite neutral concerning the clearness of the symbol. This could be due to inadequate provided choices concerning the symbol interpretation or the circumstances of being unused to the visualization approach. The diversity of answers concerning the reference symbol for the position of the bounding face (rectangle symbol) could be based on difficulties raised by the linguistic ambiguity of the used term “position surface” or on the inadequate symbol itself.

The symbol concerning geometric imprecision was rated as “unclear” and the main answer was “I have no idea”. Similar results were identified for the symbol concerning the missing information. Thus, these symbols are not understandable without explanations and the gestalt of the symbol could be improvable. Since the majority of participants have recognized the vagueness set symbol correctly, this symbol seems to be intuitive. The symbol concerning the vagueness range was in general recognized either as vagueness set or range. Thus, an additional explanation of the symbol is recommended when using it in visualizations. The submitted answers concerning the clearness of additional probability distribution for geometric vagueness set and range were miscellaneous. This result could be based on the different interpretation of the clearness of a symbol. While some persons consider the meaning of the symbols with probability distribution within the context of the whole presentation. The question about the origin of the probability distribution could result in an unclear interpretation of the symbol. In contrast to that, other persons could consider only the probability distribution and the symbol itself, which could result in the answers “clear” or “rather clear”.

All symbols concerning the semantic attributive fuzziness were generally rated as “clear” or “rather clear” and were recognized correctly. This result could be based on the circumstances that the participants are used to these symbols, since the symbols are adapted or derived from well-known symbols, e.g. “~” as mathematical expression. Furthermore, the reference information is clearly represented using textual language. Both circumstances are simplifying the interpretation of the symbols, such that an application without a closer explanation is conceivable.

8.2 Conclusion

Following the interpretation of the results, the symbols for the element-specific fuzziness representations cannot be used without additional descriptions. Similar conclusion can be made regarding the filter approach for visualizing the solution-specific fuzziness. Since the interpretation concerning the filter- and symbol approach results in a high diversity, a common understanding of the visualization is not provided and, thus, an explanation of the visualization approaches is unavoidable to ensure a reduction of horizontal distances between the mental models of the sender and receiver. The usage of the proposed visualization without explanations to ensure a common understanding of the visualization approach could result in ambiguous representation of the information. This could be an obstacle concerning an efficient communication of holistic information including deviations to accurate descriptions in the BIM-based design process.

The combined visualization approach including solution-specific and element-specific fuzziness seems to be rather confusing for the participants of the survey. The participants perceived a relation between displayed colours and border lines for the solution-specific fuzziness and the symbols for the element-specific fuzziness. Since this relation is not intended, a separated representation of solution-specific fuzziness using filter-approach and element-specific-fuzziness using symbol-approach is recommendable for the efficient communication based on the developed fuzziness visualization.

Since visualizing fuzziness is neglected in current BIM-based information and communication tools and fuzziness is an integral part within the design and its communication processes, a small-scale improvement concerning the effective communication of fuzziness could result in a noticeable added value for the project goals in terms of cost, quality and duration. Hence, the reduction of complexity regarding the fuzziness visualization could be senseful for the effective communication within BIM-based design and planning processes. The fuzziness does not have to be represented in a holistic manner but has to be visualized respective to the task to be carried out. The idea of an improvement concerning the communication in design and planning process has to be investigated and verified consequently.

8.3 Potential applications

Based on the conclusion and experiences in the structural engineering office Bollinger&Grohmann, two potential application of the proposed visualization approach were deduced. The following potential applications are the result of inspirations from real projects and extended for demonstration purposes to thought experiments. Thus, the following potential applications are suggestions and not verified. The drawings and building projects were replaced by fictional documents and projects.

8.3.1 From drawings to BIM-model

The structural engineering office receives floor plans and sections of a building (Attachment B) from the architect. Based on these drawings the structural engineers want to create a BIM-model for demonstration and analysis purposes. During the modeling process, the responsible engineer discovers conflicting and missing information within the received drawings (source of fuzziness) concerning building elements (element-specific). The thickness of the ceiling is either 30, 28 or 25 cm (vagueness set), the height of the door is missing (incompleteness) and thickness of one wall is 0.197 cm instead of 0.20 cm (imprecision). However, asking the architect for the respective values would take time and, thus, he decided to visualize the conflicting and missing information using the fuzziness visualization approach (Figure 56). Due to the applied visualization approach the architect can see which information are missing and the structural engineering office members see where they should be careful concerning the structural analysis. Additionally, the fuzziness would be fall into oblivion after a while, without visualizing the conflicting and missing information. Hence, the fuzziness visualization could be essential regarding documentation purposes.

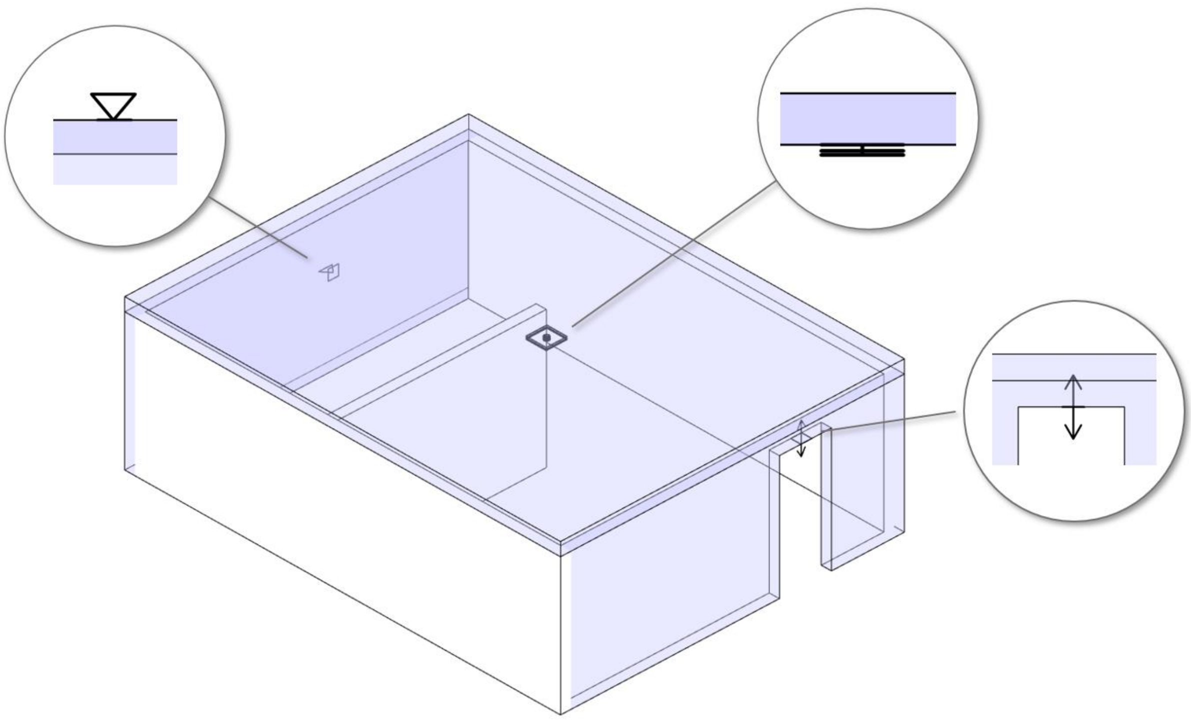


Figure 56: Symbol-approach for communicating conflicting and missing data based on drawings

8.3.2 Communication during design process

A structural engineering office has to model the foundation of a building in early design phase. However, they are not sure if they will need a strip foundation without piles, a strip foundation with piles or a foundation at all below the walls (solution-specific fuzziness). However, they have to submit a model for a first information exchange. They decided to model the strip foundation, since it seems to be the most likely solution, and visualized it using the developed visualization approach: Light green, transparent and dashed lines (Figure 57). Thus, the receiver can see that foundations are only a draft solution and not determined absolutely. For the next design step, they decided to proceed with the strip foundations without piles (Figure 58) and the next version of the model has to be submitted soon. This time, the width of the foundation of the inner wall is unclear. Since the structural engineers want to communicate the lack of information with the architect, they added the respective symbol (geometric incompleteness) to the width of the strip foundation.

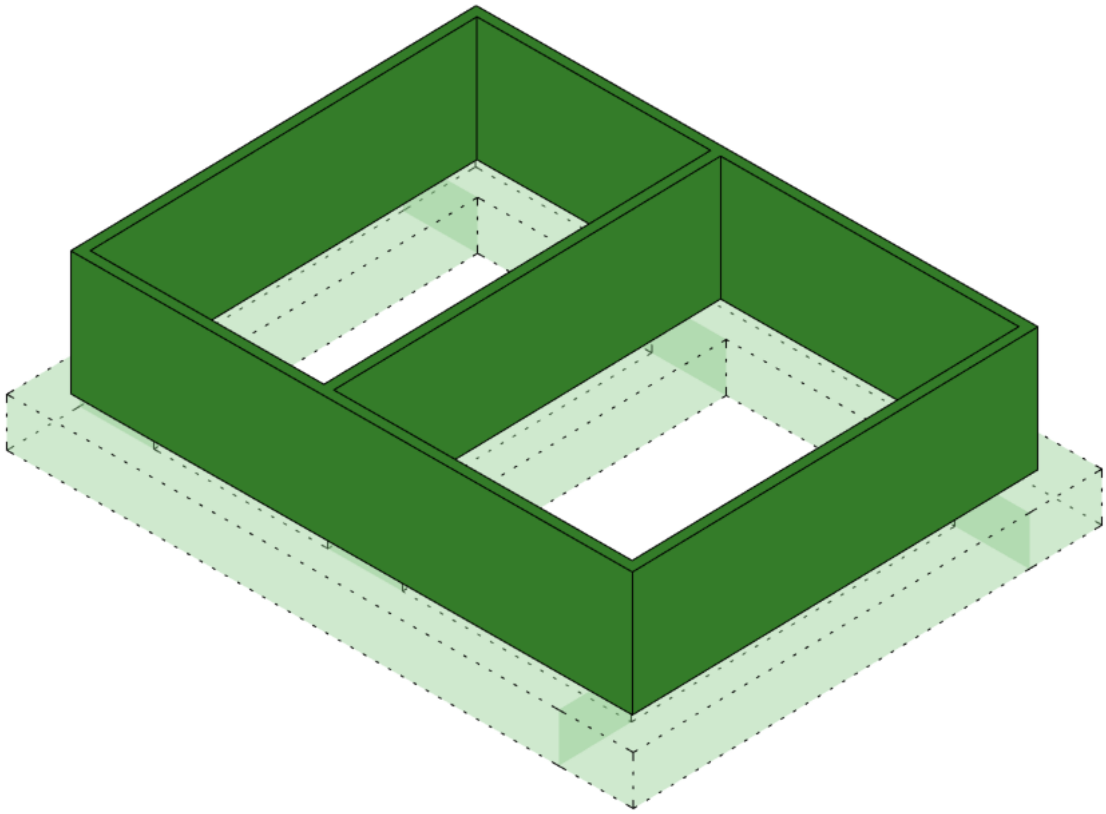


Figure 57: Solution-specific fuzziness visualization: The nature of solution concerning the foundations is not fixed

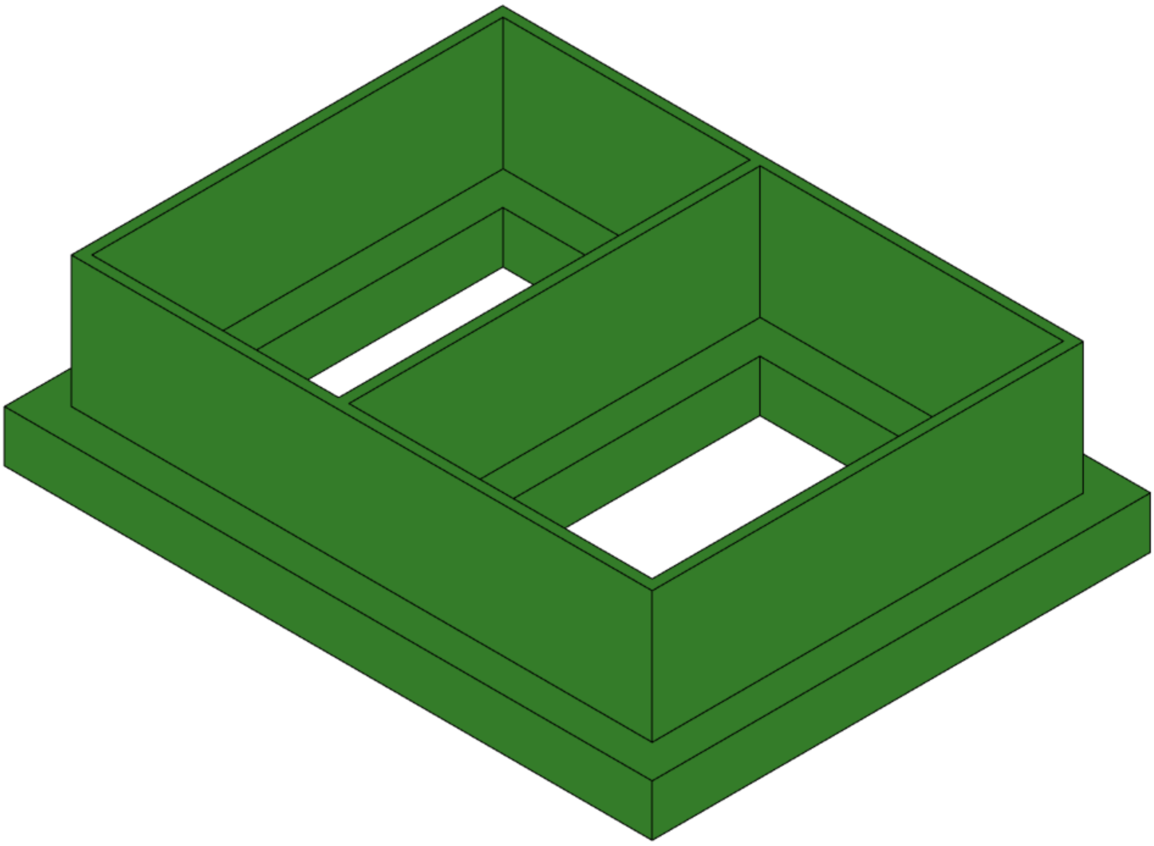


Figure 58: Solution-specific fuzziness visualization: The nature of solution concerning both walls and foundations are fixed

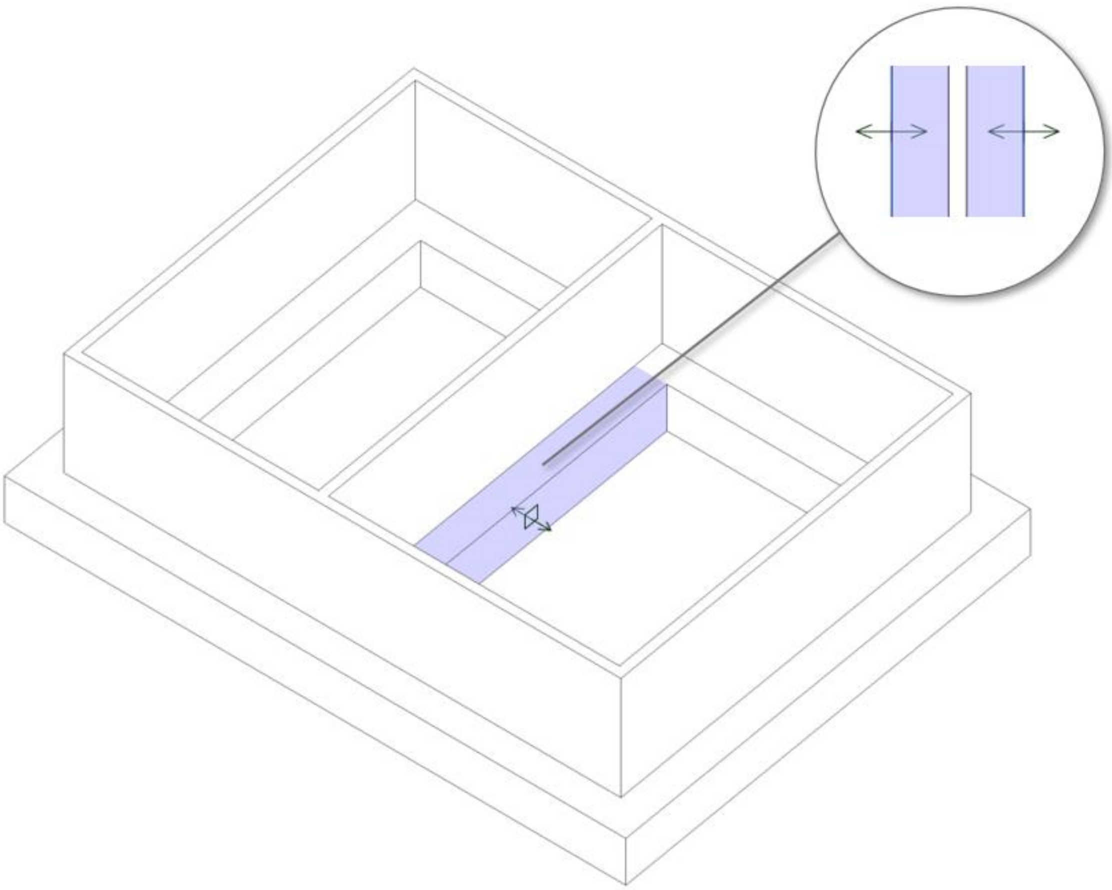


Figure 59: Element-specific fuzziness visualization: The width of the foundation below the inner wall is not fixed

8.4 Research topics

The objective of the fuzziness visualization is the effective communication of the fuzziness in the BIM-based planning process. An integral part of the thesis refers to the definition and categorization of fuzziness, although the topic of the thesis refers to the visualization of fuzziness. Thus, the discussion of the research topics is subdivided into the parts definition-, categorization-, visualization- and communication of fuzziness.

Definition of Fuzziness

A general definition of fuzziness and uncertainty and its distinction is relevant to provide a common basis for further research concerning the BIM-based communication of fuzzy information. In the thesis, fuzziness was defined as the informational distance to the degree of a complete, accurate description within a particular model world. This conceptualization of fuzziness could be extended regarding the differentiation of design steps. The complete, accurate description of the model could refer to a generalized or abstracted model with respect to the design steps (e.g. Level of Development). Hence, fuzziness would be part of the required model in terms of Level of Development and the BIM-Model could be complete and accurate regarding the respective design step. Fuzziness as part of the required model in terms of Level of Development is investigated by Abualdenien & Borrmann (2019b)

Categorization of Fuzziness

The developed categorization could be used as a research basis and extended, since the consideration was not exhaustive. Fuzzy building information is rather part of an open, linked system than a closed system without any connections to other elements and environments. These connections could be further investigated by the systematic theoretical approach (see for instance Schmid, 2015; Menges & Ahlquist, 2011), which is part of the third planning generation according to Schönwandt (2002). Furthermore, the ambiguity as informational distance to a complete, accurate description was neglected in the thesis. As promising approach concerning the reduction of ambiguous information concerning Building Information Modelling is the application of formalizing knowledge in terms of ontologies and semantic web technologies, which is investigated by Beetz (see for instance Beetz, 2009) and Pauwels (see for instance Pauwels, Zhang, & Lee, 2017). The value of fuzziness (e.g. probability value) was only sparsely discussed and must be further investigated. Further researches could for instance address the questions, how to quantify fuzziness values and if the quantification is useful. Furthermore, fuzziness could be categorized further using an abstracted and generalized model (e.g. Level of Development) as reference model. In the thesis, the reference model is an abstracted model. Consequently, *too much information* as a characteristic of fuzziness could be introduced.

Visualization of Fuzziness

The symbols have to be adapted and evaluated regarding more complex geometries, since the proposed visualization was developed using walls as reference objects. For instance, the reference geometric attributes could be the diameter of column or a complex curved surface. In the proposed visualization some characteristics were neglect to ensure the success of the evaluation by reducing the complexity. For instance, the source of fuzziness and the different alternatives were not visualized. Further research could address the visualization of these characteristics to represent and communicate fuzziness in a holistic manner. On the other side, further research could address the reduction of the proposed visualization. The evaluation results and their interpretation show that focussing on the most important information within the respective design phase could yield to an additional value for the communication in the planning process. Furthermore, interaction was not part of the evaluated visualization approach and has to be considered within the fuzziness communication process. Interaction is an integral part of the visualization pipeline (Ware, 1999/2013) and essential for the performance of the cognitive system. Thus, the visualization including interaction has to be surveyed to identify an adequate visualization approach for the fuzziness communication. Because the purpose of visualization is to help people carry out tasks more effectively" (Munzner, 2015, p. 1), an evaluation concerning the usage of the proposed visualization within a task- or problem solving process is necessary to identify its adequacy for fuzziness communication.

Communication of Fuzziness

The visualization of fuzziness is one relevant component of the communication process regarding the communication of fuzziness in the BIM-based design process. However, there are further relevant components and further research questions have to be investigated: Is the modeler able to identify and externalize fuzziness in the design process? How can fuzziness be formalized computer accessible? How could an adequate modelling approach look like? How can the information adequately be sent to the respective person? When does it make sense to communicate fuzziness and in which granularity? These questions are a segment of potential research questions which must be answered for an effective fuzziness communication in the BIM-based design process.

Attachment A

Abschnitt 1 von 6

Design-based communication

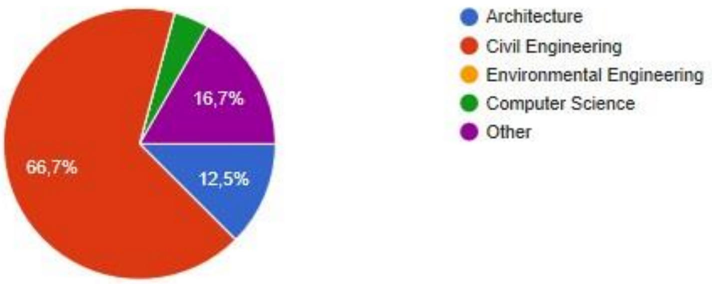
The purpose of the evaluation is to find an adequate way for visualizing and communicating uncertainties concerning the current design of a building.

As always, some questions to find out more about your previous knowledge.
And no worries, you don't need previous knowledge for the evaluation.

Please select your domain: *

- ◯ Architecture
- ◯ Civil Engineering
- ◯ Environmental Engineering
- ◯ Computer Science
- ◯ Other

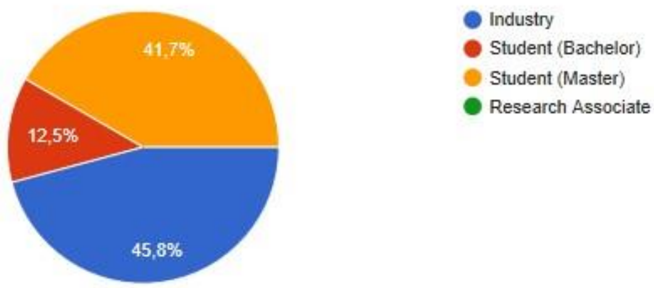
24 Antworten



Please select what fits best: *

- Industry
- Student (Bachelor)
- Student (Master)
- Research Associate
- Weitere...

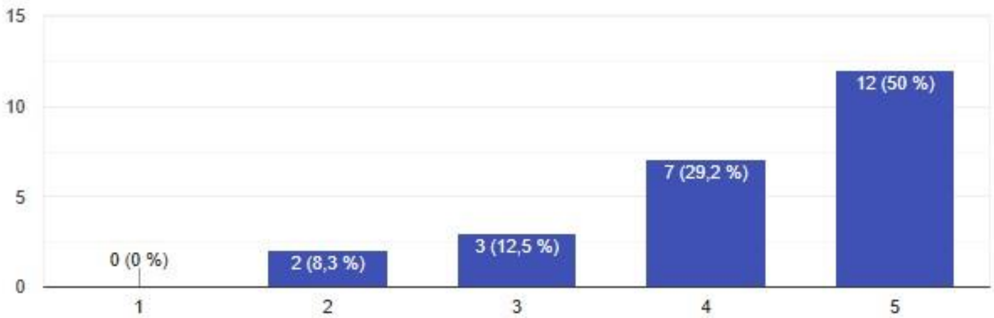
24 Antworten



Are you familiar with floor plans and CAD-drawings? *

	1	2	3	4	5	
No	○	○	○	○	○	Yes

24 Antworten

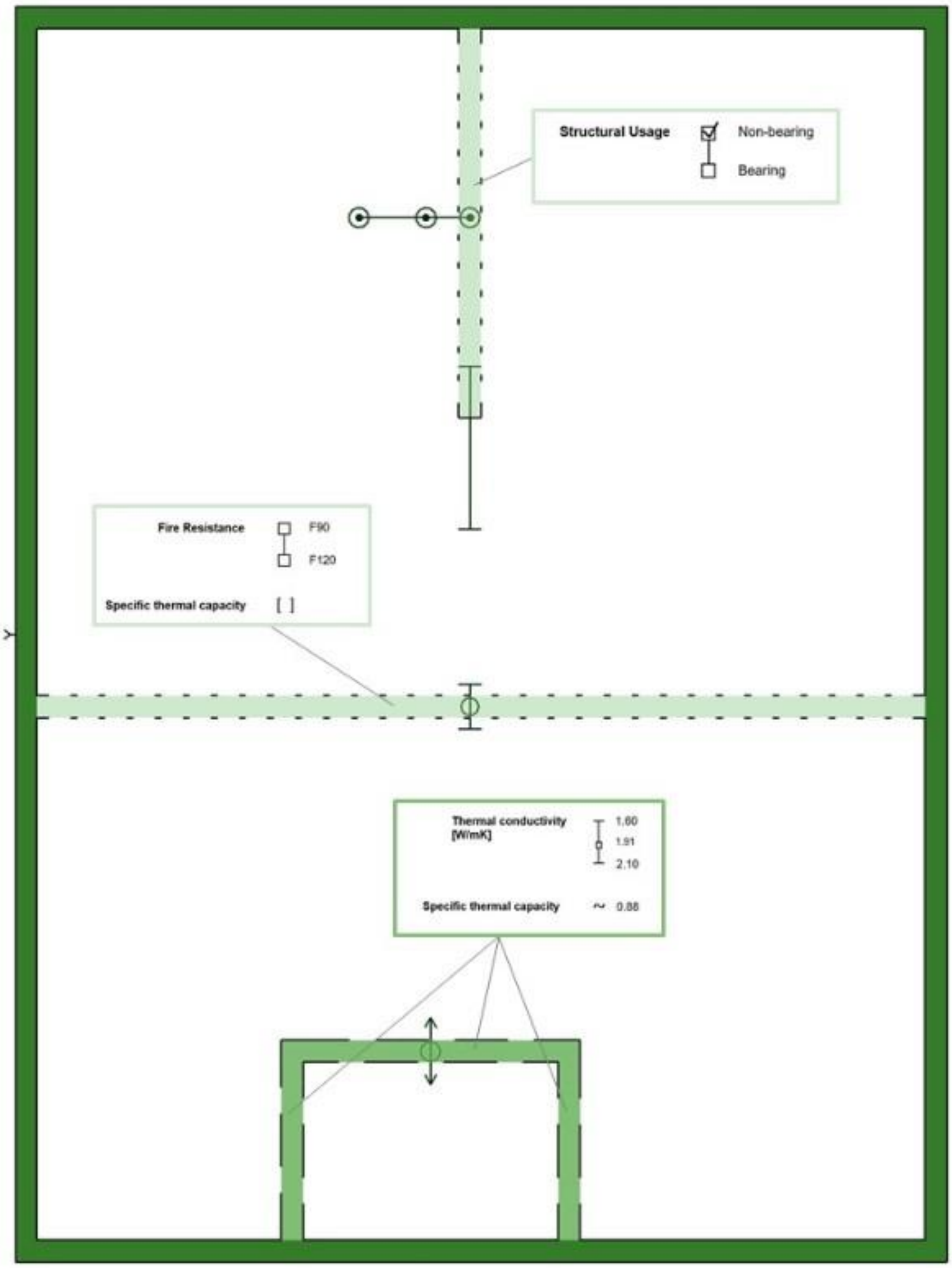


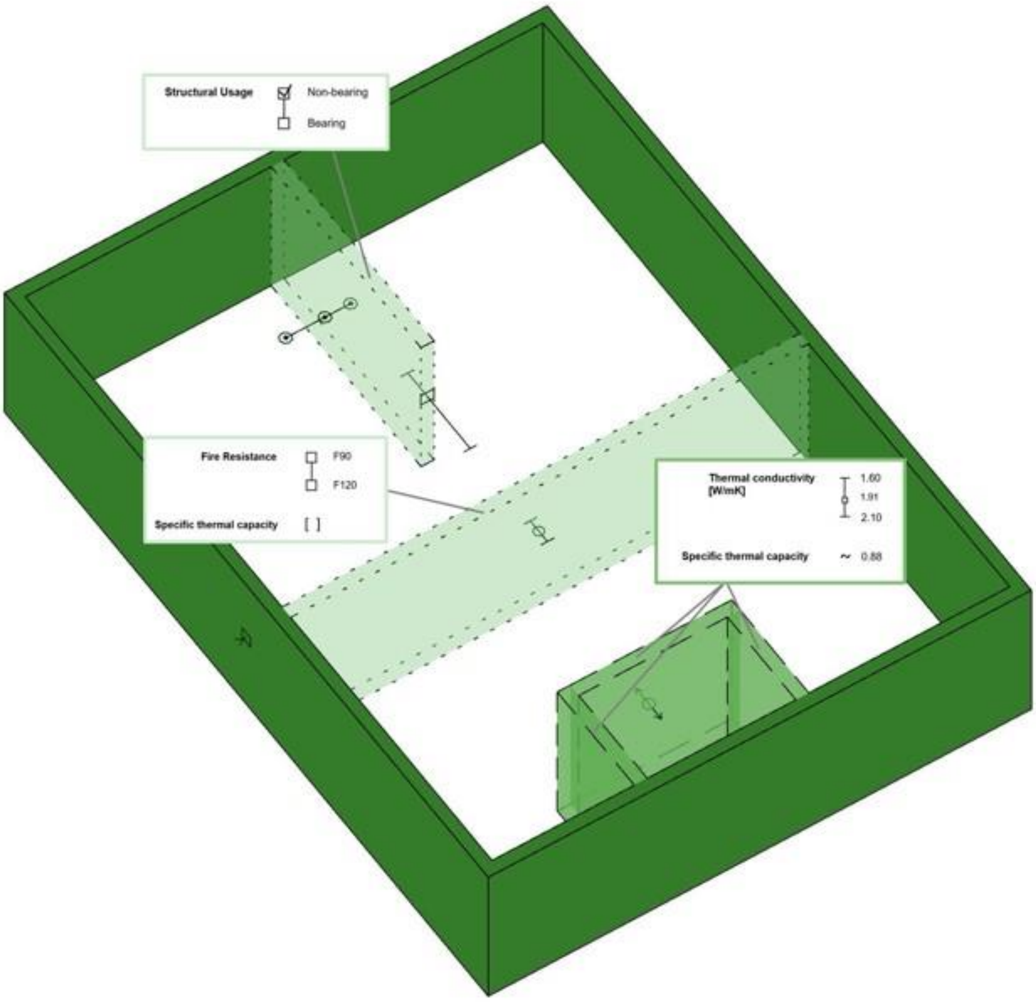
Abschnitt 2 von 6

Introduction - Part 1

In the early design stages, the architect has created a building model. However, he is not sure about some information of the model and wants to communicate this uncertainty with you. For that, the architect has developed a visualization approach.

We want to know your opinion concerning the visualization approach. Thus, there are no right or wrong answers!



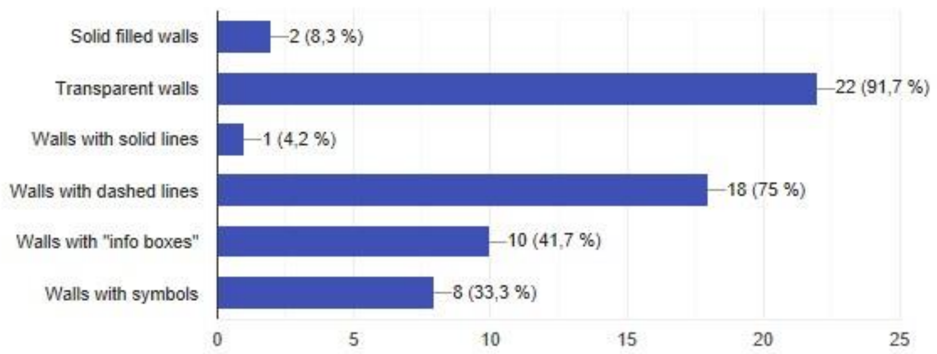

Structural Usage
Non-bearing
Bearing
Fire Resistance
F90
F120
Specific thermal capacity
[ ]
Thermal conductivity [W/mK]
1.60
1.91
2.10
Specific thermal capacity
~ 0.88

How do you interpret the visualization?

Select the walls which could be uncertain (multiple choice):

- [ ] Solid filled walls
- [ ] Transparent walls
- [ ] Walls with solid lines
- [ ] Walls with dashed lines
- [ ] Walls with "info boxes"
- [ ] Walls with symbols

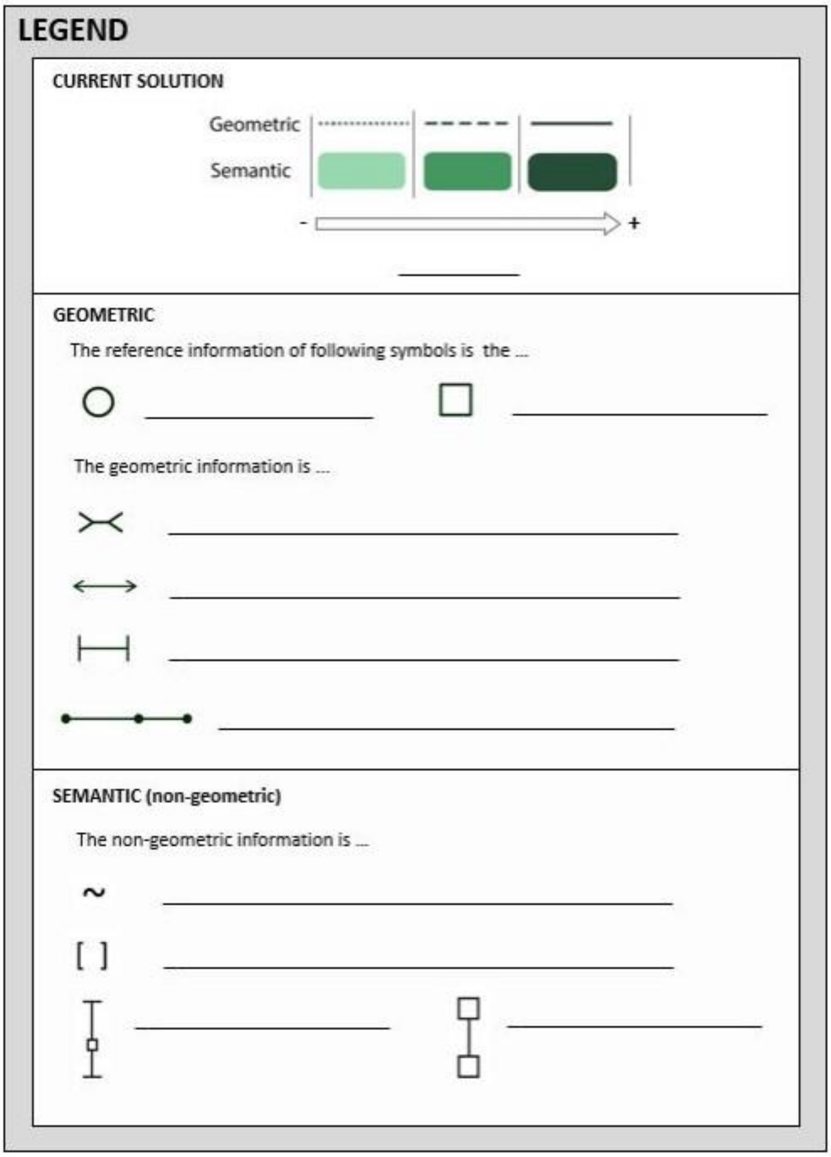
24 Antworten



Abschnitt 3 von 6

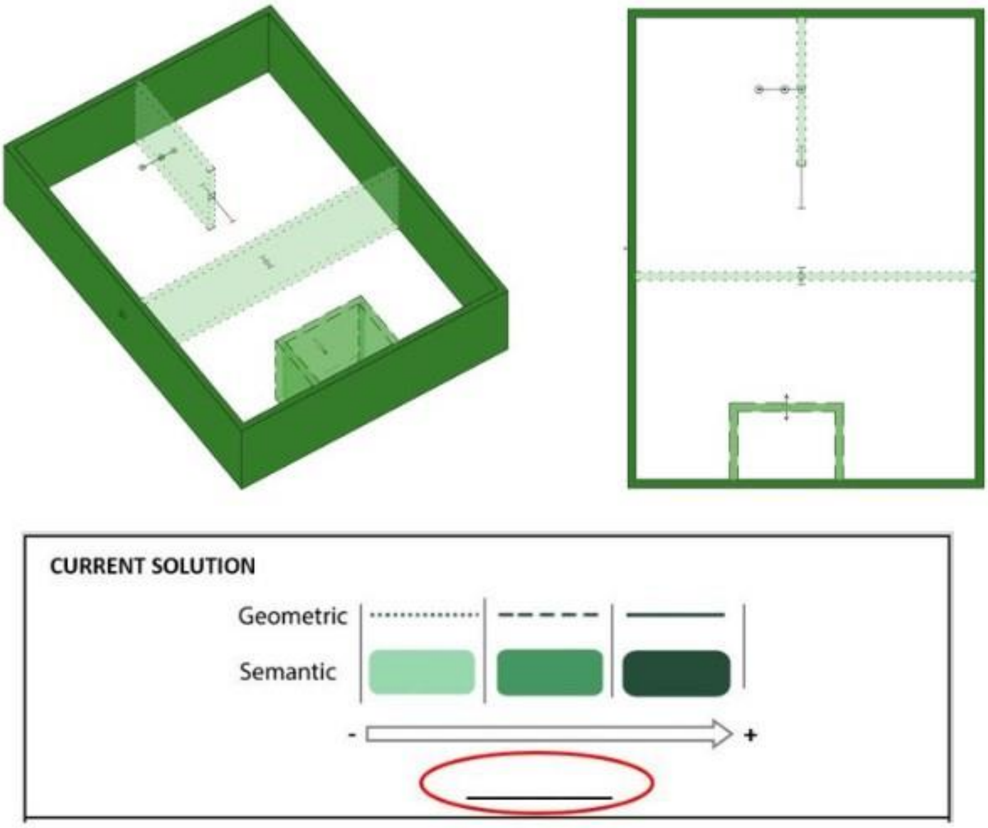
Introduction - Part 2

The architect has sent a legend describing the used colors and symbols. However, the legend explaining the visualization approach is not complete.



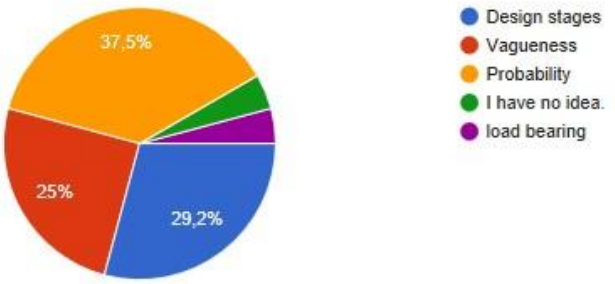
How do you interpret the used colors and symbols?

Which word fits best? (gap is marked with red circle) *

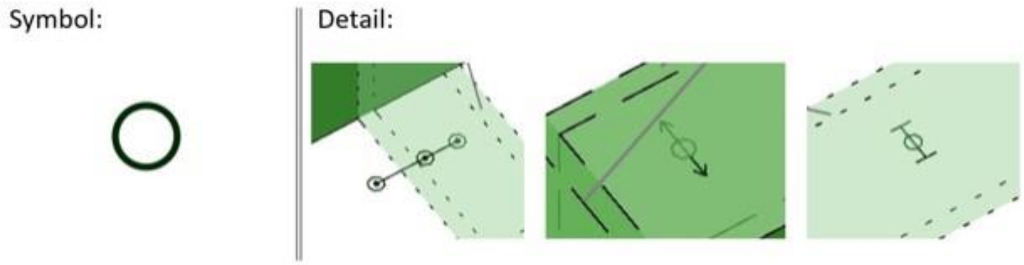


- ○ Design stages
- ○ Vagueness
- ○ Probability
- ○ I have no idea.
- ○ Weitere...

24 Antworten

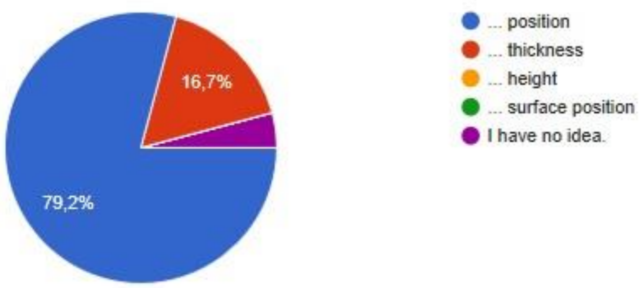


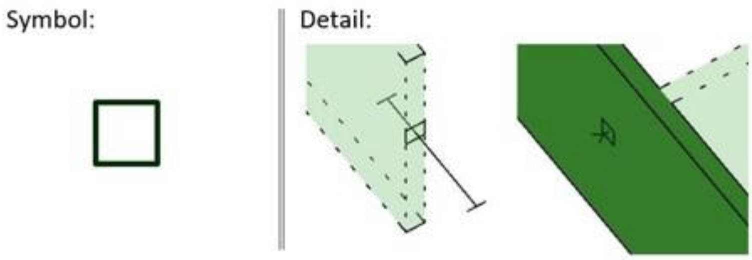
The reference information of following symbols could be the ...



- ... position
- ... thickness
- ... height
- ... surface position
- I have no idea.
- Weitere...

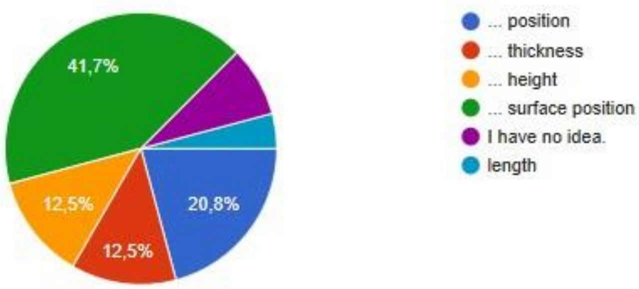
24 Antworten



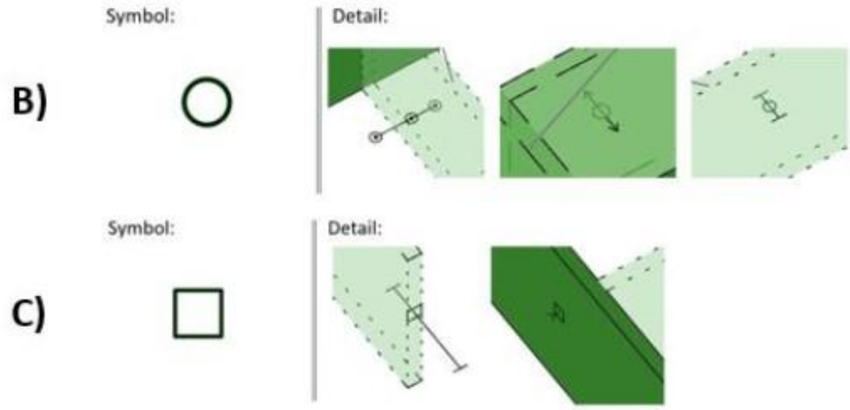


- ... position
- ... thickness
- ... height
- ... surface position
- I have no idea.
- Weitere...

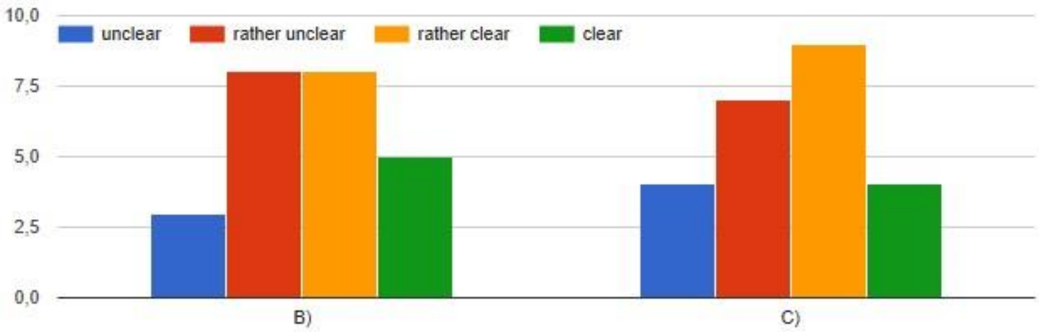
24 Antworten



Is the meaning of the symbols clear to you?



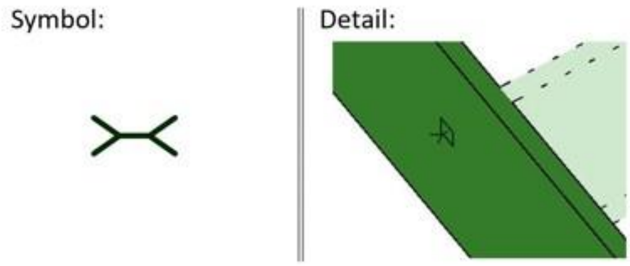
	unclear	rather unclear	rather clear	clear
B)	○	○	○	○
C)	○	○	○	○



Abschnitt 4 von 6

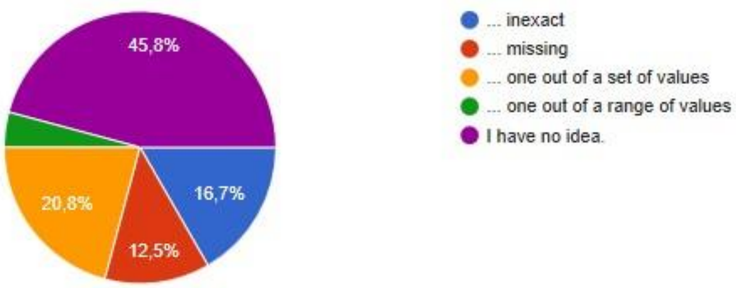
How do you interpret the symbols concerning geometric information?

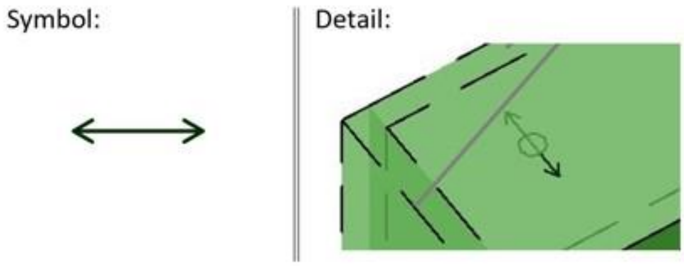
The geometric information is ...



- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of a range of values
- I have no idea.
- Weitere...

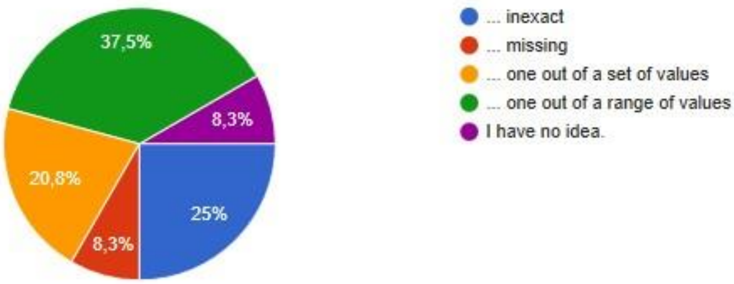
24 Antworten

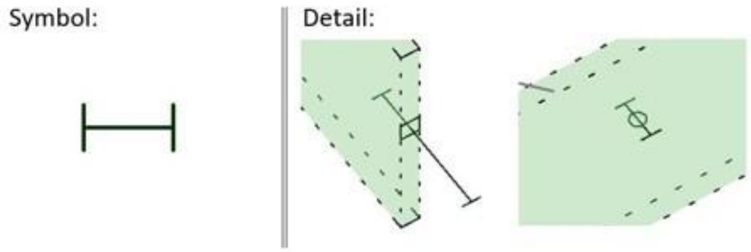


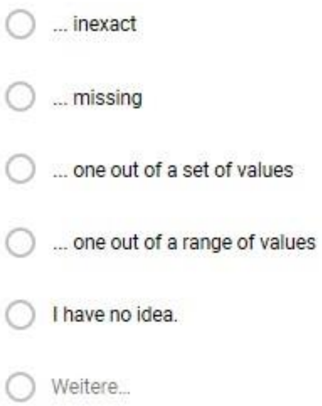


- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of a range of values
- I have no idea.
- Weitere...

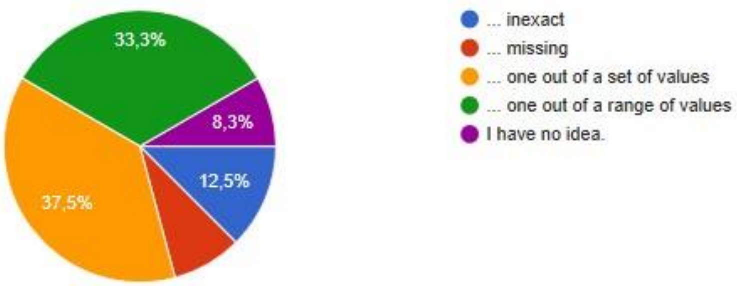
24 Antworten

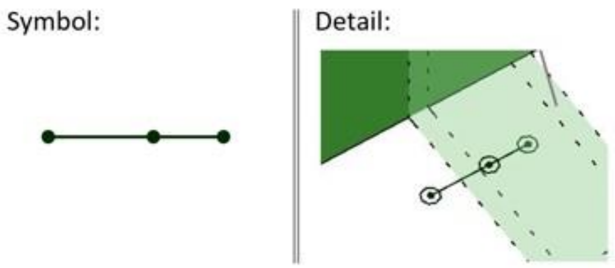






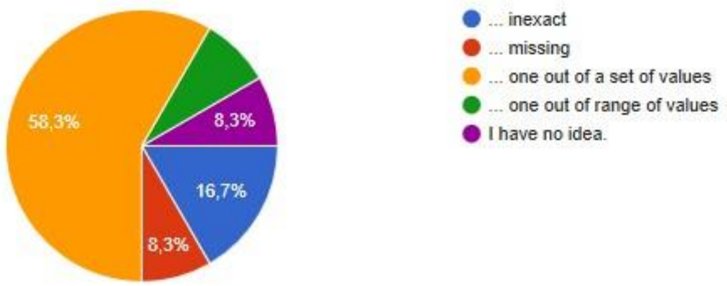
24 Antworten



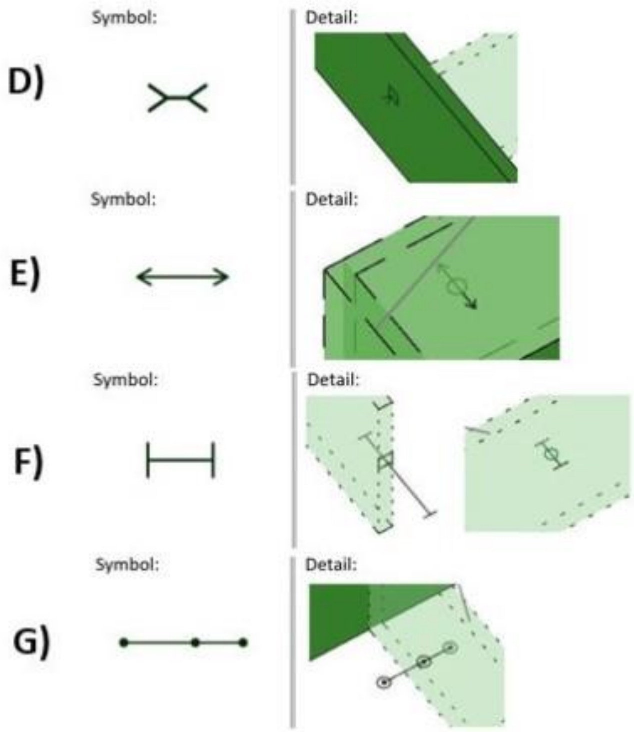


- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of range of values
- I have no idea.
- Weitere...

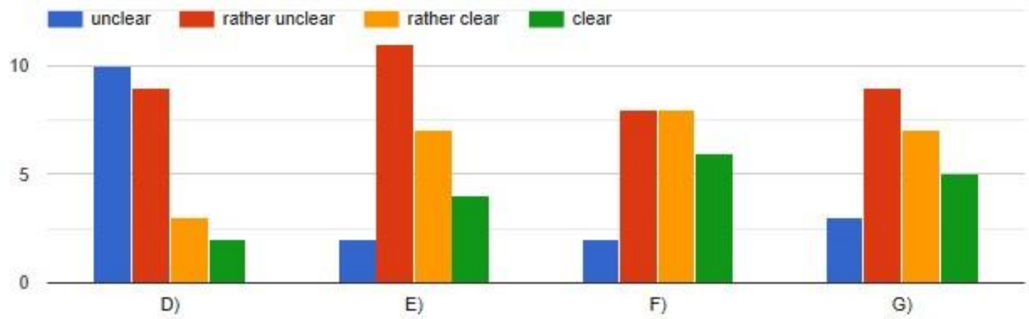
24 Antworten



Is the meaning of the symbols clear to you?

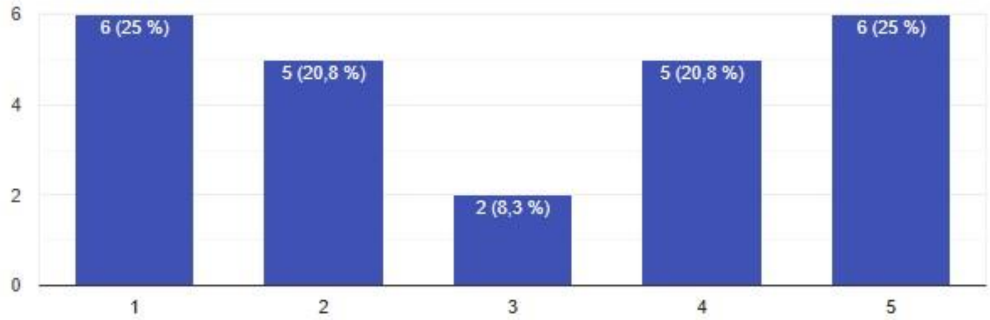


	unclear	rather unclear	rather clear	clear
D)	○	○	○	○
E)	○	○	○	○
F)	○	○	○	○
G)	○	○	○	○



Would an additional probability distribution be clear to you?

24 Antworten



Abschnitt 5 von 6

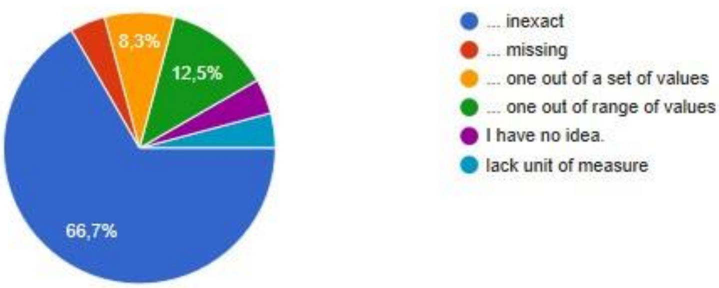
How do you interpret the symbols concerning non-geometric information?

The non-geometric information is ...

Symbol:	Detail:
~	**Specific thermal capacity** ~ 0.88

- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of range of values
- I have no idea.
- Weitere...

24 Antworten

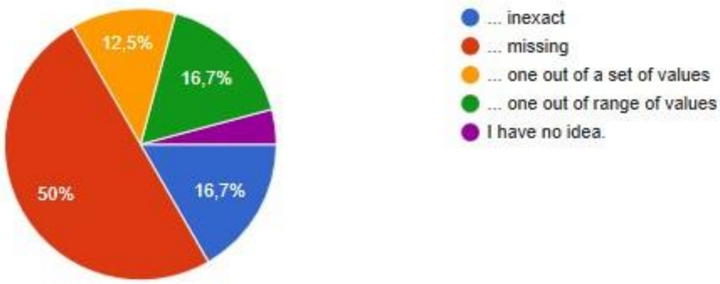


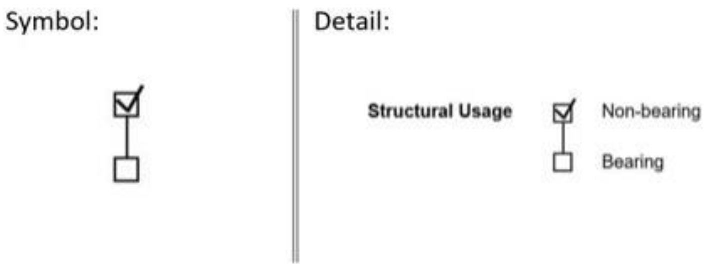
Symbol: [ ]

Detail: Specific thermal capacity [ ]

- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of range of values
- I have no idea.
- Weitere...

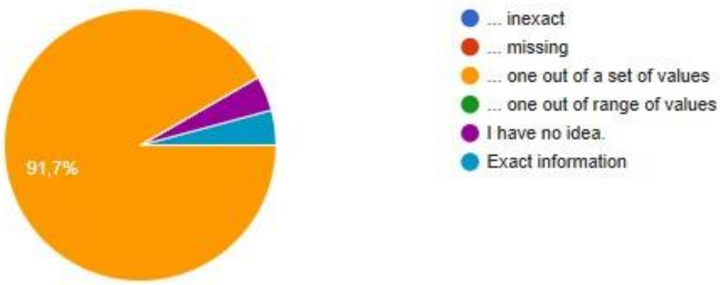
24 Antworten

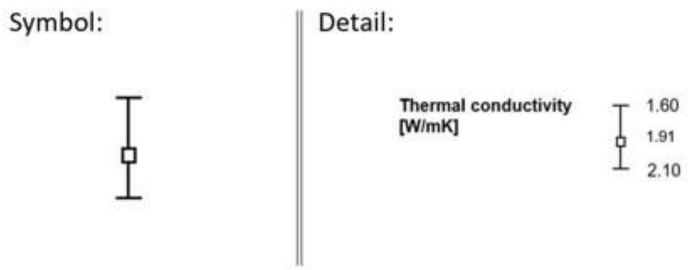




- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of range of values
- I have no idea.
- Weitere...

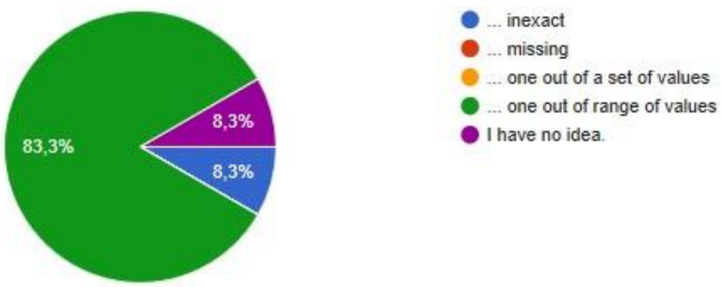
24 Antworten



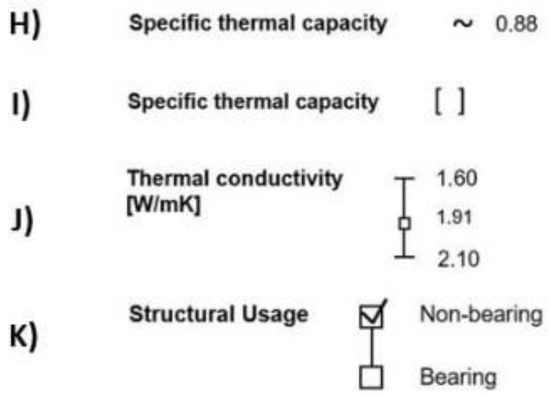


- ... inexact
- ... missing
- ... one out of a set of values
- ... one out of range of values
- I have no idea.
- Weitere...

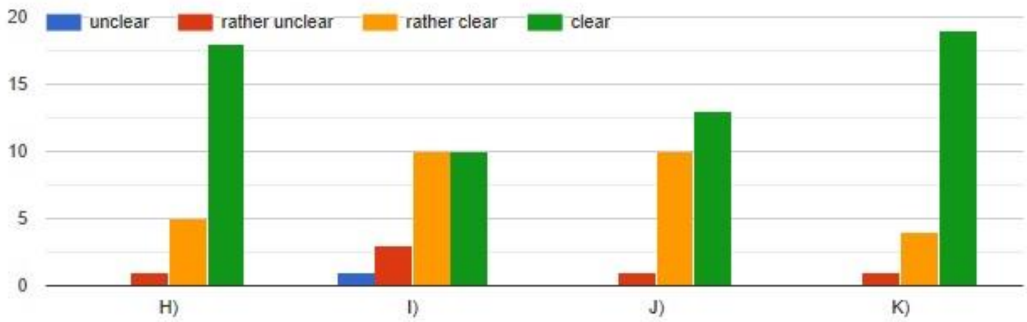
24 Antworten



Is the meaning of the symbols clear to you?



	unclear	rather unclear	rather clear	clear
H)	○	○	○	○
I)	○	○	○	○
J)	○	○	○	○
K)	○	○	○	○

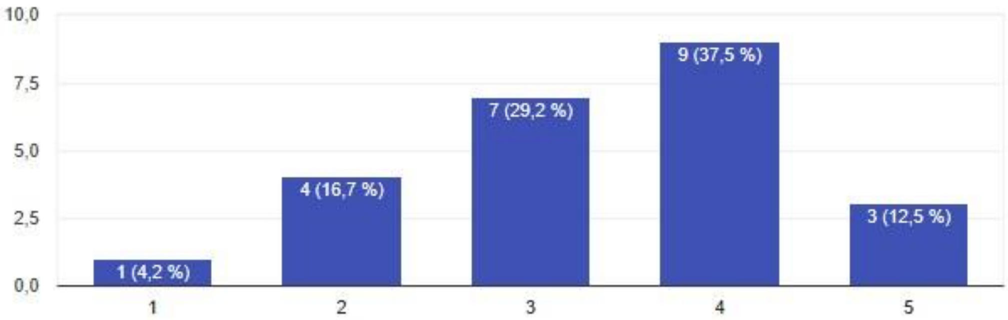


Abschnitt 6 von 6

Do you like the visualization approach?

	1	2	3	4	5	
No	○	○	○	○	○	Yes

24 Antworten



Do you have ideas for improvements?

No

Bezüglich Planungspraxis würde es einfacher Halten. Wahrscheinlichkeiten sind im Planungsalltag schwer zu fixieren ggf. ist das auch ein zusätzlicher bürokratischer Akt im Projektgeschäft. Im Rahmen der Masterarbeit halte ich das Vorgehen aber für sinnvoll und wichtig! An sich sehr interessant und gut dargestellt.

Different layers to separate the structural from the non structural informations, and another one to present all the probabilities (position, thickness...)

Maybe the single color is not enough for interpretation. For example you can try to use different colors only on the section of the walls to emphasize the position and the thickness, or some other color on the fixed walls to explain it more evidently.

no

Could you imagine to use the visualization approach? If yes, when would you use it?

If I would use it, then only to communicate with other Engineers. I don't think a client would be able to understand the symbols if he doesn't have a technical background.

Doesn't this approach mean way more work for the civil ingeneere during the design process, which should be done by the architects?

Im Prinzip bei Entwurfsphase bzw. auch nachträglichen Änderungen aus Umplanungen und Bauherrnwünsche. Daher im Einzelnen auch bis zum Ende des Projekts. Die Visualisierung ist ein guter Maßstab um die "Confidence" der Planung abzubilden.

Yes. I think it would be a good approach in the early design phase. I can imagine that it makes the communication between civil engineers and architects easier.

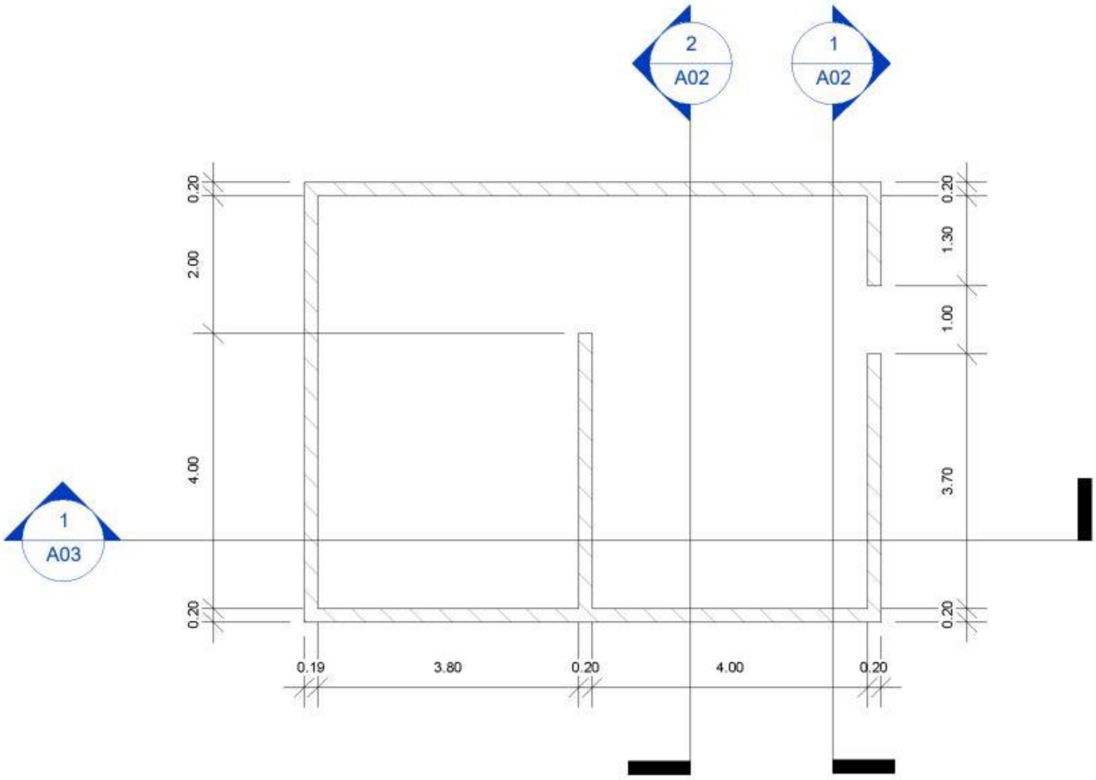
during concept and schematic design, probably useful when several disciplines work on a shared model

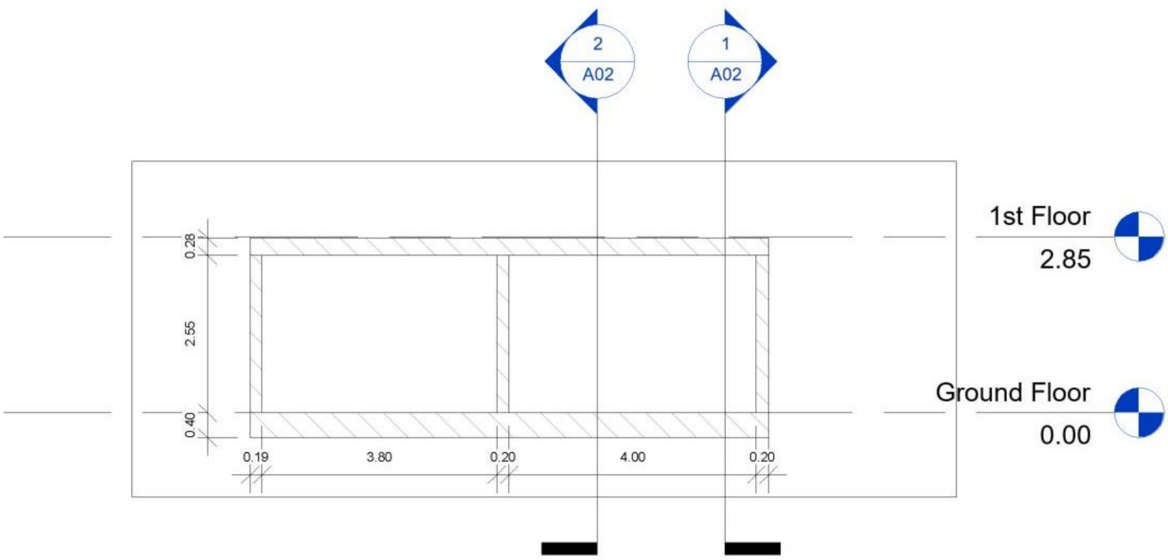
Yes, preliminary design

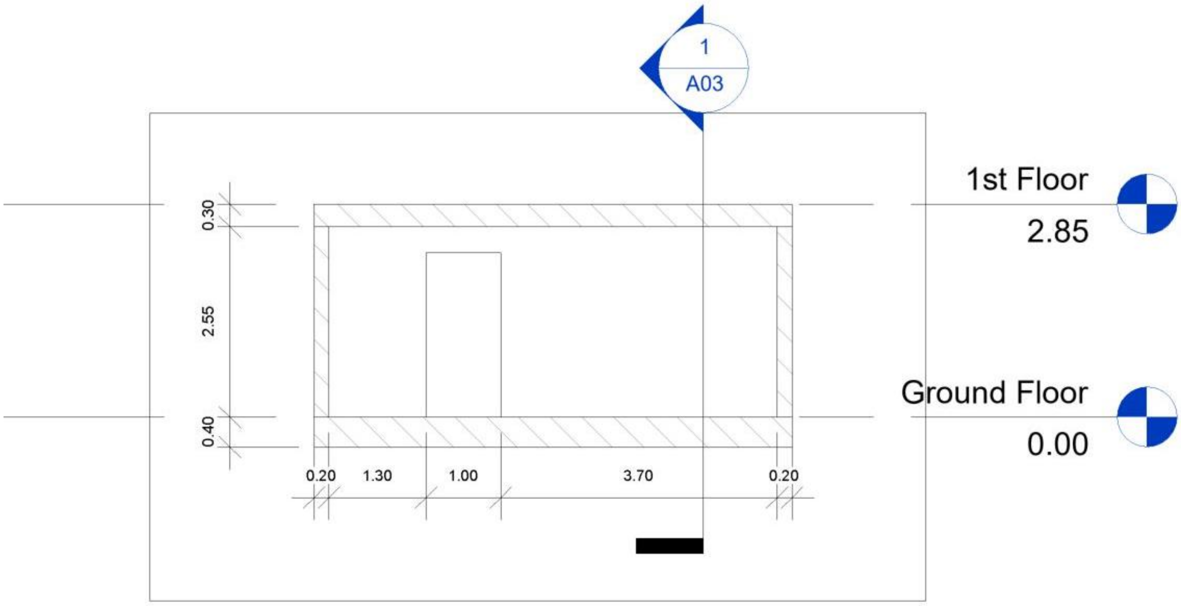
No

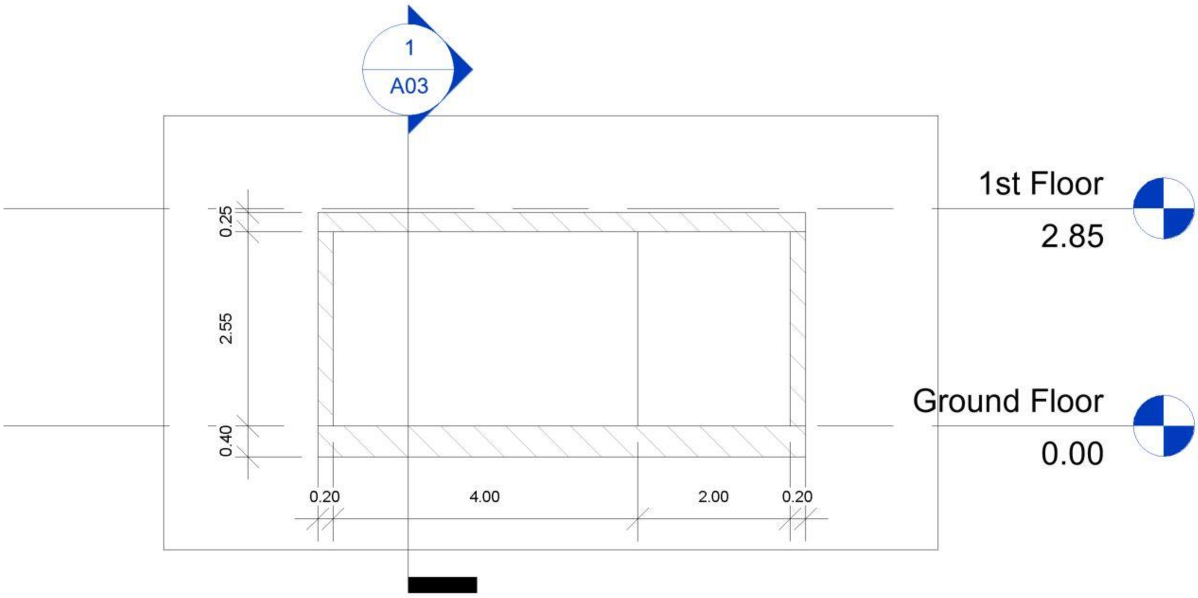
LP1-6

Attachment B






1
A03
1st Floor
2.85
Ground Floor
0.00
0.30
2.55
0.40
0.20
1.30
1.00
3.70
0.20


1
A03
1st Floor
2.85
Ground Floor
0.00
0.25
2.55
0.40
0.20
4.00
2.00
0.20

References

Abualdenien, J., & Borrmann, A. (2019a). A multi-LOD model for visualizing building information models' vagueness. In *Proceedings of The 2019 ASCE International Conference on Computing in Civil Engineering.*

Abualdenien, J., & Borrmann, A. (2019b). A meta-model approach for formal specification and consistent management of multi-LOD building models. *Advanced Engineering Informatics*, *40*, 135–153. https://doi.org/10.1016/j.aei.2019.04.003

Albrecht, M. (2015). *Building Information Modeling (BIM) in der Planung von Bauleistungen*. Hamburg: Diplomica Verlag GmbH. Retrieved from https://www.wiso-net.de/document/DIPL,ADIPL__9783954253456131

Beetz, J. (2009). *Facilitating distributed collaboration in the AEC/FM sector using Semantic Web Technologies.* https://doi.org/10.6100/IR652808

Bense, M. (1965). *Aesthetica Einführung in Die Neue Aesthetik*: Agis-Verlag.

Bertin, J. (2007). *Semiology of graphics: Diagrams, networks, maps*. Ann Arbor, Mich.: UMI (Original work published 1983).

BIMForum. Level of Development Specification Guide. Retrieved from https://bimforum.org/lod/

Bolpagni, M., & Ciribini, A. (2016). *The Information Modeling and the Progression of Data-Driven Projects.*

Bonneau, G.-P., Hege, H.-C., Johnson, C. R., Oliveira, M. M., Potter, K., Rheingans, P., & Schultz, T. (2014). Overview and State-of-the-Art of Uncertainty Visualization. In C. D. Hansen, M. Chen, C. R. Johnson, A. E. Kaufman, & H. Hagen (Eds.), *Mathematics and Visualization. Scientific Visualization* (pp. 3–27). London: Springer London. https://doi.org/10.1007/978-1-4471-6497-5_1

Borrmann, A. (2015). Building Information Modeling. *DETAIL*. (6), 602–607.

Borrmann, A., König, M., Koch, C., & Beetz, J. (Eds.). (2015). *VDI-Buch*. *Building Information Modeling: Technologische Grundlagen und industrielle Praxis*. Wiesbaden: Springer Vieweg.

Borrmann, A., König, M., Koch, C., & Beetz, J. (Eds.). (2018). *Building information modeling: Technology foundations and industry practice*. Cham: Springer.

Bundesministerium für Verkehr und digitale Infrastruktur. (2015). *Stufenplan - digitales Planen und Bauen.*

Buxton, W., & Myers, B. (1986). A Study in Two-handed Input. In *CHI '86, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 321–326). New York, NY, USA: ACM. https://doi.org/10.1145/22627.22390

Cain, B. (2015). *Visualizing Uncertainty for Data Fusion Graphics: Review of Selected Literature and Industry Approaches.*

Card, S. K., Mackinlay, J. D., & Shneiderman, B. (2007). *Readings in information visualization: Using vision to think* ([Nachdr.]). *The Morgan Kaufmann series in interactive technologies*. San Francisco, Calif.: Morgan Kaufmann.

Chandrasekaran, B. (1990). Design problem solving: A task analysis. *AI Mag*, *11*(4), 59.

Chatfield, C. (2018). *Statistics for Technology: A Course in Applied Statistics, Third Edition* (3rd ed.). *Chapman and Hall/CRC Texts in Statistical Science: v.3*. Boca Raton: Routledge (Original work published 1983).

Dengel, A. (Ed.). (2012). *Semantische Technologien: Grundlagen - Konzepte - Anwendungen*. Heidelberg: Spektrum Akademischer Verlag. Retrieved from http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10501466

Eastman, C., Liston, K., Sacks, R., & Teicholz, P. (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*: Wiley. Retrieved from https://books.google.de/books?id=Iio-ygN0nYzMC

Eco, U. (1972). A Componential Analysis of the Architectural Sign /Column. *Semiotica*, *5*(2). https://doi.org/10.1515/semi.1972.5.2.97

Fiske, J. (1990). *Introduction to Communication Studies* (2nd ed.). *Studies in Culture and Communication*. London: Routledge.

Forte, M. (2002). *Unschärfen in Geschäftsprozessen*. Berlin: Weißensee-Verl.

Gerbner, G. (1956). Toward a General Model of Communication, *4*, 171–199.

Gibson, J. J. (2015). *The ecological approach to visual perception* (Classic edition). *Psychology Press classic editions*. New York, Hove, England: Psychology Press (Original work published 1979).

Griethe, H., & Schumann, H. (2006). *The Visualization of Uncertain Data: Methods and Problems*, *2006*.

Grunwald, A. (2006). In G. Banse (Ed.), *Erkennen und Gestalten: Eine Theorie der Technikwissenschaften.* Berlin: Ed. Sigma.

Grunwald, A. (2012). *Technikzukünfte als Medium von Zukunftsdebatten und Technikgestaltung*. *Karlsruher Studien Technik und Kultur: Vol. 6*. Karlsruhe: KIT Scientific Publishing.

Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. *Journal of Motor Behavior*, *19*(4), 486–517.

Hahn, A. (Ed.). (2012). *Ausdruck und Gebrauch. Dresdner wissenschaftliche Halbjahreshefte für Architektur - Wohnen - Umwelt: Vol. 11*. *Ausdruck und Gebrauch. Dresdner wissenschaftliche Halbjahreshefte für Architektur - Wohnen - Umwelt/Ausdruck und Gebrauch. Themenheft: Raum und Erleben: Über Leiblichkeit, Gefühle und Atmosphären in der Architektur* (1., Aufl.). Herzogenrath: Shaker.

Hannus, M. (1998). Island of Automation in Construction. Retrieved from http://cic.vtt.fi/hannus/islands/

Hansen, C. D., Chen, M., Johnson, C. R., Kaufman, A. E., & Hagen, H. (Eds.). (2014). *Mathematics and Visualization*. *Scientific Visualization*. London: Springer London. https://doi.org/10.1007/978-1-4471-6497-5

Hawer, S., Schönmann, A., & Reinhart, G. (2018). Guideline for the Classification and Modelling of Uncertainty and Fuzziness. *Procedia CIRP*, *67*, 52–57. https://doi.org/10.1016/j.procir.2017.12.175

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, *45*(3), 188–196. https://doi.org/10.1037/h0056940

Jakobson, R. (1960). Closing Statements: Linguistics and Poetics.

Jeschke, S., Jakobs, E.-M., & Dröge, A. (Eds.). (2013). *Textlinguistik & Technikkommunikation*. *Exploring uncertainty: Ungewissheit und Unsicherheit im interdisziplinären Diskurs*. Wiesbaden: Springer Gabler.

Karbach, W., & Linster, M. (1990). *Wissensacquisition für Expertensysteme: Techniken, Modelle und Softwarewerkzeuge*. München, Wien: Crl Hanser Verlag.

Koffka, K. (2014). *Principles of Gestalt psychology*. *Psychology (Mimesis International): n.1*. [Place of publication not identified]: Mimesis International (Original work published 1935).

Kohfeld, D. L. (1971). Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology*, *88*(2), 251–257.

Kruse, R., Gebhardt, J., & Klawonn, F. (1993). *Fuzzy-Systeme*. *Leitfäden und Monographien der Informatik*. Stuttgart: B. G. Teubner.

Kudraß, T., & Hupfer, P. (1991). *unveröffentlicher Forschungsbericht zum Thema intelligente CAAD-Systeme und Unschärfe: Fuzzy Objects*. Weimar.

Lasswell, H. D. (1948). The structure and function of communication in society. *The Communication of Ideas*, *37*, 215–228.

Lindblom, C. E. (1959). The Science of "Muddling Through". *Public Administration Review*, *19*(2), 79–88. https://doi.org/10.2307/973677

Lindemann, U. (2009). *Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden* (3., korrigierte Aufl.). *VDI-Buch*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg. Retrieved from http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10323208 https://doi.org/10.1007/978-3-642-01423-9

Lobel, J. (2008). *Building Information: Means and methods of communication in design and construction.* Massachusetts: Massachusetts Institute of Technology (MIT).

MacEachren, A. M. (2008). *How maps work: Representation, visualization, and design*. New York: Guilford Press.

MacLeamy, P. (2004). Retrieved from https://kcuc.org/wp-content/uploads/2013/11/Collaboration-Integrated-Information-and-the-Project-Lifecycle.pdf

Marr, D. (2000). *Vision: A computational investigation into the human representation and processing of visual information* (14. print). New York: Freeman.

McGraw Hill. (2009). *The Business Value of BIM: Getting Building Information Modeling to the Bottom Line*: McGraw Hill.

Menges, A., & Ahlquist, S. (2011). *Computational design thinking*. *AD reader*. Chichester, UK: John Wiley & Sons.

Menz, S. (2015). *Planen und bauen - bald nur digital.*

Munzner, T. (2015). *Visualization analysis & design*. *A.K. Peters visualization series*. Boca Raton: CRC Press, Taylor & Francis Group.

Naumann, R. (2011). Neue Planungswerkzeuge im Schlüsselfertigbau – Visionen, Herausforderungen und Grenzen.

Newcomb, T. M. (1953). An Approach to the Study of Communicative Acts, *60*, 393–404.

Ogden, C. K., & Richards, I. A. (1923). *The Meaning of Meaning*: Harcourt, Brace and World.

Page. (1973). In G. Broadbent (Ed.), *Design in Architecture.* London: Wiley&Sons.

Pang, A. T., Wittenbrink, C. M., & Lodha, S. K. (1997). Approaches to uncertainty visualization. *The Visual Computer*, *13*(8), 370–390. https://doi.org/10.1007/s003710050111

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145–165. https://doi.org/10.1016/j.autcon.2016.10.003

Peirce, C. S. (1931-58). *Collected Papers*. London: Paladin.

Rambow, R. (2012). Entwerfen und Kommunikation. In A. Hahn (Ed.), *Ausdruck und Gebrauch. Dresdner wissenschaftliche Halbjahreshefte für Architektur - Wohnen - Umwelt: Vol. 11. Ausdruck und Gebrauch. Dresdner wissenschaftliche Halbjahreshefte für Architektur - Wohnen - Umwelt/Ausdruck und Gebrauch. Themenheft: Raum und Erleben: Über Leiblichkeit, Gefühle und Atmosphären in der Architektur* (1st ed., pp. 103–124). Herzogenrath: Shaker.

Reddy, M. J. (1993). The conduit metaphor: A case of frame conflict in our language about language. In A. Ortony (Ed.), *Metaphor and Thought* (pp. 164–201). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139173865.012* (Original work published 1979).

Reder, B. (1995). Modellierung attributiver Unschärfe in CAD-Systemen (Dissertation). Hochschule für Architektur und Bauwesen Weimar - Universität, Weimar.

Rittel, H.W.J. (1972). *On the Planning Crisis: Systems Analysis of the "First and Second Generations*. *Reprint / Institute of Urban & Regional Development, University of California*: Institute of Urban & Regional Development, University of California. Retrieved from https://books.google.de/books?id=fAgvtAEACAAJ

Rittel, H. W. J., & Reuter, W. D. (1992). *Planen, Entwerfen, Design: Ausgewahlte Schriften zu Theorie und Methodik*. *Facility management: Vol. 5*. Stuttgart: W. Kohlhammer.

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169. https://doi.org/10.1007/BF01405730

Roth, R. E. (2016). Visual Variables. In D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu, & R. A. Marston (Eds.), *International Encyclopedia of Geography: People, the Earth, Environment and Technology* (Vol. 80, pp. 1–11). Oxford, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg0761

Rowe, P. G. (1991). *Design Thinking*. Massachusetts: MIT Press Cambridge.

Meisel, P., & Saussy, H. (Eds.). (2011). *Course in general linguistics* (W. Baskin, Trans.). New York: Columbia University Press (Original work published 1915).

Scherer, R. J., & Schapke, S.-E. (2011). A distributed multi-model-based Management Information System for simulation and decision-making on construction projects. *Advanced Engineering Informatics*, *25*(4), 582–599. https://doi.org/10.1016/j.aei.2011.08.007

Scherer, R. J., & Schapke, S.-E. (Eds.). (2014). *VDI-Buch*. *Informationssysteme im Bauwesen 1: Modelle, Methoden und Prozesse*. Berlin: Springer Vieweg. Retrieved from http://dx.doi.org/10.1007/978-3-642-40883-0 https://doi.org/10.1007/978-3-642-40883-0

Schmid, F. C. (2015). *Methodisches Gestalten und systematisches Entwickeln am Beispiel zukünftiger Fassadenlösungen* (1. Aufl. 2015). Wiesbaden: Springer Fachmedien Wiesbaden GmbH; Springer Vieweg.

Schönwandt, W. L. (2002). *Planung in der Krise?: Theoretische Orientierungen für Architektur, Stadt- und Raumplanung*. Wiesbaden: Vieweg+Teubner Verlag.

Stachowiak, H. (1970). Grundriß einer Planungstheorie. In *Kommunikation* (VI/1, pp. 1–18).

Stachowiak, H. (1973). *Allgemeine Modelltheorie*. Wien [etc.]: Springer.

Steinmann, F. (1997). Modellbildung und computergestütztes Modellieren in frühen Phasen des architektonischen Entwurfs (Weimar, Bauhaus-Univ., Diss.,).

Tufte, E. R. (2015). *The visual display of quantitative information* (2. ed., 9. printing). Cheshire, Conn.: Graphics Press.

Tulke, J. (2015). BIM zur Unterstützung der ingenieurtechnischen Planung. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling* (pp. 271–282). Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-05606-3_16

Ware, C. (2013). *Information visualization: Perception for design* (3rd ed.). Amsterdam, Boston: Elsevier/MK (Original work published 1999). Retrieved from http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10547255

Weaver, W. (1953). Recent Contributions to the Mathematical Theory of Communication. *ETC: a Review of General Semantics*, *10*(4), 261–281.

Werkl, M. (2013). *Risiko- und Nutzenverhalten in der Bauwirtschaft: Eine entscheidungstheoretische Betrachtung im institutionenökonomischen Kontext*. *Schriftenreihe des Instituts für Baubetrieb und Bauwirtschaft: Vol. 34*. Graz: Verl. der Techn. Univ.

Westley, B. H., & MacLean, M. S. (1955). A conceptual model for communications research. *Educational Technology Research and Development*, *3*(1), 3–12. https://doi.org/10.1007/BF02713344

Wolfe, J. M. (1988). Visual Perception. In R. Held (Ed.), *Readings from the Encyclopedia of Neuroscience. Sensory system* (pp. 93–94). New York: Springer.

Zimmermann, H.-J., & Altrock, C. v. (1993). *Fuzzy Logic*. München: Oldenbourg.

Zimmermann, J., & Eber, W. (2015). BIM als Medium der Bauorganisationswissenschaft.

Erklärung

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

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

München, 2. May 2019

Fritz Beck

Fritz Beck
[redacted]