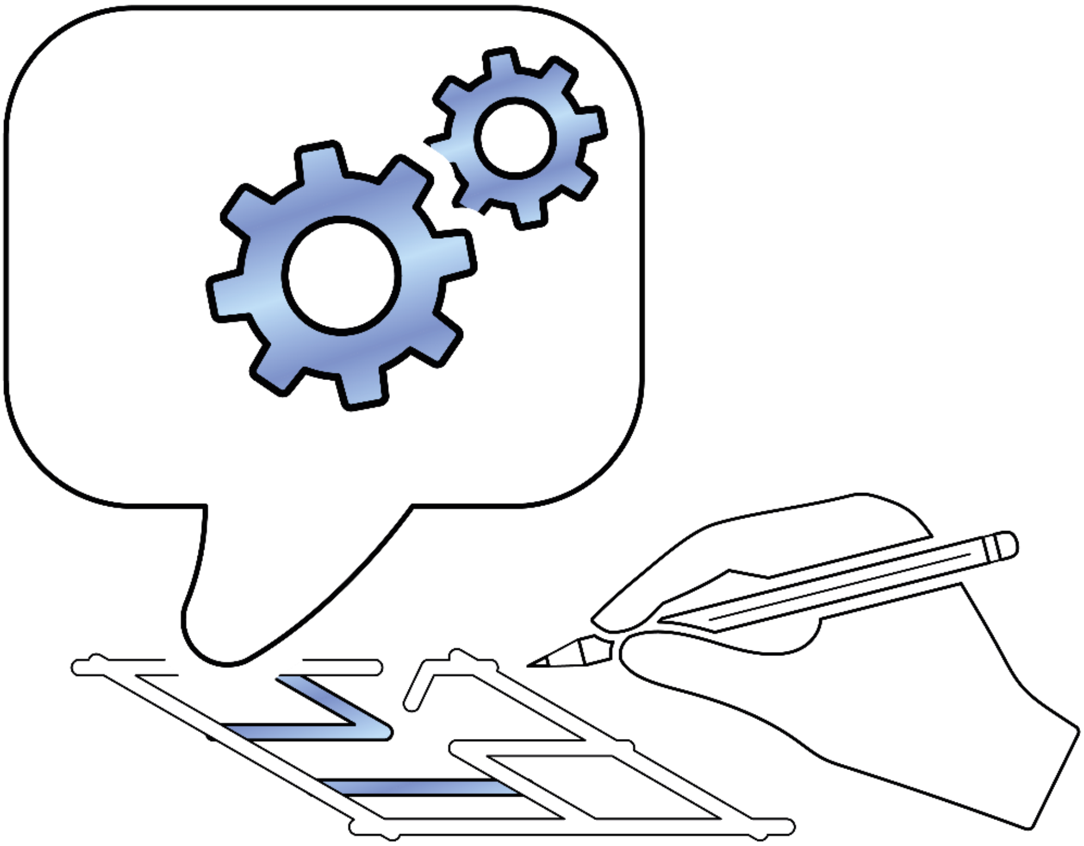
Faculty of Architecture
TECHNICAL UNIVERSITY OF MUNICH

Master Thesis
Chair of Architectural Informatics

Computational aids for architects for early design phases

Explainability of auto-completion tools for spatial layouts in early architectural design phases



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Computational aids for architects for early design phases

Explainability of auto-completion tools for spatial layouts in early architectural design phases

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Date: May 10, 2021

Hiermit erkläre ich eidesstattlich, dass ich diese Master Thesis selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

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München, den 10. Mai 2021

Abstract

In the next thirty years the world population is expected to approach the amount of ten billion people (Statista Research Department, 2020), posing a huge challenge on the construction industry. In order to meet the housing requirements of the future, the architects need to work in a faster and more efficient manner without compromising the architectural quality.

The aim of this thesis is to explore if additional information can support architects in understanding suggestions of a hypothetical intelligent design assistant like WHITE BRIDGE and reduce the cognitive workload of design decision in early design stages. Furthermore, the influence of the representation of this information on the visually driven target group is examined through the mixed methodology of triangulation, derived from social sciences. The used triangulation consists of literature research and a user study. The theory-driven explanations and explanation visualisations are based on the framework of Wang et al. (2019), as well as a literature review of architects' design decision making process, workflow and architectural quality assessment. The user study is conducted with working architects, utilising a digital paper prototype created from the theoretical research.

The results show that the cognitive limits of the architects are expanded by the explanations, while the visualisation methods significantly influence the usefulness and utilisation of the conveyed information within the explanations. The architects themselves identify opportunities for using a hypothetical intelligent design assistant. In order to make well-informed decisions, they seek even further support in terms of visualised explanations for the suggestions and the visibility of choice. Thus, the architects are supported, while ensuring a sense of ownership over the design decisions.

Acknowledgments

I want to thank all the participants in the study for their time, their effort and dedication in completing the interview sessions with me, as well as their valuable feedback.

I want to thank Prof. Petzold and everyone else at the chair for their effort, helping me to finish my thesis, even through postponing and these difficult times, marked by the pandemic. My special thanks go to my two advisors Christoph and Christoph for their continuous support through these especially difficult times for me personally. Thank you for your indulgence and trust in me, and thank you for your occasional push that I needed. I also want to thank Hardik for his time and helpful input.

My dear two families, the literal and my dearest people, thank you for love, help and support, which you gave me in every way you could possibly think of. I want to thank my parents, who have supported me through all these years and I know, will celebrate the h*ll out of this – I finally did it. Thank you so much, Elena, that I could come to you and tell you all my sorrows, and you would turn them into laughter. Thank you, Sarah, who I could call at 3 am without feeling bad and staying on the line until I fall asleep.

And my dearest, Aimen, thank you for being there for me, when I was about to break apart, for caring for me at my lowest and celebrating with me every tiny thing as it was the best that has ever happened.

I want thank the artist Slumberjack for the song Horus, the soundtrack of my thesis, without it, I would probably still be stuck on the introduction.

And - as not even five years ago nobody knew if I can physically complete even my bachelor studies - I want to finish with the words of Calvin Cordozar Broadus Jr. aka Snoop Dogg:
Last, but not least, I wanna thank me, I wanna thank me for believing in me, I wanna thank me for doing all this hard work, I wanna thank me for having no days off, I wanna thank me for never quitting.

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1 INTRODUCTION

1.1 Thesis statement

As the world population is expected to approach the ten billion mark by 2050 (Statista Research Department, 2020), so within the next thirty years, meeting the demands on the housing market is becoming an even greater challenge for the construction industry. This situation is exacerbated by the fact that about two thirds of the population will be living in an urban area (United Nations, Department of Economic and Social Affairs, Population Division, 2019, p. xix). Therefore, architects need to be able to work even faster and more efficiently, while keeping the level of architectural quality. In order to satisfy both these requirements, the decisions of the early design stages are of significant importance (Harputlugil et al., 2014, p. 140).

Intelligent systems have been applied in other fields to support the user in completing work tasks faster and more efficiently, such as digital keyboards on everyday digital devices, predicting and auto-completing words and sentences. Through adaptation and specific extensions within the workflow of Computer-Aided Architectural Design (CAAD), the methods of intelligent systems have been applied in supporting the architect to fulfil the complex tasks of architecture as well.

A hypothetical vision of such an intelligent system for the early design stages, called WHITE BRIDGE, is presented within the introduction. However, this thesis concerns itself with the specific aspect of explainability for architects, needed for such an intelligent system.

Firstly, definitions and background information, including statements, problems within the research field, paradigms and an introduction to the exemplary intelligent system used as a hypothetical application, are presented. Following, the problem statement as well as the two research questions are defined to further constitute the reason for the chosen methodology. For the latter, I draw from, as explained later, social sciences to meet the demands of the specific target group. The main contribution of this thesis is comprised of theoretical research, utilising the framework provided by Wang et al. (2019), and adapting it to the user group, based on various works on the workflow and methods used by architects as well as architectural quality assessment, and further translating these findings into an online paper prototype, befitting the exemplary intelligent system. A study is conducted to test this paper prototype in order to evaluate the findings and solutions used in the paper prototype. The evaluation is the used to propose an agenda on further steps. Finally, the thesis will be summarised through a reflection and discussion, leading to the definition of future work and a conclusion.

In summary, this thesis proposes methods of explainability for an intelligent system for auto-completion of spatial layouting for architects, adopting the support of architects within the decision making of the design process in the early design phases as a fundamental goal. I aim to define impulses for ways of future interactions of intelligent systems and architects to allow better use and understanding, in order to help the user fulfil architectural design tasks.

1.2 Definitions and background

As previously stated (see sub-chapter 1.1), within this sub-chapter definitions, statements, problems within the research field, paradigms, and an exemplary intelligent system are presented.

Firstly, the field of explainability of intelligent systems and early design phases, as which they are further referred to in the following thesis, will be defined. Further, the essentials of the work of architects, their work methods and the impact of said methods are stated. Following the problems of the research field, divided into problems of defining the design problem and problems of defining the decision making process within the design process, are presented. Afterwards, the paradigm used as the basis for the exemplary intelligent system is clarified in order to complete this sub-chapter with the introduction to the intelligent system for architects, which is used within this thesis as an example of application for the found methods.

Explainability of an intelligent system

As the topic of this thesis is set within the field of Explainable Artificial Intelligence (XAI), the subject is shortly touched upon, as its complex entirety and implementation is outside of the scope of this thesis. The purpose is to give a short definition for the explainability of an intelligent system or explainable intelligent system, as further referred to in the thesis.

Eiband (2019, p. 3) defines intelligent systems through the inclusion of their complexity by dealing with a large number of variables, the interrelation of variables, the mechanics behind the system which are often not apparent for the user, dynamical changes, both dependent and independent from actions taken by the user, within the system, and finally by serving multiple ill-defined goals that could possibly conflict. The necessity for explanations of decisions or results of such an intelligent system, as part of positive Human-Computer-Interaction (HCI), stems from the need to facilitate understanding, trust, and management. The purpose of an explainable intelligent system is to make itself more intelligible to its respective user. Depending on the task, abilities and expectations of the user, the “definitions of interpretability and explainability are, thus, domain dependent” (Gunning et al., 2019), because of varying explanation goals, reasoning grounds and prior knowledge.

Early design phases

The design and construction process is comprised of several steps. Originally, the “ideas and images of the design objects exist prior to and instead of the physical design objects in early design phases." (Harputlugil et al., 2014, p. 147). The American Institute of Architects, East Tennesee Chapter (2021), defines the first two phases as ‘Pre-design’ phase or ‘Programming’, and the ‘Schematic design phase’, also occasionally combined as one and then only referred to as ‘Schematic design phase’. In these phases the architect creates rough sketches based on the requirements of the project according to the owner’s wishes, “which show the general arrangement of rooms and of the site” (American Institute of Architects, East Tennesee Chapter, 2021).

The work of architects

Architects design and create spaces. Therefore, it is their responsibility to translate the "needs and aspirations of the client, theories and schedules and budgets into [an] appropriate and exciting building" (Elango & Devadas, 2014a, p. 18). They are utilising their education, professional knowledge, experience, and skills to give their abstract ideas shape as a building design.

As their work process can be described as an iterative and incremental learning process, it can be further divided into the divergence phase of generating alternatives and the convergence phase, in which the most promising solution or solution aspects are selected (Elango & Devadas, 2014b, p. 1034). Therefore, attempts have been made to describe the architectural design process as an Analytical Hierarchy Process (AHP) through Multi-Criteria Decision Making (MCDM), as the different criteria within the design are weighed and ranked against each other to create a priority list of design factors, e.g. the client wishes far and foremost for a courtyard or the site as a unique view (Harputlugil et al., 2014).

Problems of defining the design problem

However, Harputlugil et al. (2014, p. 139) themselves point out that the architectural design process is comprised of a chain of highly complex tasks because of the individual combination of content, context, stakeholders, ill-defined problems - "wicked problem" (Rittel & Webber, 1973, pp. 160-167) - multifaceted interactions, and unique conditions, making standardisation nearly impossible.

Problems in defining the decision making process

Additionally to the problems of defining the design problem itself, the decision making within the design process proves to be difficult. The architectural design process is referred to as a cognitive model of action based problem solving tasks to solve the overall design problem by Chan (1990, p. 61), whereas Simon (1969, pp. 55-118) calls it an ill-defined process by creating problems. Lawson (2005, pp. 120-125) summarises the problems of defining the design process by concluding that design problems cannot be stated in an exhaustive manner and, while requiring subjective interpretation, they can mostly be hierarchically organised. This can be traced back to the challenge of quantifying the quality of architectural design, since it consists of both tangible and intangible facts and objective-subjective components (Gann Salter & Whyte, 2003, p. 320). Thus, architects are accustomed to use an intuitive method for decision making based on their knowledge and experience to design spaces (Elango & Devadas, 2014a, pp. 13, 18), as previously mentioned, making it also prone to mistakes due to biases of architects.

Fingerprints of architecture

In order to describe architectural designs, Langenhan (2017, pp. 54-86) introduces a paradigm, the 'Fingerprints of architecture'. It formalises topological semantic information of buildings among other parameters by defining spatial configurations and representations through graphs. It draws from the interpretation of the uniqueness of every building as previously explained, comparable to human fingerprints. Therefore, Langenhan describes that buildings are individually identifiable by the means of their spatial configuration in combination with their respective categories, like building type, and attributes, like construction year.

'WHITE BRIDGE' - an intelligent design assistant

The 'Fingerprints of architecture' was adopted as a paradigm for the creation of projects of 'metis', funded by the Deutsche Forschungsgemeinschaft (DFG), which was "proven to be robust enough and the methodological approaches have been confirmed" (Dengel et al., 2019) within its first project.

Within the 'metis' projects, artificial intelligence approaches are used to suggest further design steps to the architect during the design process in the manner of auto-completion. 'metis' aims to offer suggestions based on a large database, while ensuring the quality of data used in a neural network to create alternatives, as well as variants to the user (Dengel et al., 2019). The idea is derived from referencing buildings as a common practice of architectural design, which are used for source of inspiration, source of design conditions, a tool for evaluation of the own design, and as a medium for communication and explicit information (Richter, 2011, p. 106). Referring back to the work of architects as an iterative and incremental process, the point of action of 'metis' is the divergence phase through suggestions of further design steps. The architect selects the most promising solution or solution aspects of the suggested design steps.

WHITE BRIDGE is a possible hypothetical realisation based on the methods developed within the projects of 'metis'. Further, the hypothetical application contains methods of explainability for auto-completion as a computational aid tool for designing spatial layouts in early architectural design phases. The purpose of WHITE BRIDGE is to provide suggestions of further design steps, generated by an intelligent system, and moderate necessary information through explanations for supporting the decision making process of architects to make well-informed design decisions. By taking the definition of intelligent systems by Eiband (2019, p. 3) into account, WHITE BRIDGE is further referred to as an intelligent design assistant.

1.3 Summary and overview of the thesis

Within this introduction I have clarified the objective of this thesis: Defining explanations, as well as developing visualisation methods for the explainability of an intelligent design assistant like WHITE BRIDGE which supports architects through auto-completion of spatial layouting during the early design phases.

Chapter 2 states the problem addressed within this thesis, as well as the derived research questions and the methodology used to answer these questions. Chapter 3 presents the theoretical research and its respective findings. These findings are translated into a paper prototype for the hypothetical intelligent design assistant WHITE BRIDGE in Chapter 4, which is used in a small study, as described in Chapter 5. Finally, I summarise this thesis through discussion, reflection, and defining impulses for future work in Chapter 6.

2 PROBLEM STATEMENT, RESEARCH QUESTIONS AND METHODOLOGY

After this introduction the problem will be stated, as well as the resulting research questions. Finally, the methodology chosen to answer these research questions will be described.

2.1 Problem statement

Currently, research for intelligent design assistants is being conducted, based on Case-Based Reasoning (CBR) and Deep Learning (DL), which are both concepts of intelligent systems. Even though CBR approaches have been adapted as Case-Based Design (CBD) as early as the 1990s, the application of DL in the field of architecture is fairly recent. Most of DL research is focusing on retrieval (Sharma et al., 2017) or design style manipulation (Newton, 2019; Silvestre, Ikeda, & Guéna., 2016), meaning no research on the explainability of an intelligent system for architects has been conducted yet, but only on the mechanisms and possibilities of the system. On the other hand, explainability of an intelligent system against the backdrop of a specific target group, such as physicians for medical diagnoses (Wang et al., 2019, pp. 9-12), has been researched. The research problem of this thesis concerning the explainability of an intelligent design assistant for architects for the early design phases, is formulated as the following:

Problem statement

So far, there is no concept of what and how to communicate information to an architect in order to understand the suggested design steps of an intelligent design assistant like WHITE BRIDGE, which is intended to reduce the cognitive workload of design decisions on the architect in early design stages.

The taxonomy of scientific research for Human-Computer-Interaction (HCI) as proposed by Oulasvirta and Hornbæk (2016, pp. 4957-4958) suggests three types of research problems towards scientific progress: empirical, conceptual, and constructive. As 'empirical' research aims to provide "descriptions of real-world phenomena", Oulasvirta and Hornbæk (2016, p. 4958) divide them into three sub-types: concerning the phenomena themselves as 'unknown phenomena', the influencing factors of 'unknown factors' and the outcomes called 'unknown effects'. The objective of 'conceptual' research work is to explain the occurrence of "previously unconnected phenomena" (Oulasvirta & Hornbæk, 2016, p. 4958). Therefore the 'implausibility' of an unreasonable phenomenon is explored, the 'inconsistency' of a phenomenon is examined, or the 'incompatibility' of a phenomenon of two non-reconciling problems is looked into within this category. Finally, for the 'constructive' research problems dealing with "producing understanding about the construction of an interactive artefact for some purpose in human use" (Oulasvirta & Hornbæk, 2016, p. 4958), understanding is the key objective. Thus, this category is tapping into a field of no understanding called 'no known solution', not enough understanding as 'partial ineffective or inefficient solutions', or insufficient understanding for creation, which the authors call 'insufficient knowledge or resources for implementation or deployment'. Taking these categorisations and sub-categorisations into account, the problem within this thesis is divided as follows:

1. The information in the form of explanations that is communicated to the architect as the user is to be defined as an 'empirical' one, because of its 'unknown phenomena' of the interaction of architects and an intelligent design assistant, and therefore, no established methods which can be applied.
2. The methods used to communicate the information to the architect are to be categorised as the 'no known solution' of the 'constructive' research problems, as it is a novel concept in interaction.

2.2 Research Questions

Resulting from the two different types of research problems, the research questions emerging from this problem statement are two different ones.

The first question responds to the empirical research problem (see sub-chapter 2.1), which deals with the explanations provided for the suggestions of an intelligent design assistant. It needs to question the capabilities of the conveyed information, while addressing the overall goal of the explanations to support the architect. Therefore, Research Question 1 has been phrased as follows:

Research Question 1

Can explanations for design impulses, suggested by an intelligent design assistant like WHITE BRIDGE, support the architect to expand the cognitive limits of the decision making process in the early architectural design phases?

The second research question emerging from the sub-category 'no known solution' of the constructive research problems (see sub-chapter 2.1) needs to respond to the presentation used for the explanations. The possibility of different affects and effectiveness because of the used visualisation methods of the explanations needs to be taken into account, especially considering the visually driven target group of architects. Thus, Research Question 2 has been formulated as:

Research Question 2

How does the presentation and visualisation of the explanations affect the fulfilment of this goal of supporting the architect to expand the cognitive limits of the decision making process in the early architectural design phases?

2.3 Methodology

As the problem statement and the research questions show, the creation of explainability within architecture is a rather untapped field. This thesis aims to provide clarification on the aspects and elements which are relevant within the interaction of an intelligent design assistant and architects, as well as the extent of the impact of these aspects.

Within this sub-chapter, I present the chosen methods of the research design, the methodology of triangulation, consisting of theoretical, empirical research and a study with the user group, and finally the data collection and analysis, as well as the reasoning behind each of these choices.

Mixed-method of post-positivist and interpretivist research designs

A positivist research design is typically attempted to mitigate all possible future problems while providing a rather straight-forward roadmap for the researcher (Denzin & Lincoln, 2017, p. 550). It utilises the factual knowledge gained through observation while depending on the quantifiability of these observations in "accordance with the empiricist view that knowledge stems from human experience" (Dudovskiy, 2019a). It builds on the independent position of the researcher from the study to be able to make non-biased observations, as well as the assumption that the observations made are quantifiable.

However, this thesis aims to find the underlying issues that call for explanations to optimise the interaction between an intelligent design assistant and an architect. Furthermore, quantifiable results from this thesis are not of scientific significance for addressing the essential research problem. It calls for the 'process of Verstehen' by the researcher (Denzin & Lincoln, 2017, p. 660):

> The process of Verstehen involves understanding the intention and context of these social realities for the subject herself or himself. For social researchers to gain knowledge about actors in a field will require that the meanings and interpretations of those subjects are fully acknowledged and understood. Understanding rather than causality is the key element to this approach.

Further, as the researcher conducting this study is an architect, a value-free inquiry cannot be presumed. Thus, a qualitative research method is chosen to present this premise with more clarity (Denzin & Lincoln, 2017, p.548). A post-positivist manner (Given, 2008, pp. 659-664) is assumed, integrating possible biases by the researching architect.

Finally, the results and their elements need to be interpreted for further evaluation. Therefore, Interpretivism is used, which further "integrates human interest into a study" (Dudovskiy, 2019b). Accordingly, I include contextual facts into the evaluation, such as the interviewed group, architects, the amount of participants, as well as the researcher being an architect with pre-existing knowledge on the topic and the target group.

Summarising, a mixed-methods approach is used within this thesis. For the creation of the study, Post-Positivism is presumed (Dudovskiy, 2019b) due to possible "cognitive blindness" (Shepherd, Sattari & Patzelt, 2020, p. 38) while the evaluation and derived design impulses for future steps will be of the interpretivist design (Dudovskiy, 2019a). In order to mitigate the possible involvement of biases by me as an architect, the methodology of triangulation from the empirical social sciences is chosen.

Triangulation

"Triangulation refers to the application and combination of multiple (theoretical and methodological) approaches in the study of the same phenomenon" (Denzin & Lincoln, 2017, pp. 561-562), which means that the issue of the research is viewed from at least two different points or perspectives and therefore involves at least two different methods. Moreover, triangulation provides a deeper understanding of the topic, resulting in a surplus of knowledge. As it utilises different perspectives on the topic, diverse methods for answering the research questions, and manifold answers, it combines various types of data. Therefore, it produces knowledge on different levels and finally, increases the quality of research (Denzin & Lincoln, 2017, pp. 784, 789)

Therefore, triangulation is deemed the appropriate manner to address the research questions of this thesis. The methodologies of theoretical research of available literature will be used to create a paper prototype in a post-positivist manner, which will be evaluated through a case study with subsequent interviews with the future user group of architects. The results of these findings will be evaluated with Interpretivism.

Theoretical research

After a review of literature, the paper of Wang et al. (2019) was found to provide the only available and applicable framework fit for the theoretical creation of explainability methods while offering steps for adaptability in designing an explainable intelligent system for a specific target group. Other current solutions either build on unvalidated guidelines for design and evaluation, based on the author's respective knowledge with little further justification, empirically derived taxonomies of explanation needs with limited user studies, or psychological constructs from formal theories without any further instruction on how to operationalise their findings (Wang et al., 2019, p. 2).

Wang et al. (2019, pp. 1-3) combine and refine the content of different literature about cognitive psychology, philosophy and decision making theories. Based on this review, they suggest lower-level building blocks to construct solutions, which are both based on the identification of relevant reasoning goals of the user group and the selection of corresponding explanation techniques. Further, they develop a framework which builds on the purposes and patterns for causal reasoning to link human reasoning and intelligent system domains to provide operational pathways. Finally, Wang et al. present the reader with further steps to design a user-centred explainable intelligent system with targeted features for explainability, suggesting the use of literature review of the specific target group and further co-design exercises with real users in the form of User-Centred Design (UCD).

The UCD approach is based on ethnography which "serves as a corrective on the process of theory building" (Denzin & Lincoln, 2017, p. 611) for the adaption of the framework. UCD demands a deep understanding of the users, their respective goals and demands, as well as their specific issues, in order to work effectively and efficiently to their satisfaction (Chammas, Quaresma & Mont'Alvão, 2015, pp. 5397-5399). The technical standards for the iterative UCD approach is specified within the ISO 9241-210 by the International Organization of

Standardization, addressing the entire user experience:

> The user experience is a result of the presentation, functionality, system performance, the interaction behavior and assistive capabilities of an interactive system, both in terms of hardware and software. The user experience is also consequent of previous user experience as well as their attitudes, skills, habits and personality.... [The] capabilities, limitations, preferences and expectations must be taken into account in the specification that features are the user's competence and what system of competence.

Consequently, a UCD approach for the specific target group of architects to utilise the framework of Wang et al. (2019) becomes apparent. Therefore, a literature review of the goals and values of the target group, befitting the topic of explainability, is the second and main part of the theoretical research.

Summarising, the theoretical research consists of the framework, provided by Wang et al. (2019), as well as its adaption through a comprehensive research on architectural workflow, architectural decision making during the design process, architectural evaluation methods, and architectural design quality assessment. These two parts are then synthesised to design a paper prototype for a study with the user group.

Study with the user group

A case study with architects using a paper prototype created from the theoretical research is presented as the second method of the triangulation process. I draw from Shepherd's, Sattari's, and Patzelt's emphasis on "open community engagement" (2020, p. 23) to explore non-anticipated and surprising observation and therefore, solutions, as well as the recommendation of Wang et al. (2019) of co-creation with the target group and utilising a UCD approach in general.

Denzin and Lincoln divide case studies into three different categories of practice: the intrinsic, which involves one single case or process, the collective case approach, involving a number of cases on specific and generic properties, and multiple instances of a process, meaning multiple cases of one process in different fields of application (2017, pp. 552). An intrinsic case study, utilising one paper prototype, is found to befit the subject of the explainability of a hypothetical intelligent design assistant, as case knowledge is not less valuable than general knowledge. Further, generalisation from a single case or case study is possible, case studies are suitable for further theory building, and there is no tendency of confirming the researcher's biases (Denzin & Lincoln, 2017, p. 557).

Case studies have unique conceptual structures, goals and issues. Therefore, they are to be further categorised by their uses (Denzin & Lincoln, 2017, pp. 557, 607): description, hypothesis generation or theory development, hypothesis and theory testing, and the development of a normative theory. As the "exploratory use of [a] case [study]" (Denzin & Lincoln, 2017, p. 610) is used to answer the research questions through triangulation, the second category is selected for this thesis, making it an intrinsic case study for hypothesis generation and theory development for further steps, leaning towards hypothesis testing.

The case study is conducted in the form of interviews, which are categorised in three major variants: structured, unstructured, and open-ended (Denzin & Lincoln, 2017, p. 900). As previously mentioned, the "open community engagement" (Shepherd, Sattari & Patzelt, 2020, p. 23) is essential for the design and therefore, the "importance of capturing unexpected information about (…) potential opportunities" (Shepherd, Sattari & Patzelt, 2020, p. 22) needs to be taken into consideration. Therefore, semi-structured interviews were chosen because they are the most open type for knowledge-producing potentials through dialogue as the interviewee chooses the perspective, deemed important, while the interviewers themselves become involved in the knowledge-producing process (Denzin & Lincoln, 2017, p. 1002). Meanwhile, the questions are directed towards specific issues of interest and the validity of the participants and their respective agenda can be kept in mind (Denzin & Lincoln, 2017, p. 1013).

An interview as a case study consists of four different building blocks, such as the purpose of the interview, a concrete description of how the interviewee views the world, first-hand experience of the lifeworld of the interviewee as an expert, and the interpretation of the meaning for possible new findings or even disproving the interviewer (Denzin & Lincoln, 2017, pp. 1003-1005). For the following thesis, this means:

1. Purpose of the interview: evaluate findings of the theoretical research and its realisation within the paper prototype
2. Description: ask questions of descriptive nature, e.g. 'How did you feel?'
3. Lifeworld: integrate lived experience of user/participant
4. Interpret the meaning: welcome all feedback, including approval, dismissal and propositions made by the participants

Summarising, an intrinsic, exploratory case study in the form of semi-structured interviews, utilising a paper prototype, is conducted with a small group of architects to evaluate the findings of the literature research and realisation within said paper prototype.

Data collection and analysis

The word 'data' is used in a manifold context: "big data; little data; raw, hard, and soft data; slices of data; first-order data; qualitative and quantitative data; bedrock data; biased data; primary and secondary data; reliable data; and emotional data" (Denzin & Lincoln, 2017, p. 563). In the scientific field, data is generally divided into two main categories: qualitative, real and deep, as well as quantitative, hard, data. The systematic collection methods of both are to be seen independently from the types of data produced. Data collection involves certain problems, such as involvement of the researcher in the issues etc., confidentiality, interest groups who have access to or control data, anonymity of subjects, and the audience's ability to distinguish between raw data and the interpretation by the researcher (Denzin & Lincoln, 2017, p. 810-811), which all need to be addressed.

The data used within this thesis is of qualitative nature and secondary data, as defined by Walliman (2006, pp. 52-54), which is interpreted data. The primary data of video and textual data of transcriptions is transformed into secondary data via interpretation for evaluation.

'Qualitative data analysis' is defined as the process of transformation of raw data, extracting meaning from it and readying it for 'consumption' (Denzin & Lincoln, 2017, p. 806). Therefore, I conduct qualitative data analysis on both the secondary data, as well as the primary data of the transcripts of the answers to the descriptive questions of the interview, i.e. questions asking about user perception.

After clarifying the used mixed methods for triangulation, involving theoretical research and an intrinsic case study of semi-structured interviews, the contributions of this thesis to the research field will be described. The following chapter presents the empirical literature research and its findings.

3 THEORETICAL RESEARCH

This chapter presents the conducted empirical literature research, as well as its findings and implications for the creation of the paper prototype, described in Chapter 4.

The first sub-chapter (see sub-chapter 3.1) of the Theoretical Research describes the used framework by Wang et al. (2019) and the necessary steps for the adaptation for a specific target group. The adaptation requires a comprehensive literature research on architectural workflow, architectural decision making during the design process, architectural evaluation methods, and architectural design quality assessment. The findings of the literature review are outlined according to the proposed steps by Wang et al. (2019, pp. 9, 12) in the following three sub-chapters. The second sub-chapter (see sub-chapter 3.2) presents architects' design requirements. Thereafter, the biases of architects are identified (see sub-chapter 3.3). Finally, the framework and the literature research on the reasoning goals and possible cognitive biases of architects are synthesised sub-chapter 3.4.

3.1 Framework by Wang et al. (2019)

In their paper 'Designing Theory-Driven User-Centric Explainable AI' Wang et al. (2019) present a "conceptual framework for building human-centered, decision-theory-driven XAI" (Wang et al., 2019, p. 1) to support high-consequence human decisions. Wang et al. (2019, pp. 1-3) offer lower-level building blocks for creating solutions through identifying relevant reasoning goals and selecting corresponding explanation techniques for the user as well as a transferable framework to other domains, linking human reasoning and intelligent system domains, based on purposeful, patterned causal reasoning. Additionally, propose a co-design exercise with real users, but make it clear in the end that the justification of explanations, i.e. 'Is the decision good?', and social context, i.e. cooperative conversation between the user and the intelligent system, are not part of the paper (Wang et al., 2019, pp. 3, 12-13).

The framework of Wang et al. (2019, p. 3) builds on four different paradigms: ideal human reasoning and grounding for explanation, the modelling of an intelligent system and its explainability facilities development for certain reasoning methods, human error due to cognitive biases, and finally that an explainable intelligent system is to mitigate decision biases.

The conceptual framework (see Figure 3-1) is divided into the human reasoning process on the left and explainable intelligent system methods on the right. Human reasoning is further separated into the ideal ways of reasoning, including explanation goals, inference methods, explanation methods and decision theories, and the reality of human reasoning with errors, categorised by the dual process model of human thinking. The dual process model consists of 'System 1' for fast thinking using pattern matching, potentially resulting in heuristic biases, and 'System 2' for slow, logical and analytical processes. 'System 2' of human reasoning also has certain weaknesses based on the user, e.g. lack of knowledge. On the other side stands the intelligent system, which generates explanations through Bayesian probability, similarity modelling, intelligibility queries, explainability elements, data structures and visualisations of said explanations. Further, it supports the reasoning of the user and mitigates errors which occur in the reality of non-ideal human reasoning. The explainable intelligent system utilises different techniques to mitigate representative bias, availability bias, anchoring bias and confirmation bias, and is responsible for moderating trust between the system and its user. As seen in Figure 3-1, Wang et al. include exemplary pathways between the human reasoning process and the appropriate intelligent system techniques, as their methods 'inform' the needed facilities, coloured in dark blue. Further, they point out the interrelations between the different reasoning processes and associations between different explainability features in light grey.

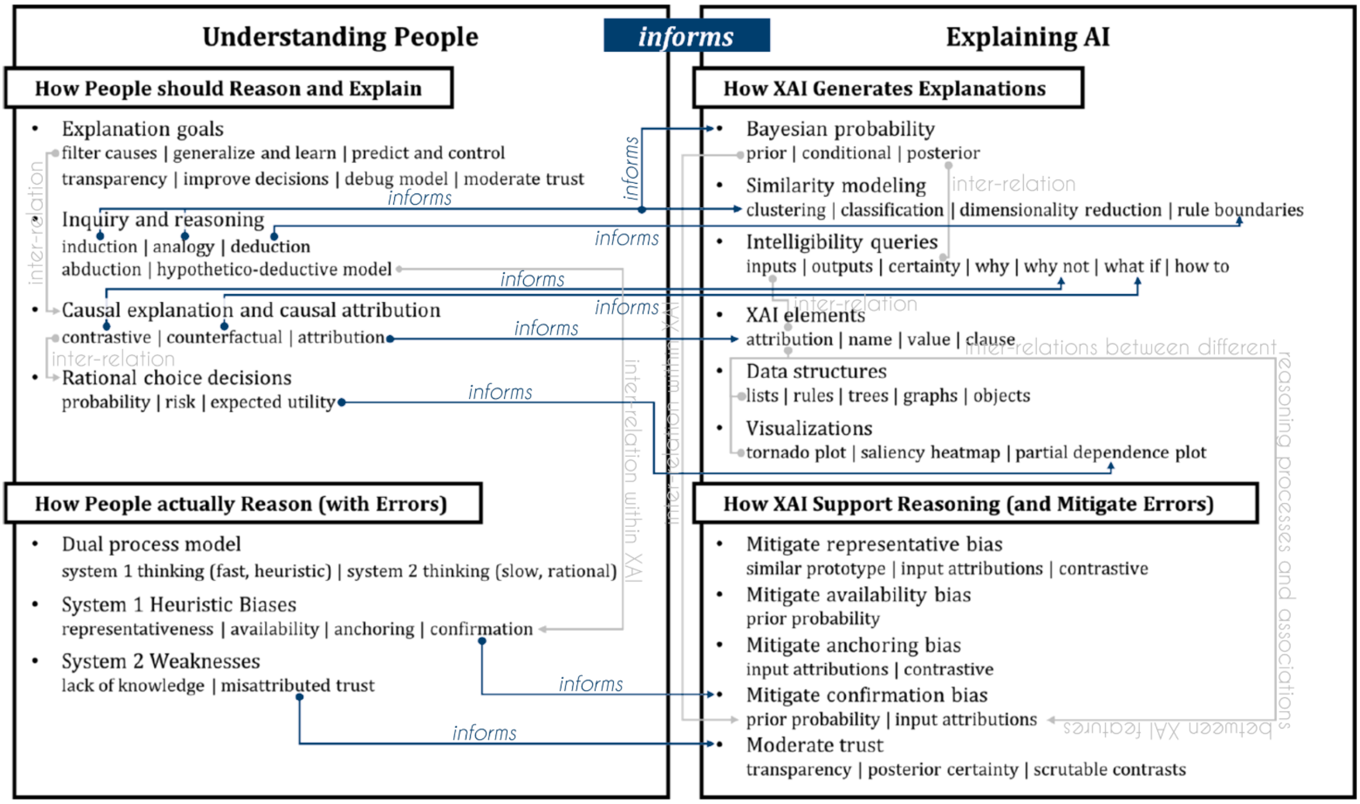

Figure 3-1: Conceptual framework for reasoned explanations based on human reasoning informs XAI techniques (Adapted from Wang et al., 2019, p. 4)

After discussing the framework in general, the different sub-categories within ideal and realistic human reasoning of the left side, followed by the right side, are further detailed and summarised.

Ideal and true human reasoning

Wang et al. (2019, pp. 3-4) identify four categories of explanation goals (see Figure 3-1, upper, left):

1. simplified observations through filtering to 'Generalise and Learn'
2. future prediction of results or events, also called 'human simulatability', as 'Predict and Control'
3. improved own decision making
4. concerning the system: transparency, moderated trust, scrutability, and debugging

Because of these explanation goals, inquiry and reasoning are used by the human user as inferences to find their respective causes or for the generalisation of knowledge and reason about the received information and explanations (Wang et al., 2019, pp. 4-5). Four different general types are identified, such as deductive ('top-down'), inductive ('bottom-up'), abductive ('bottom-up' with prioritising hypotheses) and analogical ('bottom up' with one instance, i.e. basis for CBR). Within the explanation methods, causal explanations are to be identified as a key type (Wang et al., 2019, p. 5). Causal explanations consist of selected causes, relevant for interpreting observations, and can be divided into contrastive reasoning of fact and foil ('Why?'/'Why not?'), counterfactual ('What if?'), and the prospective version of the counterfactual called transfactual ('How to?'). Finally, rational choice theory was chosen from decision theories for optimised choice, specifically 'Expected Utility' through 'Value-Risk-Measurement' and 'Priority and Probability' ranking (Wang et al., 2019, p. 5).

After discussing ideal human reasoning and presenting the different building blocks, as well as their types, reasoning with errors and its causes are revealed (see Figure 3-1, lower left). A dual process model is used to describe human decision making (Wang et al., 2019, p. 7). 'System 1' of human thinking is fast and intuitive using 'heuristics' and pattern matching. It leads to cognitive biases, namely anchoring bias, availability bias, representative bias and confirmation bias, due to oversimplification and context factors of the thinking person, such as overconfidence, fatigue and time pressure. Whereas 'System 2' is used for slow, analytical, and high effort thinking through rational reasoning, whose weaknesses include trust in a miscalibrated tool or lack of domain knowledge, as well as interferences from 'System 1'. This completes the left side of Figure 3-1 for human reasoning. The techniques of an intelligent system to generate explanations are presented in the following.

Explanations generated by an intelligent system

In the following paragraphs, the techniques of an intelligent systems to generate explanations and their purposes (see Figure 3-1, upper right) are introduced. Additionally, their representation methods, e.g. visualisations and data structures (Wang et al., 2019, p. 5), are described and linked to the previously detailed human thinking.

Wang et al. refer to the use of Bayesian probability of an intelligent system as stochastics operations based on "prior and posterior probabilities and likelihood" (Wang et al., 2019, p. 5). It highlights the probability of a certain outcome, by how influential certain factors are, to allow inductive reasoning. Similarity modelling is seen in distance-based methods, e.g. in CBR. It is used for explanations supporting inductive and analogical reasoning, identifying causal attributions for the boundaries between dissimilar groups (Wang et al., 2019, pp. 5-6). Intelligibility queries ask "colloquial questions about the system state …, and inference mechanism" (Wang et al., 2019, p. 6) of an intelligent system from a user-centric perspective, based on contrastive reasoning.

The representation methods of these techniques and their generated explanations by an intelligent system are divided into three different types. Firstly, XAI elements themselves often are textual. They consist of attribution and influence required for rational choice theory. The XAI elements highlight similar or different instances from the training data for causal chain reasoning of the user. Finally, name and value of input or output of the XAI elements are shown, as well as a clause for its threshold for transparency (Wang et al., 2019, p. 6). Further, explanations can be represented through data structures (Wang et al., 2019, p. 6), like lists and rules, to create decision trees, graphs for concept maps of a concept and its relationships, allowing deductive reasoning, and domain dependent representation of example or prototype for analogical and inductive reasoning, called extensible object data. Lastly, visualisations are discussed as a representation method, as they are better fit for explaining complex concepts through showing interrelations (Wang et al., 2019, pp. 6-7). Basic charts and canonical visualisations, e.g. node-link diagrams for graphs, are recommended for the transparency of the system. The authors propose tornado diagrams for lists of attribution to support causal attribution, and saliency heat maps for image-based models or text, supporting counterfactual reasoning through contrastive explanation. Scatterplots are advised for similarity depiction for inductive reasoning, even though they are very complex and therefore need thorough studying. Partial dependence plots are to visualise feature attribution across different feature values, which has been extended to sensitivity analysis of changing factors for rational choice using counterfactual reasoning, as well as expected utility or expected risk from decision theories.

After summarising how an intelligent system is able to support the decision making process of ideal human reasoning, the ways of supporting the user through mitigating biases (see Figure 3-1, lower right), including their causes and solutions is presented (Wang et al., 2019, pp. 8-9). Starting with the heuristic biases of 'System 1' of human thinking, the representative bias is caused by a lack of experiences or misplaced focus on salient features, i.e. 'Medical Student Syndrome', which can be mitigated by providing prototype instances to represent different outcomes using similarity distance. The unfamiliarity with regularity is the reason for availability bias, mitigated by showing prior probability within the training set. The anchoring bias happens due to the disproportionate evaluation of factors and early closure of the decision, which is to be mitigated through highlighting, how input findings may lead to different outputs, input attributions, counterfactual explanations and sensitivity analysis. Whereas confirmation bias happens due to deductive reasoning, which is mitigated through showing input and input attributions, and prior probability of decision solutions. Finally, the weaknesses of the analytical reasoning of 'System 2' are addressed through moderating trust, as overconfidence in the output of an intelligent system require the visibility of certainty ratings for transparency and possible debugging.

Framework summary and recommendations

Wang et al. formulate the following four steps to summarise the instructions for using this framework for adaptation in other fields (Wang et al., 2019, p. 9):

1. identify the user's reasoning goals through literature review, ethnography, and participatory design
2. clarify the user's biases for respective apps through literature review, ethnography, and participatory design
3. deduce appropriate explanation ways for the user's reasoning goals and/or mitigating cognitive biases using the pathways of the framework (see Figure 3-1)
4. integrate explainable intelligent system facilities to create an explainable user interface

Generally, the authors (Wang et al., 2019, pp. 9, 12) recommend to provide explanations to allow counterfactual reasoning, show feature values and attributions before class attribution to avoid deductive reasoning, keep the information load low, while multiple explanations are still recommended, support the visibility of coherent factor, support the access to source and situational data, and support probability analysis of the user by providing prior probability.

After this summary of the building blocks and framework by Wang et al. (2019), each sub-category of ideal and realistic human thinking will be examined for architects within the next two sub-chapters per the authors' recommendation. First, the architects' reasoning goals are presented, further referred to as architects' design requirements (see sub-chapter 3.2). The following sub-chapter 3.3 describes the biases of architects, their cause and their impact. Finally, within the last sub-chapter of THEORETICAL RESEARCH (see sub-chapter 3.4), the appropriate explanation ways of an intelligent design assistant to support the architect in reaching the reasoning goals and to mitigate cognitive biases by using the appropriate representation methods, are addressed, using the pathways of the framework.

Moreover, it has to be explicated that the integration of the explainability facilities, the fourth step of the summary of the framework, will be in form of a paper prototype and will not be implemented into an operating intelligent system within this thesis.

3.2 Architects' design requirements

In order to deduce explanation goals of architects for an intelligent design assistant, the use of reference building using floor plans, pictograms and other kinds of visualisations, has to be examined. As Richter points out, based on a wide variety of literature and studies, reference objects are a common practice within the architectural design process, sometimes referred to as architectural precedents (2011, pp. 139-141). However, unlike when this word is used in legal context, these references are free to use with originality and for creating innovation, as these precedents are rather defined as recognised, exemplary designs. Architects use these designs as a basis for their process, as well as their gained knowledge from other sources and previous experiences to synthesise a new original architectural design (Elango & Devadas, 2014b, p. 1033). Therefore, an intelligent design assistant utilising such reference buildings for suggesting further design steps builds on the principles of the original architectural design process. Consequently, the explanation goals expected for an intelligent design assistant are similar to the explanation goals within the common procedure in an architectural design decision making process.

Explanation goals

The general human explanation goals of Wang et al. (2019, pp. 3-4) are examined through the terminology of Richter for the different purposes of architectural reference objects (2011, p. 154) to present the explanation goals of architects for an intelligent design assistant. As humans aim to generalise and learn through simplification of observation through filtering, the architect uses reference buildings as a source of design conditions to evaluate their use as a source of inspiration. This implicit information is also used for improving one's own decision making, as it is used as a tool for evaluation of the own design, deepening the learning process. The "human simulatability" (Wang et al., 2019, p. 3) of 'Predict and Control' (see above) is applied to reference buildings to use the implicit information of the reference objects to deduce if it can be used as a source of inspiration by comparing the design conditions. Finally, the necessary transparency of an intelligent design assistant, including scrutability of the model, debug possibilities and moderation of trust, is to be categorised as the explicit information contained in a reference building. It needs to be used as a medium of communication between the architect and the intelligent design assistant.

Architectural design decision making process

In order to deduce the inference methods and explanation methods, the decision making process of architects needs to be examined first. Rational choice decisions are applied through value-risk-measurement and expected utility. However, due to the highly complex and "wicked" (Rittel & Webber, 1973, pp. 160-167) problems of design and the ill-defined decision making process (see sub-chapter 1.2), as well as different interest groups involved, the architectural design decision making process cannot be described that linear. This "weighted sum of qualitative and quantitative preferences of the stakeholders" (Harputlugil et al., 2014, p. 140) composes the quality of architecture, of which an architect aims to achieve the highest grade as the overall goal. Therefore, the different decision perspectives of each stakeholder need to be collected and categorised to improve the decision making and forecasting, 'human simulatability', to improve the architectural design quality during the entire design process. Especially the decisions of the early design phases (see sub-chapter 1.2) have shown to be definitive for the architectural quality of the finished building (Harputlugil et al., 2014, p. 140).

The Vitruvian principles suggest that architectural design is a process of 'utilitas' (eng.: utility), 'soliditas' (eng.: stability), and 'venustas' (eng.: beauty), varying due to era, technology, culture and society (Elango & Devadas, 2014b, p. 1033). The three categories similar to the Vitruvian principles were adopted by the Construction Industry Council (CIC) in 1999 to create the Design Quality Indicator (DQI). It is applicable in all design stages and uses the 'Likert Scaling' of isolatedly weighing individual features. Laseau (2000, p. 86-87) calls his three main categories 'design', 'performance' and 'context'. He further divides them into subcategories by their 'need', e.g. space requirements, relationships and access, 'context' like zoning and site, and finally the form, such as the zoning, circulation and structure.

Harputlugil et al. formalise (2014, pp. 140, 143, 146, 147, 149) the architectural design process, based on the principles of Vitruv, the DQI and Laseau, as an Analytical Hierarchy Process (AHP) with the means of Multi-Criteria Decision Making (MCDM) methods. The authors also assume three main categories, defining them as 'functionality', i.e. the use and its respective usefulness of the building, the 'build quality', meaning the quality of the built substance itself, and the 'impact', which includes the aesthetics of the building itself and in relation to its context. These three terms are adopted for further use within this thesis.

Harputlugil et al. reason that cognitive psychology shows that a maximum amount of seven factors can be simultaneously processed, differentiated, compared and held. However, the average amount is said to be two or three items of information, if it includes consequential action. An AHP allows the multi-level structuring of the decision problem, decision makers, criteria and sub-criteria within a hierarchy through representing and quantifying its tangible and intangible elements for relationships and evaluating alternatives. Within the beginning of the early stages, the architect commonly identifies a preferred design intention of the highest priority for the AHP, which Elango and Devadas call the “primary generator” (Elango & Devadas, 2014b, p. 1034). This pre-conceived idea or multiple ideas then lead to a generation of variants communicated through sketches, plans, models and text, ready for MCDM methods. MCDM utilises a pair-wise comparative scaling technique, replacing the ‘Likert Scaling’ used within the DQI, and highlighting the importance of the criteria and their interrelations (Harputluigl et al., 2014, p. 141-142). Thus, the evaluation of alternatives is used for the ranking and selection based on qualitative and quantitative criteria of different measurement units.

The use of an AHP provides applicability, simplicity, easy use, and flexibility (Harputlugil et al., 2014, p. 146) through hierarchy construction, priority analysis and consistency verification, while MCDM means that multiple, possibly conflicting, criteria can be taken into consideration, resulting in no absolute optimal solution. However, it allows for a ‘best solution for the circumstances’ by weighing the criteria against each other.

Elango and Devadas (2014a), as well as Harputlugil et al. (2014), explore the priority rankings of different criteria and their sub-criteria by architects in the early design phases within their papers. Elango and Devadas (2014a, pp. 17-18), using the principles of Laseau (2000, p. 86), reveal that the ‘design variables’ are the most important for the four different groups of ‘established architects’ with more than ten years of experience, ’architects’ with up to ten years of experience, the ‘members of the faculty of architecture’, and ‘post-graduate students’, except for governmental architects, which view the context as more important. Within the ‘design variables’, the efficiency of the building is placed highest by all groups, except post-graduate students and the governmental architects.

Harputlugil et al. (2014, pp. 152-153) examine the ‘functionality’, ‘build quality’ and ‘impact’, including their respective sub-categories, in a more detailed approach. Table 1 is constructed from their findings for the groups of project management architects (PM.-architects) and the total average of all stakeholders. Further, the combined information of two consecutive tables of Harputlugil et al. (2014, pp. 152-153) was restructured into one and further ranked by the numbers of each category, the sub-categories and sub-sub-categories of ‘functionality’. The numbers show the distribution of the priorities within the respective group of inquiry.

Table 1
Ranked priorities of early design stages with categories and sub-categories of 'Functionality', as prioritised by architects and total average of all stakeholders involved in the project (Adapted from Harputlugil et al, 2014, pp. 152-153)

Criteria	PM.-architects	TOTAL AVERAGE
FUNCTIONALITY	**0.504**	**0.553**
USE	**0.254**	**0.236**
Fit for functionality	0.129	0.105
Adaptability	0.070	0.083
Flexibility	0.054	0.048
ACCESS	**0.176**	**0.185**
Inter-unit access	0.048	0.060
Local Acess	0.048	0.051
Interior access	0.041	0.039
Inter-floor access	0.039	0.034
SPACE	**0.074**	**0.133**
Fit for purpose	0.023	0.041
Settlement	0.015	0.016
Relation with spaces	0.012	0.021
Access	0.012	0.020
Space size and proportions	0.008	0.021
Privacy	0.004	0.014
BUILDING QUALITY	**0.239**	**0.291**
IMPACT	**0.257**	**0.169**

The highest rated category 'functionality' is at the top of priorities for more than half of the participants (see Table 1). It is further separated into its sub-criteria of 'use', 'access' and 'space', ranked by their priority. Finally, these three are again divided into their respective underlying sub-sub-criteria and shown ranked by their priority. The table highlights how the 'use' for both the building and its individual rooms is seen by the architects and the average stakeholder as the most important sub-criteria of 'functionality', which includes far and foremost the 'fit for functionality', followed by the 'adaptability' and its 'flexibility'. Second is the 'Access' to, as well as within the building, of which the highest ranking are 'inter-unit accesses'. Finally, the 'space' itself is addressed with the 'fit for purpose' at the top.

Thus, 'functionality' and its respective sub-criteria and sub-sub-criteria are ranked at the top of the AHP for the early design phases. This also reveals the possible applicability of an intelligent design assistant in these stages, suggesting further design steps for spatial layouting including room types and access types in the form of auto-completion.

Inquiry and reasoning

From an AHP with MCDM, as well as the use of reference buildings, the inference methods of architects can be deduced. Architects utilise inductive and analogical reasoning to use reference buildings as a source of inspiration as well as for design conditions, as previously mentioned. The AHP-based generation of alternatives, a major characteristic of the early design phases, serves the purpose of applying these kinds of reasoning to select the most promising solutions or solution aspects (Elango & Devadas, 2014b, p. 1034).

Explanation methods

The MCDM process is supported by contrastive explanations, whereat architects heavily rely on counterfactual reasoning by using 'What if?' causal chain scenarios of both changing the priorities, the 'weight', within the AHP, as well as changing criteria and sub-criteria themselves. This deduction for the use of counterfactual explanations is substantiated by the demand of the design team for more 'What if?' scenarios within the paper of Harputlugil et al. (2014, p. 157). Further, the authors recommend the pair-wise comparison of tangible and intangible, and subjective and objective criteria for highlighting relationships to support contrastive reasoning.

Summarising, the individual parts of ideal thinking of an architect through the design requirements have been explored. The explanation goals of 'Generalise and Learn', 'Predict and Control' and 'Transparency', when using reference buildings have been found to be 'Source of inspiration', 'Source of design conditions', 'Tool for evaluation of own design', and 'Medium for communication', composed from both implicit and explicit information. Inductive and analogical reasoning are applied by architects for creating contrastive and counterfactual explanations through a design decision making process, categorisable as an AHP with MCDM methods. In the following sub-chapter the architects' true reasoning with errors is examined.

3.3 Biases of architects

Within this sub-chapter the biases of architects are presented. Each of the different heuristic biases, caused by 'System 1' human thinking using pattern matching, and the weaknesses of slow logical thinking of 'System 2' of human reasoning, as defined by Wang et al. (2019, p. 9), are introduced. They are illustrated with their possible occurrence within the architectural workflow and their impact are identified. Further, each of them is shortly illustrated with an example.

Representative bias/ 'System 1' bias

The representative bias is misjudging the similarity of the conditions of two or more items and therefore applying their respective solutions, even though they are not transferable. A representative bias is possible to happen for architects as they misinterpret the design conditions of a reference building to be the same as the project. Even though the design conditions differ, non-applicable reference buildings are perceived as a possible source of inspiration.

Example: A floor plan from the 1920s is used as a reference for a contemporary housing project. Due to the outdated technology of the construction industry, as well as the style, the walls are larger, while the rooms are far smaller and the amount of rooms is a lot higher than when using today's knowledge and possibilities. Therefore, the reference building does not correlate with the current style. A non-applicable representative of reference plans for inspiration has been selected.

Availability bias/ 'System 1' bias

The availability bias is the error of perceiving memorable, unusual and adverse events or solutions as a common outcome. Due to the availability bias, an architect might perceive certain reference buildings or aspects of reference buildings as highly likely, even though they are not of a high probability. Thus, the architect selects non-applicable reference buildings as an inspiration or aims to integrate the highly uncommon features.

Example: The architect reviews a floor plan of an extravagant home for possible inspiration in which a window connects the bathroom to the living room, providing a view into the shower. Due to its memorability, the architect integrates it into the design for the client, even though it is highly uncommon.

Anchoring bias/ 'System 1' bias

A skewed perception of the value of an item constitutes the anchoring bias. As previously mentioned, architects use an AHP with MCDM for decision making within the design process. Thus, a skewed interpretation of a criterion leads to the misalignment of priorities within the architectural design process. Architects typically identify a preferred design direction at the beginning of the process, the "primary generator" (Elango & Devadas, 2014b, p. 1034). Focusing on a false anchor causes a chain of misaligned priorities and disrupts the overall architectural design as well as its overall quality. Further, the anchoring bias can happen in each level of the hierarchy, but the higher the level, the more disrupted the final design.

Example: Elango and Devadas (2014, p. 18) point out that in their results of prioritising the sub-categories of Laseau's 'design variables' the priorities of 'post-graduate students' are often different and skewed compared to the 'established architects' (more than ten years of work experience) and 'architects' (less than ten years of work experience). The students view the importance of shape and geometry too high while disregarding the necessity for efficiency of rooms and building.

Confirmation bias/ 'System 1' bias

The confirmation bias is the collection of redundant information for confirming a hypothesis instead of evidence for other possibilities. It occurs within the architectural design process, as only reference buildings are reviewed which confirm the pre-conceived ideas of the architect for the design, which are then further used to generate a limited number of variants (Elango & Devadas, 2014a, p. 12) instead of alternatives. The architect neglects to use a variety of reference buildings as a source of inspiration and tool for evaluation, even though they have the same design conditions.

Example: The architect designs only using the own, usual style, utilising standard floor plans. For inspiration and reviewing, as well as evaluating their own design, only other standardised floor plans and the architect's former works are used, basically 'staying in the own comfort zone'.

Misplaced trust/ 'System 2' weakness

An intelligent design assistant is created and debugged by humans, mostly computer scientists. It can generate suggestions based on its database and the rules implemented. It can have flaws, i.e. due to inferior system capabilities, bad coding, and lack of quality of the database, both of the data itself, as well as an insufficient amount of data. Therefore, the intelligent design assistant may make wrong assumptions and suggest false further design steps to the architect. If the architect has a complete trust in the system, all suggestions are assumed correct and applicable without further questioning, especially if the architect has low experience.

Example: The database is created mostly from floor plans with enclosed rooms. Based on the high amount, it uses the high probability of the floor plans to create suggestions for an architect. Even though floor plans of residential housing have a far greater variety in reality, the architect accepts the design suggestion because of an unconditional trust in the intelligent design assistant.

The identification of the different causes and impacts of the different biases of architects within the architectural design process – namely, representative bias, availability bias, anchoring bias, confirmation bias and misplaced trust - completes the first two steps of the building blocks of Wang et al. (2019, p. 9) in order to use their framework. The following, and last, sub-chapter of Chapter 3 presents the deduction of explanation techniques for architects for the previous two sub-chapters of the architects' design requirements and biases of architects, so step three (see sub-chapter 3.1, p. 15).

3.4 Explanation techniques for architects

The explanation techniques, deduced from the findings of sub-chapters 3.2 and 3.3, for architects is divided into supporting the architect in fulfilling the design requirements and mitigating possible biases of architects. Within each of the two following sections, the methods to either support or overcome are presented, as well as the strategies of an intelligent design assistant to generate these facilities. Finally, the theoretical basis for creating explanation representations, fit for architects, are introduced.

Supporting the architects' design requirements

As architects use an AHP with MCDM methods, the intelligent design assistant needs to support inductive and analogical reasoning with contrastive, counterfactual, and therefore potentially transfactual, explanations. The intelligent design assistant facilitates this through a multitude of suggestions for comparison, supporting the convergence phase of the architect when the most promising solutions or solution aspects are selected for further designing. Further, the easy access to contextual information, needed for the design process, and 'What if?' and 'How to?' scenarios, i.e. simulations, support the design decision making. The intelligent design assistant provides these through the strategies of Bayesian probability, intelligent system elements and intelligibility queries.

Mitigating methods for biases of architects

The mitigation of the representative bias is achieved through presenting prior probability in correlation with coherent factors, i.e. 'building context information' like construction year, to the architect. The intelligent design assistant uses Bayesian probability, intelligent system elements and similarity modelling from the intelligent system facilities to present these to the user.

The availability bias is mitigated through providing access to the probability of a suggestion. This explanation is created through Bayesian probability by an intelligent design assistant.

As the anchoring bias happens due to misinterpretation of the priority of a criterion or sub-criterion, it can be mitigated by supporting the AHP of an architect. Therefore, contrastive and counterfactual, possibly transfactual, explanations are used. The system provides these by utilising Bayesian probability and Intelligibility queries of 'What if?' and 'How to?' scenarios, under the backdrop of intelligent system elements.

By showing the similarity of the input design by the architect and the suggestion of the intelligent design assistant, created from a database of reference buildings for the same coherent factors, i.e. 'building context information', the confirmation bias is overcome. In order to create these coherent factors and the classification of the input sketch, the intelligent design assistant uses similarity modelling while accounting for the intelligent system elements.

Finally, the trust of the architect in an intelligent design assistant is moderated through highlighting what is recognised within the input sketch and as what, i.e. a room is recognised and its room type is recognised and proposed as 'bedroom'. The system utilises attribution, names and values of the intelligent system elements for this. Further, it discloses its confidence in the classification calculated for the input design. In order to do so, the strategies of similarity modelling and intelligent system elements are applied. Finally, the intelligent design assistant allows access to the raw data, i.e. the reference floor plans, in a second step.

Explanation representation for architects

After presenting the conveyed information within the explanations, their representation for architects needs to be discussed. As architects are a visually driven target group, the obvious choice of representation is visualisation. Further, visualisations themselves enrich data by combining tangible and intangible information by emphasising relationships, increasing the quality and amount of data for the architect. Therefore, they support pattern recognition and 'human simulatability' for supporting future decisions (Medler, 2012, pp. 46, 101), which is especially suitable for the architectural design process as an AHP with MCDM. However, the 'Usefulness' of the depicted data is determined through a user and quality filter (Medler, 2012, p. 47, 50, 65-68, 83), determining the level ambiguity, complexity and intensity. In order to avoid information overload or filter failure and therefore decreased efficiency of cognitive processing, the visualisations need to be created with the architect as the user in mind. Thus, the visualisation language of architects needs to be used, what Zammitto calls "established conventions" (2008, p. 269). This concerns both domain knowledge, i.e. heat maps of daylight simulations, and common knowledge, i.e. colour coding for 'red is bad' 'green is good'.

This concludes Chapter 3 of the thesis. Summarising, the architects' design requirements and the biases of architects are identified to use the framework of Wang et al. (2019) to create explainability of an intelligent design assistant for architects. The purpose of an intelligent design assistant is to aid the architect within this process through both directly supporting the decision making with contrastive and counterfactual explanations for inductive and analogical reasoning, as well as mitigating possible errors of the two systems of human thinking (fast and intuitive of 'System 1', and slow and analytical of 'System 2') by providing information and their interrelations. The deduced explanation methods, created from the pathways of said framework, are to be preferably represented as visualisations to emphasise relationships, as the architectural design process is classifiable as an AHP with MCDM. The next chapter, Chapter 4, is the graphical execution of these findings within a paper prototype, meaning a provisional implementation of step 4 of the framework without coding, created for testing the possible interaction of the architect with an intelligent design assistant.

4 PAPER PROTOTYPE

The explanation methods of architects for support and for mitigating biases, as well as the appropriate representations of Chapter 3 are used to generate a paper prototype for an intelligent design assistant. Firstly, the contentual findings are the basis for the design of explanation visualisations, which are followed by sub-chapter 4.2, presenting guidelines for graphic user interfaces (GUIs) for an intelligent design assistant for architects. Finally, the two sub-chapters are combined to create a digital paper prototype for the hypothetical application WHITE BRIDGE.

4.1 Explanation visualisations

In the following sub-chapter, the visualisations for supporting architects in fulfilling the design requirements, mitigating the different heuristic biases of representativeness, availability, anchoring and confirmation, as well as moderating trust, are individually presented. These first drafts of visualising the explanations were created as simple 2D drawings, using Adobe Illustrator, Adobe Photoshop and Autodesk REVIT.

Supporting architects in fulfilling the design requirements

In order to support the architect in fulfilling the design requirements, the inductive and analogical reasoning of architects is addressed with contrastive explanations. Therefore, the architect needs to be presented with multiple suggestions to compare them against each other, while the difference between the sketch of the architect and the suggestion has to be made clear. Thus, as a reference to the common practices and tools of an architect the multitude of suggestions is presented on scrollable layers that resemble sketch paper sheets (see Figure 4-1).

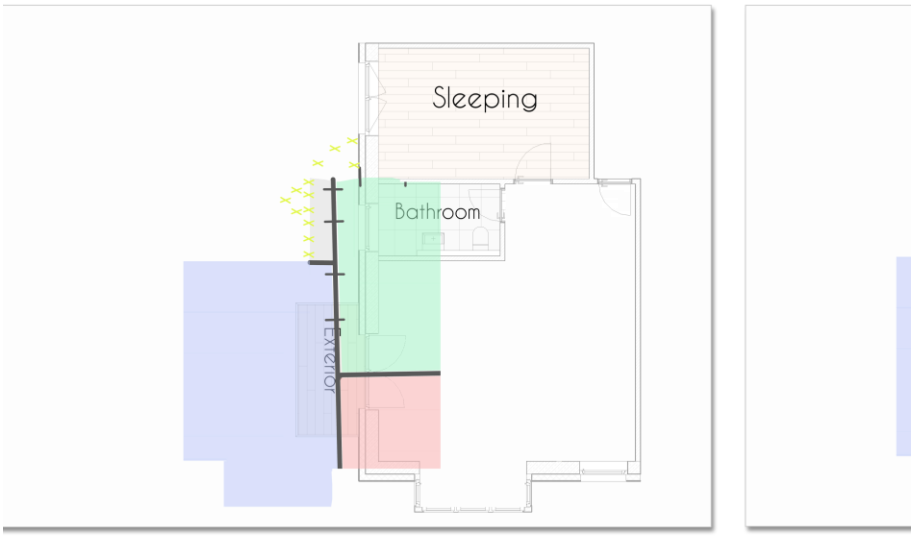

Figure 4-1: Multiple suggestions on a different layer, resembling sheets of sketch paper for sliding through.

Further, the counterfactual and transfactual reasoning of architects is supported with simulations for architectural design. These 'What if? And 'How to?' scenarios are situated on the individual suggestion layer, utilising specific domain knowledge of visualisation, e.g. daylight simulations and how the demolition of certain walls results in a different daylight simulation (see Figure 4-2).

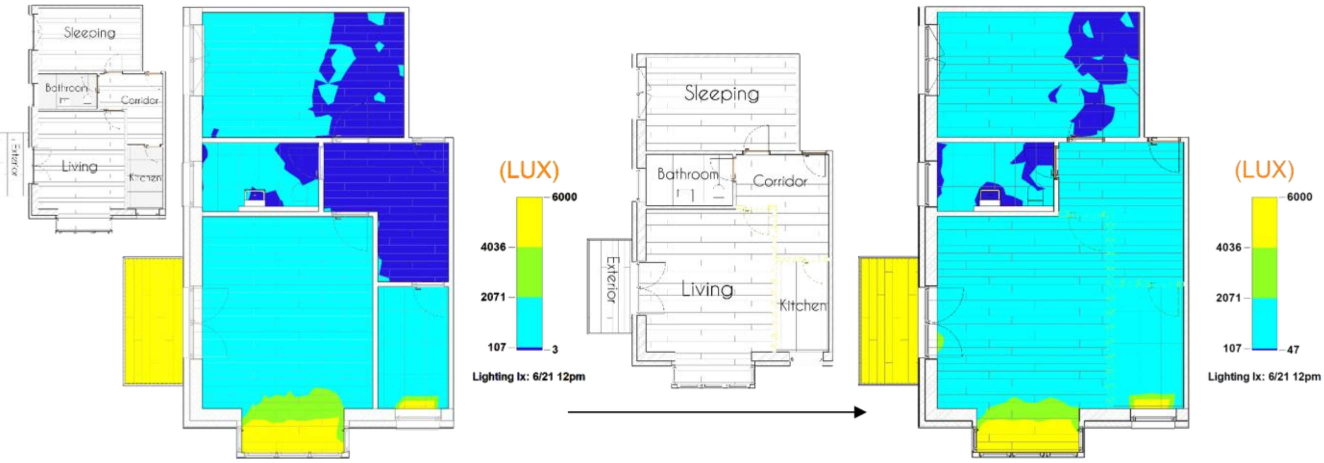

Figure 4-2: Daylight simulation within 'How to?' scenario.

Mitigating representative bias

Following, the mitigation of the different heuristic biases is addressed with visualisations, starting with the representative bias. In order to display 'building context information' of the floor plans that were used to create the present suggestion, the information needs to be accessed via a button, placed on the respective suggestion layer. Utilising common knowledge, two buttons were drafted: an icon resembling an 'i' for information, as also used for information points in the real world, and a burger menu, universally used in contemporary applications on digital devices. Further, the architectural North arrow indicates the orientation of the building as a category of the 'building context information' (see Figure 4-3).

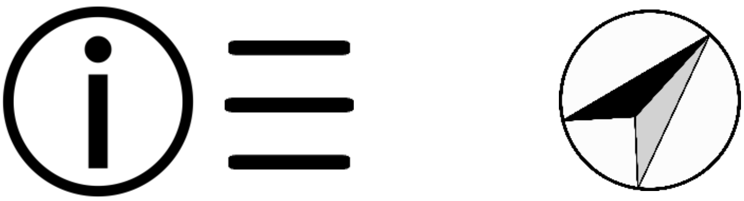

Figure 4-3: 'i' icon or burger menu to access 'building context information' and North arrow as orientation (category of 'building context information').

In order not to overwhelm the architect with information and for the display to be more spacious for sketching, the actual building information is provided within a drop-down window, accessible through the previously described buttons. Two drop-down windows for both the clickable information icon and burger menu have been drafted with different buttons for closing the window on the upper right (see Figure 4-4).

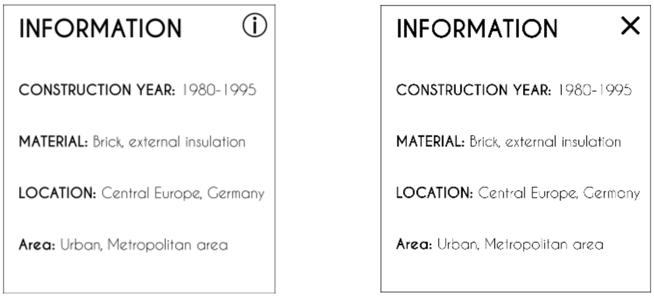

Figure 4-4: Drop-down windows with categories for 'building context information', designed for the 'i' icon and for the burger menu.

Mitigating availability bias

The availability bias is mitigated by utilising the order of the suggestions, ranked by their prior probability. Further, this ranking of likelihood needs to be communicated to the user. A toast notification (see Figure 4-5) is used when the suggestions are first accessed.

Figure 4-5: Toast notification for showing the reason for the order of the suggestions.

Mitigating anchoring bias

As previously mentioned, the anchoring bias is to be mitigated by supporting the AHP of the architect. Therefore, the same methods as well as the visualisations, previously presented in supporting the architects' design requirements (see above), are applied. This includes the variety of suggestions on a differentiable layer (see Figure 4-1) and 'What if?' and 'How to?' scenarios (see Figure 4-2) through simulations, i.e. daylight simulations, on said suggestion layers.

Mitigating confirmation bias

The fourth heuristic bias, the confirmation bias, is overcome through showing the matching of the input sketch, so the drawing itself, with the floor plans that were used to create the presented suggestion in correspondence with its respective classification of the 'building context information', see above in Mitigating representative bias. A health bar with a textual number is used to visualise the 'overlap percentage', which is further detailed with colour coding for quick understanding without reading the numbers (see Figure 4-6).

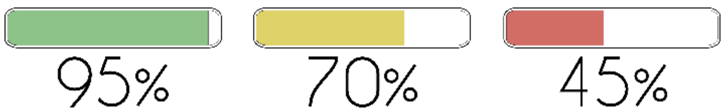

Figure 4-6: The different percentages of overlap as health bars with colour coding.

Moderating trust

Finally, the weaknesses of logical thinking due to trust in a miscalibrated tool are discussed. Transparency, scrutability and the possibility of debugging is needed to moderate the trust between the architect and WHITE BRIDGE. Therefore, the system needs to communicate what is recognised within the input sketch of the architect and how. As illustrated in Figure 4-7, the intelligent design assistant appropriately colours and hatches the recognised rooms for the room type, e.g. the bedroom called 'sleeping' has light brown wood flooring.

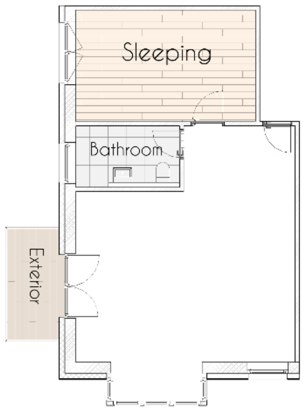

Figure 4-7: Recognition of rooms and room type visualised with colour and hatching.

Further, the 'confidence of the system' in the classification it calculated for the input sketch is stated to the user within the drawing view. As it is a progressive process, a loading visualisation was chosen to emphasise on this aspect (see Figure 4-8). The shape is a circle for further visual differentiation from the 'overlap' percentage (see Figure 4-6), which does not address the classification but the drawing itself. Further, a drop-down window contains the specifics of the classification.

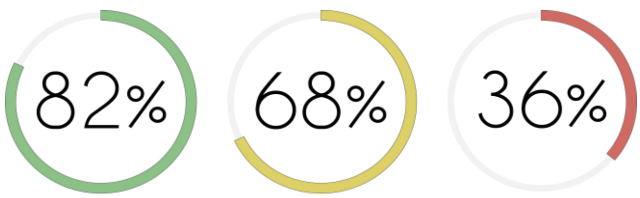

Figure 4-8: 'Confidence of the system' as updating circle to emphasise on progression, using colour coding.

Finally, the access to the raw data, so the initial floor plans used to create the displayed suggestion, is proposed for moderating trust. As recommended, this access is possible through a second step. Therefore, the drop-down window of the building context (see Figure 4-4) is extended with a button to get directed to the initial floor plans. Two versions have been drafted for this button, both written in colour to be differentiated from the textual information of the 'building context information': one is using 'Access raw data', while the other is titled with the commonly used 'See more' (see Figure 4-9).

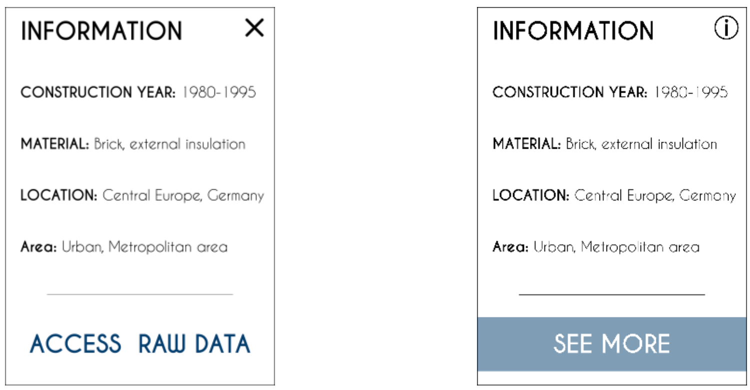

Figure 4-9: Drop-down windows with categories for 'building context information', designed for the 'i' icon and for the burger menu, including button to access raw data.

Thus, the individual visualisation used within WHITE BIRDGE are presented. As a final overview of all the findings, the necessary explanations, their individual purpose with a further description, and the strategies to support or mitigate the respective biases as well as the concluded visualisations are summarised in Table 2.

Table 2

Overview over the explanations integrated in WHITE BRIDGE, their respective purpose with a further description and their visualisation.

Purpose	Description	Strategies to support or mitigate	Visualisation
SUPPORT			
Explanation methods	**Explanation techniques for inductive/ analogical reasoning**		
Contrastive	Why? Why not?	Multitude of suggestions for comparison with contextual information	Suggestions as layer like sketch paper on top of drawing
Counterfactual	What if?	What if?' and 'How to? Scenarios (e.g. simulations)	Simulations, e.g. daylight simulation
Transfactual	How to?	What if?' and 'How to? Scenarios (e.g. simulations)	Simulations, e.g. daylight simulation
MITIGATE			
Heuristic bias	**Weaknesses of System 1**		
Representative	Misintepreting a reference building of different design conditions as a source of inspiration	show prior probability in coherence with building context factors (e.g. construction year)	Button, e.g. Burger menu or 'i' icon, to access dropdown window with building context information as text
Availability	Perceiving a reference building or a certain feature as a source of inspiration due to it memorability, even though it is of low likelihood	show probability of suggestion	Pop-up at the beginning: 'suggestions shown ranked by likelihood' (and show suggestions in ranked order)
Anchoring	Skewed perception of the value of a criterion or sub-criterion with the architectural design process (AHP with MCDM)	show multitude of suggestions for comparison with contextual information What if?' and 'How to? Scenarios (e.g. simulations)	Suggestions as layer like sketch paper on top of drawing Simulations, e.g. daylight simulation
Confirmation	Collecting redundant references buildings as source of inspiration, even though the design conditions allow for a wider variety	show similarity of input design and suggestions of intelligent design assistant on the background of the classification of the input sketch	Use health bar with colour coding to show overlap/ match percentage of input design and suggestion
Logical errors	**Weaknesses of System 2**		
Misplaced trust	Trust in miscalibrated tool, lack of knowledge	show what is recognised and how in the input sketch confidence of the system in its classification of the input sketch show raw data (i.e. floor plans used) in a second step	Colour the rooms with suitable colour and hatching (i.e. living room in light brown with wood flooring) Progression circle for showing updated certainty of the classification of the input design with colour coding and dropdown window for showing classification Provide button on dropdown menu of building context information (see above) to provide access to raw data in second step

Following the presentation of the explanation visualisations, guidelines for the GUI of an intelligent design assistant are introduced. Afterwards, the drafts of the current sub-chapter will be refined to be combinated with the guidelines in order to create the online paper prototype for the hypothetical application WHITE BRIDGE.

4.2 Design considerations for a paper prototype of WHITE BRIDGE

In order to design a GUI for the hypothetical application WHITE BRIDGE, the basics for a GUI for an intelligent design assistant for the early design stages need to be introduced. Best practices and guidelines are reviewed for the creation of GUIs for applications of the architectural design process in the early design stages. Following, the explanation visualisations of the previous sub-chapter will be integrated into the GUI within the sub-chapter 4.3.

Theoretical basis

As Lertsithichai (2005, pp. 357-358) states, the design of GUIs for current CAAD devices and software is still largely focused on the implementation on a computer system, without accounting for the architectural design process and its tools. However, during the early design phases the architect utilises sketching for the conceptualisation and visualisation of abstract ideas, as well as communication. WHITE BRIDGE answers to these conditions and workflow in the form of a drawing surface for hand sketching with integrated suggestions for further design steps by an intelligent design assistant and corresponding explanations, generated for the architect.

Chammas, Quaresm & Mont'Alvão (2015, p. 5398) separate the design approaches for interactive products into four different categories (see Table 3): activity centred design, based on the tools used, the system design, focusing on system components, the genius design, solely relying on the 'genius' of the developer, and finally the user-centred design, focusing on the needs and goals of the user.

Table 3
The four main design approaches for interactive products (Adapted from Chammas, Quaresma & Mont'Alvão, 2015, p. 5398)

Approach	Focus	User role	Designer role
ACTIVITY CENTRED DESIGN			
	tasks activities	practitioners	creator of tools for the tasks
SYSTEM DESIGN			
	system components system capabilities	set of system goals	ensure that all parts of the system are in place
GENIUS DESIGN			
	abilities of the designer experience and knowledge of the designer	validation source	inspiration source
USER-CENTRED DESIGN			
	needs of the user goals of the user	lead interface design	reflects the needs and goals of the user answers to the needs and goals of the user

A UCD approach is advised for the design of GUI of an intelligent design assistant – even without explanations – due to the high specifications for both the user group of architects, and the interaction devices and technologies. Four major components need to be considered in the interaction between WHITE BRIDGE and the user (Lee, Chuang & Wu, 2011, p. 2): the architect as the user, the particular task of sketching architectural design within the context of the early design phases, and finally the technological system utilising paper and pen, or paper-and-pen-like tools. Taking the previously stated circumstances of WHITE BRIDGE of both novice interaction method for a CAAD and the used intelligent system technology into account, the GUI as the interaction point between visually driven user and intelligent design assistant becomes clear. The more intuitive and aesthetically pleasing the GUI is for the architect, the higher the satisfaction with the application (Lee, Chuang & Wu, 2011, p. 3), making the GUI the most important component when architects interact with WHITE BRIDGE. The previously mentioned ISO standard 9241-210, based on UCD, for user experience (UX) aims to increase the acceptance and productivity of interactive systems. Through supporting a fast learning process and the mitigation of errors, the need for training is reduced and the efficiency of the system and the users' work are increased. In order to focus on the users' needs and goals, the techniques of ergonomics and usability are applied. Thus, the efficiency and effectiveness of an interactive system are increased through providing accessibility, while health, safety and user performance are considered.

In order to draft a GUI for WHITE BRIDGE, the comprised design principles for user interfaces (see Table 4) were reviewed. Further, the visualisation methods for architects have to be applied, i.e. the visualisation language and domain knowledge. These were used to generate simple guidelines for an intelligent design assistant, using hand-sketched drawings on a digital device, e.g. tablet.

Table 4
Comprised design principles for user interfaces (Adapted from Lee, Chuang & Wu, 2011, p. 4):

Scholar	Design Principles for user interfaces	
BEN SHNEIDERMAN (2006)		
	strive for consistency	prevent errors
	seek universal usability	permit easy reversal of actions
	offer informative feedback	keep user in control
	design dialogues to yield closure	reduce short-term memory load
JAKOB NIELSEN (2005)		
	visibility of system status	recognition rather than recall
	match between system and real world	flexibility and efficiency of use
	user control and freedom	aesthetics and minimalist design
	consistency and standards	support user in recognising, diagnosing and recovering from errors
	prevent errors	help and documentation
JENIFER TIDWELL (2005)		
	safe exploration	incremental construction
	instant gratification	habituation
	satisfy	spatial memory
	changes in midstream	prospective memory
	deferred choices	streamlined repetition
DEBORAH J. MAYHEW (2008)		
	user compatibility	control
	product compatibility	WYSIWY
	task compatibility	flexibility and efficiency of use
	work flow compatibility	responsiveness
	consistency	invisible technology
	familiarity	robustness
	simplicity	protection
	direct manipulation	
ISO 9241:171 (2008)		
	suitability for task	error tolerance
	self-descriptiveness	suitability for individualisation
	controllability	suitability for learning
	conformity with user expectations	

Summarising, the following design considerations for the GUI of an intelligent design assistant are formulated:

1. Use the symbolism of familiar architectural tools, such as a pen for drawing and an eraser for deleting.

2. Buttons should be simple and meaningful, located in obvious areas, as well as clearly differentiated from textual information.
3. Provide different views for drawing and for suggestions based on domain knowledge, emphasising on the non-definitiveness. Further, support the recognition of the different views through reminders to indicate which layer is currently active.
4. Keep the interface as clean and minimalistic as possible, so the architect can focus on the drawing surface and task at hand.
5. Emphasise on meanings, relationships, and consequences of each action taken by the user.

GUI of the paper prototype (without explanations)

Based on these guidelines, the GUI of an intelligent design assistant without explanations was drafted. The drawing view can be viewed in the Appendix under 11.1 (p. 71). It features a simple menu of drawing tools at the top and in the bottom left corner an icon of three pens symbolising the currently active drawing view. Further, at the bottom a blue coloured toast notification, labelled 'design suggestions available', can be seen, which stays on screen for five seconds. Afterwards, the notification slides to the right side of the interface and turns into a side bar with a burger menu at the top.

When this burger menu is clicked, the suggestion view is activated (see 11.2, p. 72). This transition is facilitated by the drawing tools and the pen icon at the bottom left sliding out to the left, while the first suggestion on a slightly transparent layer is sliding in, onto the top of the sketch with an icon symbolising 'suggestion' in the bottom left corner of the transparent layer. Additionally, the blue sidebar – initially the suggestion notification – is slightly sliding further in as well, while the burger menu turns into an X. It emphasises the fact that the suggestion view is active and gives space to two arrow-shaped buttons for skipping back and forth through the suggestions. The upper arrow, pointing to the left, is slightly transparent for the first suggestion, signifying its inactivity. When the arrow below, pointing to the right, is clicked, the current suggestion 'paper sheet' slides out to the left while simultaneously the next suggestion slides in from the right side. In order to exist the suggestion layer, the user can either click the X button at the top of the blue sidebar or double click the current suggestion to accept it and it becomes part of the drawing. Both actions are completed with the drawing tools and drawing icon sliding in from the left and the sidebar retracting, while the X returns to being a burger menu.

Thus, the design of the GUI for an intelligent design assistant without explanations is completed. It builds on the UCD approach and utilises the common guidelines and best practices for user interfaces with the focus on the user group and interaction technology.

4.3 Implementation of the paper prototype

In the two previous sub-chapters, both explanation visualisations for architects and a GUI for an intelligent design assistant were described. Their respective findings are synthesised to create a digital paper prototype for the hypothetical application WHITE BRIDGE. As a first step the type of presentation of the paper prototype is discussed. Subsequently, the design tools and different software used for the implementation of the paper prototype are introduced. Following this, the integration of the explanation visualisations in the GUI of WHITE BRIDGE are presented.

Paper prototype presentation and design tools

As the prototype of WHITE BRIDGE is not functional, it is categorised as a paper prototype. Further, it is a digital paper prototype to be used within an online study because of contextual circumstances described in detail in the sub-chapter 5.1 Research setting of Chapter 5 STUDY. In order to avoid incorrect handling of the prototype by the study participants, the digital paper prototype is presented in a narrated video. This presentation follows an architect drawing a sketch for a residential housing project and experiencing suggestions for further design steps with explanation visualisations by the application WHITE BRIDGE.

The drawing of the hand sketch is created through a screen video on an Android tablet, while sketching a residential housing project within the application S Note.

An interactive paper prototype with transitions and actions is implemented with the software ProtoPie for UX design. Within the program, running on Windows and Android, interaction is realised without coding from three components: objects, triggers and response (UX Planet, 2018). A sequence of wireframes and their transitions (see 11.3 of the Appendix, p. 73), including the screen video of the hand drawing, are realised within ProtoPie to create a consistent and fluent story for the video presentation.

Finally, the previously determined choreography of wireframes is followed within the computer preview and narrated while recording a screen video and audio with the software FlashBack Pro 5. Final retouches of the video are completed with Adobe Photoshop.

Digital paper prototype within the video presentation

After describing the methods and tools used to produce the digital paper prototype as well as its video presentation, the final version of the paper prototype is described. The following paragraphs specify the integration of the explanation visualisations from sub-chapter 4.1 within the GUI, designed in sub-chapter 4.2, in the same order as seen by the study participants through the video presentation. Further, it is shortly referenced back to the purpose for each explanation visualisation. Full-sized versions of the GUI without any highlighting are provided in the appendix (see 11.1 - 11.10, pp. 71-80), while the following pictures highlight the individual explanation visualisations.

Starting with Figure 4-10 of the drawing view (see 11.4, p. 74), WHITE BRIDGE shows the user that the rooms have been recognised, as well as the room type it identified through colouring and hatching. Further the North arrow was recognised and coloured in light blue to emphasise on the identification. This moderates trust between the architect and the hypothetical application.

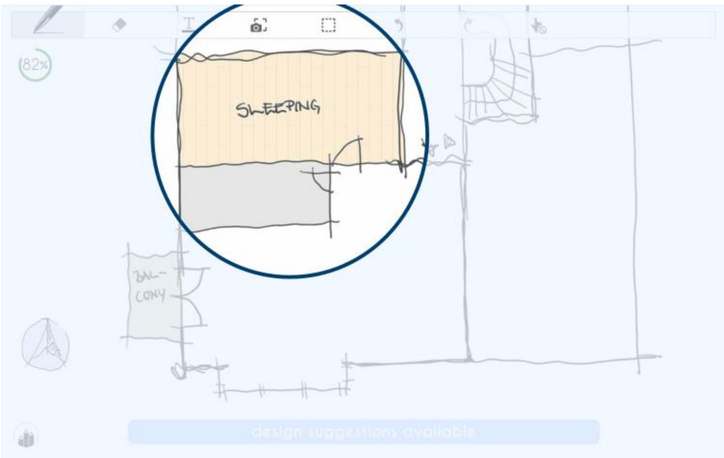

Figure 4-10: Coloured and hatched rooms within sketch.

During the drawing process, in the upper left corner, the progression circle of the 'confidence of the system' reached 82% and is green. Through hovering over the visualisation, a tooltip is dropped down, containing the specifics of the classification the system calculated for the input sketch. Per recommendation of Harpring (2019, pp. 65-69) for cataloguing architectural buildings the Cultural Objects Name Authority (CONA) was applied to derive the building context categories: 'work type' is translated into 'Building type' and 'Floor plan type', 'chronological information' is called 'Construction year' within the hypothetical application, 'technique/medium' is named 'Material', and finally the 'geographical/cultural information' is shown in 'Location' and 'Area'. However, the recommended 'Architect/ building name' of CONA are left out to avoid further representative bias by choosing a reference building based on the name of a famous architect or building.

This visualisation of the 'confidence of the system' aims to moderate trust by providing transparency and visibility of its own classification for the sketch the architect drew. Further, it aims to support the architect by offering insight in the classification for evaluation of the own design (see Figure 4-11). A full-sized illustration of this view can be seen in 11.5 of the Appendix (p. 75).

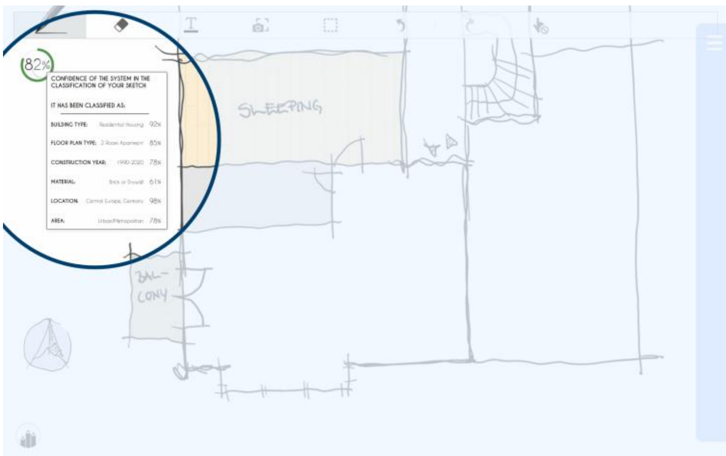

Figure 4-11: 'Confidence of the system' in drawing view.

As soon as the various suggestions (see 11.6, p. 76) are accessed, a blue toast notification (see Figure 4-12) with the label 'suggestions shown ranked by likelihood' appears at the bottom of the screen. It disappears after five seconds and is intended to mitigate the availability and anchoring bias through emphasising on the probability of the suggestion, while the variety of the suggestions themselves is proposed as a support of the architect and further mitigation of the anchoring bias.

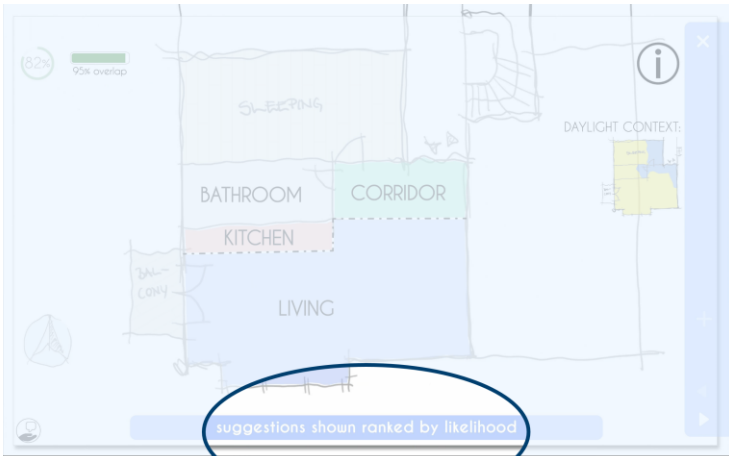

Figure 4-12: Toast notification for specifying order of suggestions, when suggestion view is opened.

In order to keep the suggestion layer as clean and minimalistic as possible, hovering over the individual visualisation is used as a gesture to access tooltips for further information and descriptions. The following two visualisations, as well as the previously described toast notification, can be seen in full size in 11.7 (p. 77). The health bar for the 'overlap percentage' (see Figure 4-13) is grouped in the upper left corner with the 'confidence of the system', as both concern the input design of the architect. The similarity visualisation aims to mitigate the confirmation bias, which is the collection of redundant or irrelevant reference buildings through showing the similarity between input sketch and the floor plans used for generating the suggestion.

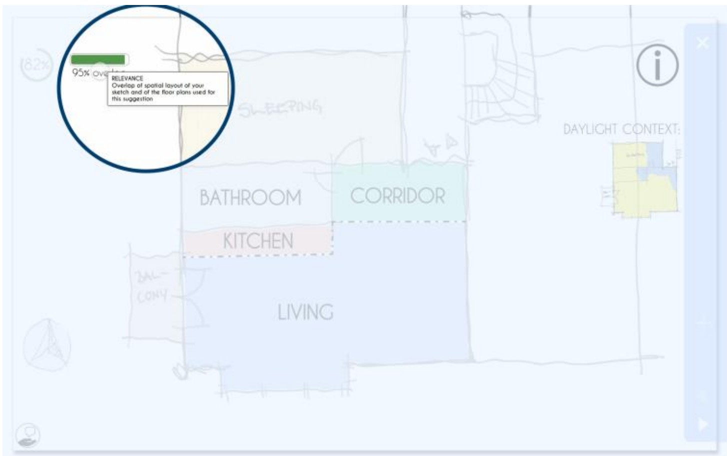

Figure 4-13: Relevance of the suggestion in suggestion view.

The 'building context information' (see Figure 4-14) is accessed through the information icon, positioned in the top right corner. This 'i' icon is implemented instead of the burger menu, reasoning that the burger menu is already in use within the sidebar and the information icon is known to a wider variety of people, including users less accustomed to technology. As WHITE BRIDGE aims to include all kinds of architects, the explanation visualisations have to comply. The 'building context information' shows in its drop-down window the same categories as the sketch classification for mitigating the representative bias. The information icon as well as the affected category of the 'building context information' is coloured red to alert the user when the 'building context information' classification differs from the classification of the input sketch (see 11.8, p. 78) in an attempt to further mitigate the representative bias. Further, the drop-down window also contains a clickable button labelled 'More details' to access the raw data of floor plans (see below).

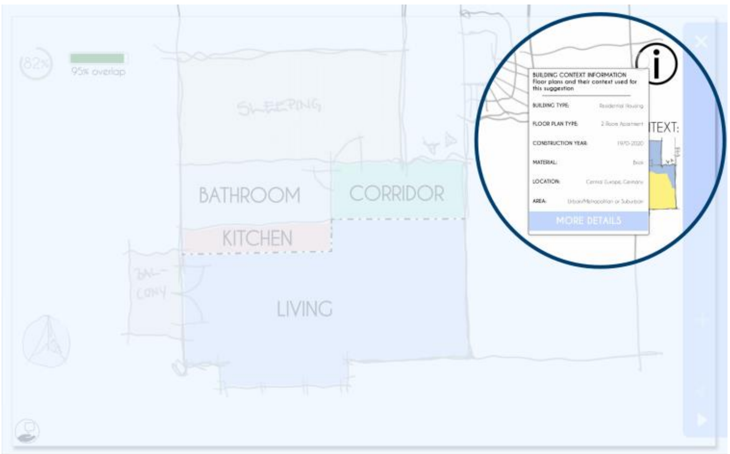

Figure 4-14: Drop-down window of 'building context information' in suggestion view.

The highlighted daylight context (see Figure 4-15) below the 'building context information' is created from the original hand sketch (Zank, 2016). It is intended to support the counterfactual and transfactual reasoning of architects through the simulation of light as well as to mitigate the representative bias through emphasising on light as a context of the building. The tooltip can be read in full size in 11.10 (p. 80).

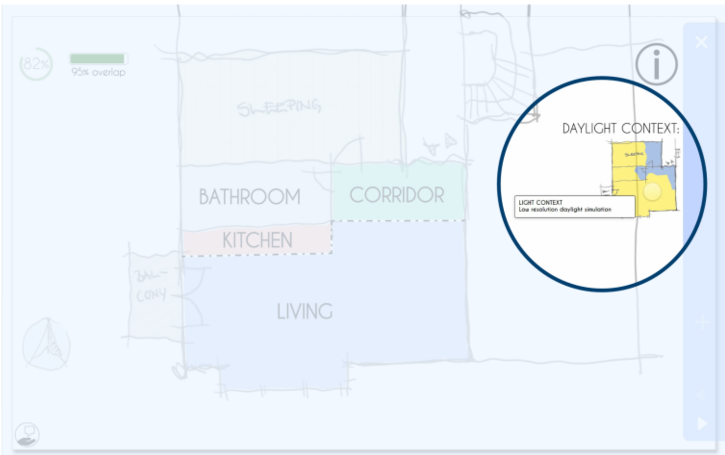

Figure 4-15: Daylight simulation, using the original sketch, in suggestion view.

After examining the daylight context, 'floor plans used for suggestions' is accessed through a click on the button of the drop-down window of the 'building context information' (see Figure 4-14). The floor plans are presented as a new opaque layer sliding in from the top like a piece of paper (see Figure 4-16). Thus, WHITE BRIDGE provides access to the raw data in a second step for the moderation of trust between the user and the intelligent design assistant (for full-size see 11.9, p. 79).

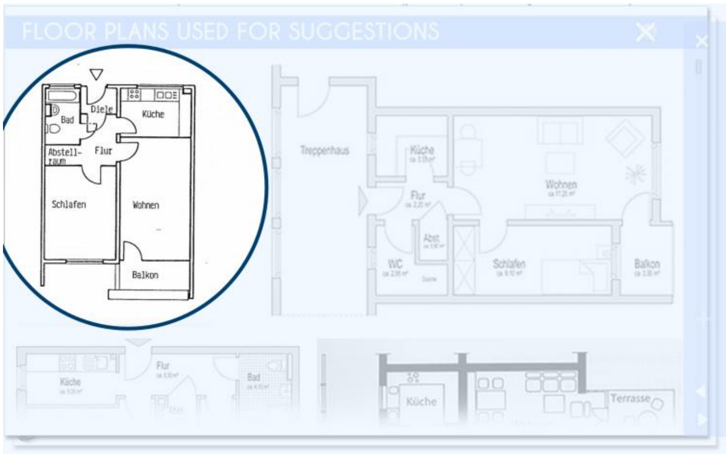

Figure 4-16: Raw data of floor plans, which were used to create the suggestion.

Finally, the different suggestions can be layered onto each other using the 'plus' sign, visible on the blue sidebar (see Figure 4-17). It offers more direct and higher detailed comparison, increasing the intended support of contrastive reasoning in the decision making process of architectural design. By highlighting the occurrence of differences for the individual explanation visualisations, using a red exclamation mark and textual label of 'DIFFERENCE' within the drop-down windows, WHITE BRIDGE aims to further support using counterfactual and transfactual explanations. Moreover, both these features are proposed to also mitigate the anchoring bias (for full size see 11.10, p. 80).

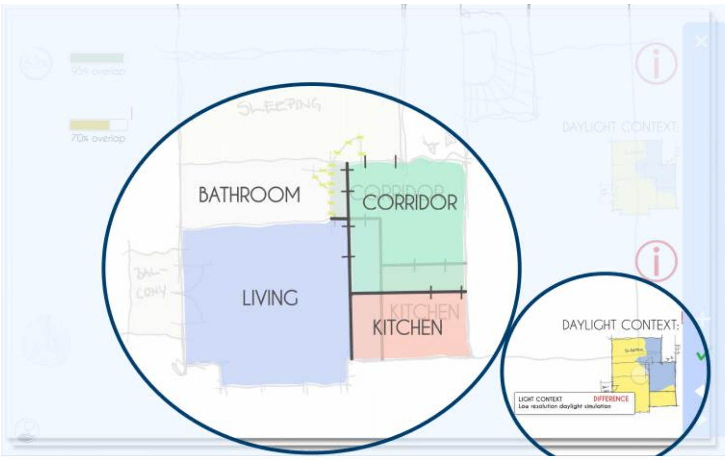

Figure 4-17: Direct comparison of two different floor plans through layered view and alerts for difference.

This concludes the design of the digital paper prototype for the hypothetical application WHITE BRIDGE. It integrates explanation visualisations intended to support the architects' design requirements, mitigate the four heuristic biases and moderating trust. Further, it complies with the formulated guidelines, based on theoretical research, for the GUI of an intelligent design assistant for architects, using a digital device and pen-and-paper-like tools. As the finished paper prototype, the tools used for its creation, and its presentation as a narrated video are fully described, the individual explanation visualisations are referred back to in order to verify the integration of all findings of Chapter 3. Therefore, the paper prototype is completed and is used within a user study as described in Chapter 5.

5 STUDY

The study is conducted with the previously described digital paper prototype to evaluate whether the further design steps suggested by an intelligent design assistant like WHITE BRIDGE support the architect in expanding the cognitive limits of the architectural design decision making process in the early phases, as well as how their presentation and visualisation affect the fulfilment of this goal (see sub-chapter 2.2). Firstly, the research setting of the study is presented and discussed, as well as its consequent organisation (see sub-chapter 5.1), followed by a textual introduction to 'WHITE BRIDGE' offered to the participants (see sub-chapter 5.2). Afterwards the data collection (see sub-chapter 5.3) and its analysis (see sub-chapter 5.4) are described. Within sub-chapter 5.5 the study is reflected upon and its findings are presented.

5.1 Research setting

Within this sub-chapter the research setting is described. The circumstances of the study are introduced and the subsequent session type, explicating its advantages and disadvantages, is reasoned, the selection criteria of the recruited participants are introduced, and finally the preparations and organisational tasks for the sessions are presented.

Remote sessions

Due to the currently on-going Covid-19 pandemic, remote online sessions were chosen for the research setting. It ensures the health of both the researcher and participants.

In general, the advantages of remote sessions is the time efficiency for both sides due to the omission of travel (Ross, 2020a), which increases the possibility to join and therefore the amount of participants. Especially the participants benefit from remote sessions due to reduced stress, as the sessions can be conducted whenever and wherever the participant prefers without accounting for travel time, while the familiar surroundings support a more relaxed atmosphere, which increases 'thinking aloud'. Further, remote sessions offer the possibility of a higher diversity of participants, because the sessions can be joined from all over the world, which increases the quality of the resulting data. For the researcher it simplifies the interaction process with the participant as there is no need to comply with "social norms of an in-person conversation" (Ross, 2020a), e.g. keeping eye-contact. Instead, the researcher is able to fully concentrate on observation and note-taking, while having a good view of the screen the participant is using. The insights from the observations can be directly noted during the session, reducing the loss of insight and increasing the quality of the notes. Finally, the video recording of sessions is easier due to the support of online platforms, which simplifies reviews for both the originally present researcher and others who initially could not join.

However, for remote sessions to be possible, a good internet connection of both the participant and the researcher is an indispensable condition, otherwise a cancellation of the sessions or significant time loss is to be anticipated. Further, the researcher needs to consider the following disadvantageous aspects of online sessions and strategies to overcome them. Initially, the goal of a qualitative study is to observe the user in their natural environment in order to understand the specific target group, as "their behavior, their typical tasks and processes, the tools and artifacts they use, the people with whom they interact, and the environment in which they're performing their tasks … [is best understood] in person" (Ross, 2020b). Because of the limited view from the participant's camera and the small size of the video on the researcher's screen, the environment and its interactions with the user, as well as the user's gestures, mimics and other body language cannot be observed. Consequently, these cues and interactions are often missed, especially in conjunction with the multi-tasking of the researcher, i.e. focusing on the screen of the participant and note-taking. Ross (2020b) offers the possibility to ask the participant to show the environment to the researcher, but remarks it often disrupts the natural flow of the session. Even in general, the situation might feel unnatural for dialogues to develop due to the lack of actual interaction and cooperation between participant and researcher, aggravated by common interruptions due to 'home office' work situations. Further, the researcher has less control over the handling of the prototype by the participants, as well as has less possibility to subtly direct them. Finally, Ross (2020b) addresses the security issues for a prototype of a commercial product or service when using an online meeting platform. He advises to have a non-disclosure agreement (NDA) signed by the participants.

In order to overcome the disadvantages of the remote sessions for the study, the following strategies are devised. The digital paper prototype is presented as a narrated video to avoid mishandling by the participants. This video is sent beforehand to the participants with the instruction NOT to watch it. Thus, it can be run on the participants' computer during session for the first time. This allows the best possible experience without any lag due to connectivity issues for the participants, as well as the observation of genuine reactions for the researcher. Nevertheless, less engagement by the participants is to be anticipated. Further, a consent form for publishing the recorded sessions and possible photographs is sent to the participants of the study before the sessions to be signed and sent back to the researcher because of data protection regulations. Finally, the circumstances of the paper prototype need to be made clear to the participants prior to the study sessions. In this case, the hypothetical application WHITE BRIDGE needs to be introduced to the participants for them to be able to focus on the particular part of explanations and their visualisations. These three files are combined into a package which is sent to the participants at least two days prior to the session. After the type of sessions and strategies to overcome its shortcomings are clarified, the selected participants of the study are introduced.

Participants

Eleven architects were recruited as representatives of the target group. They are aged between 25 and 35 years. They have been working for approximately three to five years within the active workforce of architecture offices. Therefore, they are versed in various kinds of CAAD software and used to the integration of these programs in their everyday work. The participants come from a diverse background, such as Europe, North Africa, South-East Asia and the Middle East. However, all of them currently work in different countries of Central

Europe, namely Germany, Switzerland, France and Italy. The final condition for the participants was to be comfortable to hold the sessions in English, requiring an English speaking level of B2, vantage or upper intermediate, to C2, mastery or proficiency, as set within the Common European Framework of References for Languages (Council of Europe, 2021).

Organisation

With each of the eleven architects, individual Zoom meetings were scheduled, befitting their personal preferences, within a time period of four days. As previously mentioned, they were sent a file package, consisting of necessary material for the participants prior to the study sessions. The file package was sent via a WeTransfer link within an email, which specifically contained:

1. Consent form for photo and video recording.
2. 'WHITE BRIDGE – an intelligent design assistant', a story narrated by an imaginary persona of the near future after experiencing the intelligent design assistant tool WHITE BRIDGE (see 5.2).
3. The digital paper prototype, in form of a narrated video (see sub-chapter 4.3).
4. Read me, containing one-lined descriptions and instructions for of each file.

The email also contains the descriptions, as well as the instructions to read, sign and send back the consent form before the start of the session, the request to read the narrated story 'WHITE BRIDGE – an intelligent design assistant' as an introduction for the participants to the hypothetical application, and to NOT watch the video before the session, but to set up the video at the beginning of the session on their own computer and then share their own screen. Thus, it is ensured that the participant can watch a fluent video without any complications due to connectivity issues.

Both the research setting during the Covid-19 pandemic, including advantages and disadvantages of remote sessions, and the selection of participants are discussed. The organisation, answering to these circumstances, is described. The strategy to overcome these issues is identified to be sending the participants necessary files prior to the session, including a consent form for possible publication, a narrated video presentation of the digital paper prototype to be opened on the participants' computer and an introductory narrated storytelling for the application WHITE BRIDGE. The purpose and creation process of this story is further detailed within the following sub-chapter.

5.2 'WHITE BRIDGE' introduction for the participants

An introduction to the intelligent design assistant is deemed necessary to create a foundation of basic understanding for the hypothetical application. Thereby, it is also aimed to avoid questions and issues participants might have with the intelligent design assistant during the sessions, which are intended to focus on the presented explanations and designed explanation visualisations.

Therefore, storytelling, which is an essential tool of HCI for educating and bringing concepts closer to audiences and the present (Spaulding & Faste, 2013, p. 2843), was chosen as a technique to introduce WHITE BRIDGE to the participants for the study sessions. It also provides the possibility for the participant to read the story to prepare themselves alone, whenever they find time.

Especially the emotional persuasion from stories affecting both parts of the brain, the left of logic and the right, which is responsible for visions and feelings, facilitates the informal transfer of tacit knowledge (Kernbach, 2018 p. 390). This emotional engagement through transferring and relating a told story to lived stories by the reader is essential to create believable stories of future concepts, which Spaulding and Faste (2013, p. 2850) use for deducing their usefulness or desirability:

> "Since stories are the vehicles by which we make sense of the world and by which cultures develop, there is inherent value in situating design concepts within near-future story worlds to help draw out their readers' experiences of use, particularly as it might inform the usefulness or desirability of a concept." (Spaulding & Faste, 2013, p. 2850)

Therefore, a story needs to be told in a relatable manner (Spaulding & Faste, 2013, pp. 2844, 2847) which increases the reader's ability to engage. The reader uses past experiences to compare the told situation to personally lived events as the ultimate evaluation of a prototype, which Spaulding and Faste call "rectification" (2013, p. 2845). Further, a story told by a narrator shapes the readers expectations as visions of similar experiences through ambiguity, leaving space for interpretation of incomplete concepts or projects, while intensifying the experience of a story. As WHITE BRIDGE, the intelligent design assistant, is a hypothetical, conceptual application, narrated storytelling is found to be a perfectly suitable way to introduce it to the participants for preparation.

Spaulding and Faste suggest to use dramatic narrative structures for creating a compelling story arc of 'situation' - 'struggle' – 'resolution' (Spaulding & Faste, 2013, p. 2848), which is further detailed in Kernbach's (2018) storytelling canvas. Thus, it was used to create the narrated story as an argumentative pitch by an imaginary persona who experienced the application WHITE BRIDGE (see 11.11, p. 81). The main goal of the story is to show and explain the support an intelligent design assistant like WHITE BRIDGE offers to architects. Therefore firstly, the audience and their needs are considered. The architects participating in the study vividly remember the struggle of transitioning from theoretical projects from university to designing real buildings for clients. They work full-time, are stressed and swamped with work, which is the 'situation'. Consequently, the audience wishes for support for meeting the high demand of high quality architectural design decisions during the early design stages, as well as answering to the increasing amount of projects. Thus, the 'struggle' is identified. Further, the prior knowledge about an intelligent system of this audience needs to be considered and possible concerns have to be addressed. Most of the information architects have on intelligent systems are highly likely to stem from the entertainment industry, like Sci-Fi in cinema and television, or might be identified within everyday applications. It is most likely for architects to have rather negative or sceptical feelings towards the application due to this prior interpretation of an intelligent design assistant and also being aware of the complexity of their own work. Therefore, the intelligent design assistant needs to be presented as a supporting system by comparing it to useful and familiar applications, like the auto-completion of keyboards. Thus, the use of an intelligent design assistant is showcased as a familiar 'resolution'.

Considering the specific readers and their prior knowledge of similar systems, a story, narrated by an imaginary persona named Tilman Filger from the year 2042, is devised (for full version see 11.12, p. 82) to create an immersive world as a foundation for the following study and its questions:

The story begins by addressing the struggles of architects and connecting it to the past of the narrating persona, engaging the user in comparing it to their own past experiences: as a post-graduate student starting to work in an architecture office, being inexperienced and insecure. The overarching part explains the usability and different use-cases of WHITE BRIDGE in more detail, while the narrator states emotions, as well as the change of their 'own' feelings of suspicion over curiosity to relief, as the application supports the narrating persona in everyday-work. Finally, the narrator turns to the reader to suggest trying the application. Finally, the story is complemented with an ambiguous photo collage of WHITE BRIDGE in use, as recommended by Spaulding and Faste, to complete the experience of the story (2013, pp. 2845, 2850).

This text with illustration was presented to five volunteers of different domain background, who were eventually successful in explaining what the application of WHITE BRIDGE is and how it functions. They were curious about the looks of WHITE BRIDGE and wished to see more visualisations, preferably a prototype, while having ideas and visions of it in their own minds.

Thus, the narrated storytelling of 'WHITE BRIDGE – an intelligent design assistant' was considered ready for the study participants, which completes the presentation of the files of necessary material sent to the participating architects beforehand. Therefore, the preparations for the study sessions are fully described, followed by the approach to data collection in the next sub-chapter.

5.3 Data collection

As mentioned at the beginning, the findings of the theoretical research was used to create a paper prototype through the framework of Wang et al. (2019) and literature review, which are triangulated through the described study.

The data collected from the study is comprised of primary, original data, and secondary data, interpreted data. The primary data is collected from the video recordings, including participants watching the video presentation of the paper prototype for the first time, and semi-structured interviews in one-on-one remote sessions. The secondary data consists of the combination of the interpreted primary data and notes taken by the researcher of the answers of the participants, as well as of the observations of gestures, mimic and body language.

The semi-structured interview consists of three major topics: explanations, explanation visualisations and user perception with three to four questions for each topic. The questions for explanations and explanation visualisations concern themselves with the 'Usefulness' – consciously and subconsciously recognised – and further requests by the participant, while the last mentioned section deals with the personal perception and resulting emotional involvement of the user. Further, three questions are added to create a more relaxed atmosphere and to let the seen video sink in as a transition between the video presentation of the digital paper prototype and the semi-structured interview. These three questions ask about the well-being of the participant, the comprehensibility of the video presentation and for possible questions the architect has in order to resolve any issues before the start of the interview. With these different topics and sub-categories in mind the first questions and transitions for the semi-structured interview were drafted.

These drafted question guidelines were tested with two architects who have a background of architectural informatics through working at the Chair of Architectural Informatics and the Chair of Digital Fabrication, in a full session set-up. This included the reading of 'WHITE BRIDGE – an intelligent design assistant' before the sessions and the joined watching of the video presentation via screen share of volunteer and researcher. During these two sessions, it became apparent that both volunteers struggled with the definition of 'explanations' and 'explanation visualisations' within the questions. Further, it could be observed that the 'user perception' section of questions seemed to be the most promising for the final evaluation, as the volunteers would talk the most freely and descriptively.

Afterwards, the questions of the semi-structured interview were refined with the findings of the two trial sessions. As the architects seemed to mostly struggle with the definition of words, the wording was changed. The word 'explanations' was replaced with 'additional information' for the user group, while 'explanation visualisations' was referred to as 'visualisations' or 'tiny graphics'. Further, the participants are given a clear definition of each section topic with examples in-between each question section to prepare and direct them, i.e. for the explanation visualisation section: 'talking about the visualisations, which convey the additional information' or 'the tiny graphics at the top'. Finally, a last set of guidelines for the semi-structured interviews was devised, incorporating these adaptations, which can be seen in 0 of the Appendix (p. 83).

As previously mentioned, the data gathered consists of both primary and secondary data. The secondary data is interpreted answers of the participants in combination with the notes of the researcher, which are comprised of observations of the participant during the sessions. These notes are composed of notes from the original live-sessions, was well as a review the recorded sessions as a second round.

Thus, the data collection process of the different data is described. The methods of individual analysis and the workflow through these different stages of the data are presented within the next sub-chapter.

5.4 Data analysis

The data analysis consists of three stages (see Figure 5-1), the primary data, the secondary data and the process data of the secondary data.

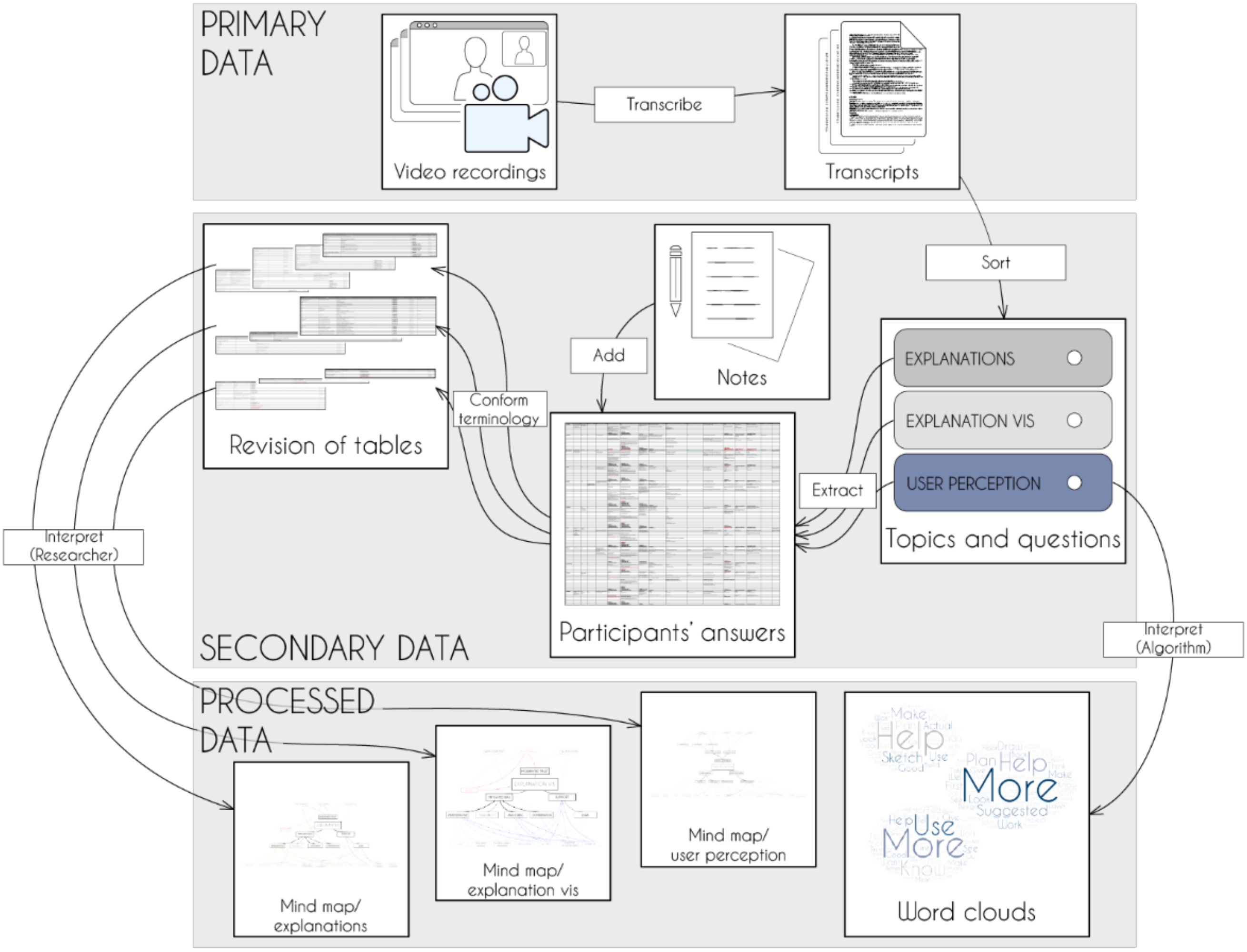

Figure 5-1: Workflow of the data analysis.

The primary data of the video recordings of the sessions is transcribed with Google Speech-to-Text, using a custom Python script for long-running asynchronous transcription. This transcription is corrected and separated into the two speakers by the researcher for readability. Afterwards, it is sorted by the different topics of 'explanations', 'explanation visualisations', and 'user perception', turning it into secondary data. Following, two different approaches are undertaken.

On one side, answers of the participants are extracted for the specific questions and the content of the researcher's notes are added to create a large Excel table sorted by participant, containing the essence of the answers for each question. Further, the meaning behind each answer is added in an interpretivist manner (see sub-chapter 2.3) through deducing from the participants' expressions if the user was supported, trust between system and user was moderated, and/or biases – and if so which ones and how – were successfully mitigated. Following, this large table is divided into individual tables for each question, while simultaneously the terminology is conformed. This leads to the revision of the individual tables, originally structured by participants, to be structured by answers instead. Finally, all three topics within the secondary data are further processed through interpretation by the researcher to create three mind maps with the interpreted observations for each question section, excluding the requests of the participants (see sub-chapter 5.5).

On the other side, the different answers of all the participants for the three questions concerning the user perception are extracted from the transcripts and combined for the respective questions. This textual data is fed into an algorithm to create word clouds as a visualisation of the frequency of used words (see sub-chapter 5.5). The algorithm uses the word count for font size and transparency to create an easily readable visualisation of the wording of the participants. In order to create these word clouds, common words and expressions are removed, and all words, which are used less than two times, are culled. These word clouds serve as a rather positivist approach, as an algorithm is used to create them. As the research is approached in a post-positivist manner (see sub-chapter 2.3), the use of word clouds aims to adjust the interpretation of a researcher with prior domain knowledge, namely the researcher as an architect.

However, both the mind maps and the word clouds are further interpreted by the researcher for formulating and formalising the findings of the study (see sub-chapter 5.5). These findings are presented within the following sub-chapter.

5.5 Findings

The findings of the study are presented within this last sub-chapter of Chapter 5, namely through mind maps of the different question sections, as well as tables for the requests of the study participants for the explanations and explanation visualisations. It is started with the explanations, followed by the explanation visualisations and finally the user perception. Further the mind map of the 'user perception' is explained in detail, using the word clouds of the participants' answer to convey the emotions towards the concept of an intelligent design assistant through their actual wording.

Explanations

The mind map of the explanations (see Figure 5-2 and see 11.14 of Appendix for full size, p. 86) was created to present the categorisation and hierarchy of the explanations: supporting architects' design requirements, mitigation of heuristic biases and moderating trust. The mind map is discussed by the means of the different explanations, randomly arranged at the bottom and top of the visualisation, and their effects in order to determine their application and usefulness for the architects. Active and Passive application techniques of the explanations were identified within the process of the architects: use, reflect and confirm for active, as well as validated by, influenced by and irritated by as passive. Within the mind map, these six different kinds of actions are represented in different colours with the line weight representing the frequency of application.

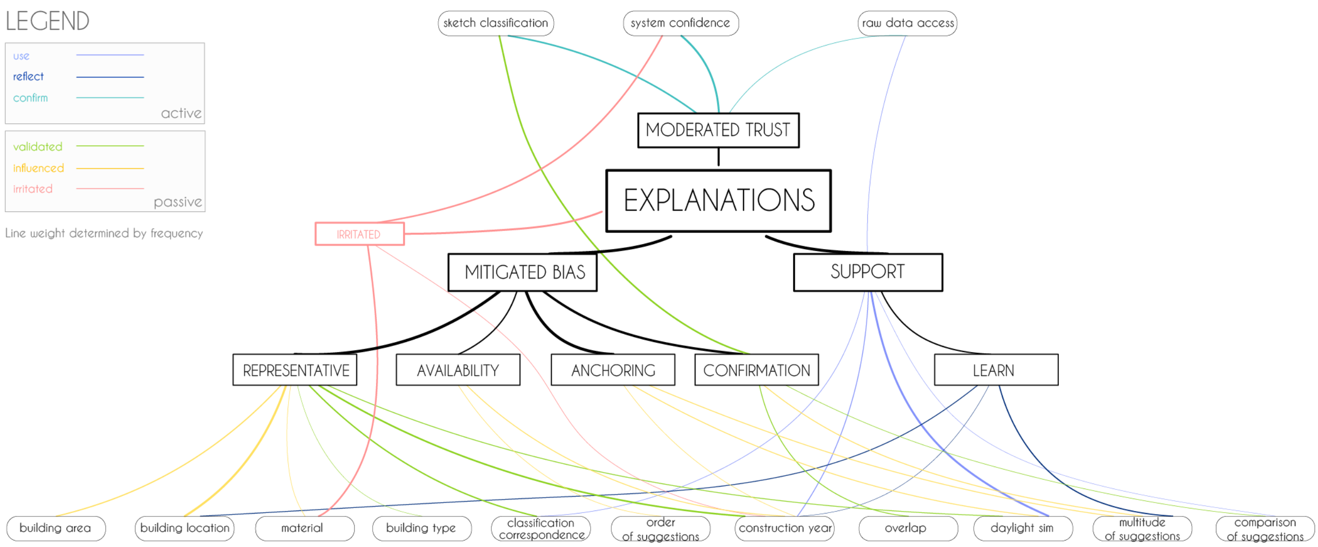

Figure 5-2: Mind map for explanations.

When directly asked about the usefulness of the explanations, every participant answered with yes, except for P8 and P10, who were unsure. It has to be noted that these two participants are the only ones with further computer programming experience. In general, the different explanation methods were applied accordingly for mitigating biases and as support, as well as the explanations aimed at moderating trust. However, some explanations were also useful for purposes of mitigation or support, other than intended, depending on the application technique by the architect.

The mitigation of biases and support for decision making within the design process was observed for all participants. The moderation of trust was observed for ten participants, excluding P2, as the participant expresses that the system might make the architect "biased" against their own ideas.

The various categories of 'building context information' are considered in different ways, but mostly according to the theoretical findings for the mitigation of the representative bias. However, when this information is actively used, it inherits a supportive role, such as the buildings' 'Location' used for reflecting on the own design, as P7 concludes: "having access to floor plans [from other countries], if you are from Europe and need to design an apartment for China, then it's definitely helpful to know", which P8, P10 and P11 agree on for the same reasons. Further 'Material' irritated more than half of the participants, as it was seen as "too early" (P5) to decide within the design process. Nevertheless, these are deemed minor categories of the 'building context information' by most architects and therefore, they were only influenced by them. Meanwhile, they were seeking validation from 'Building type' and most commonly 'Construction year' for the modernness of their own design intentions, mitigating representative bias as expected. P3 even imagines it to be especially useful for "renovations as previews for architectonic interventions" in order to maintain the specific style and atmosphere of old buildings. Furthermore, the participants mitigated the availability bias and anchoring bias when taking these two criteria into consideration during the AHP. In addition, using them as well as the classification correspondence of sketch classification and 'building context information' supported the architect's decision making. Both the construction year and classification were even utilised for reflecting on the own design and for "own research afterwards" (P6).

Participants felt validated by the daylight simulation and therefore, the representative bias was mitigated. However, the daylight simulation was more often applied for mitigating the anchoring bias. It was by far the most 'used' information within the whole study. Thus, seven architects who enjoy this information usually accessible in the "next step" (P3, P6) were supported in their design requirements.

The anchoring bias is further mitigated through the multitude of suggestions, which are also used for gaining knowledge through additional learning by five participants. The order of presentation of these suggestions serve, as intended, the mitigation of the availability bias for P7 and P9. Also, the overlap percentage as described by P1: "the higher the relevance, the higher it [is] corresponding with the original plans", served the intended purpose to mitigate the confirmation bias through validation for only two architects. However, being validated by the comparison of the suggestions and the multitude of the suggestions, also unexpectedly showed to mitigate the confirmation bias, like P3 expressed: "it does help in finding different solutions … because I especially tend to get stuck on one". Further, the comparison of the suggestions is used for contrastive reasoning within the choice process. Three participants, P2, P3 and P5, were influenced by the amount of suggestions, mitigating the anchoring bias instead of providing reasoning support. Meanwhile, P7, P8, P10 and P11 utilised the information of the multitude of suggestions to further reflect on their own design – even in an additional step to double-check. P7: "I would start questioning myself: Why is that? Why would I choose that and not 1950s? And then I would probably do a variation with the third option, just to make sure this is out of the question for this kind of the design project."

The sketch classification was majorly applied for the mitigation of confirmation bias, as 5 participants, namely P1, P3, P4, P5 and P6, felt their own design vision to be validated and contextualised: "what the context is and stuff, but I find it interesting to see, especially, when the suggestions are coming in" (P5). Simultaneously, the anticipated moderation of trust between the system and user is apparent for the same participants.

The 'confidence of the system', serving the same purpose of moderating trust, was misinterpreted by six participants, P2, P4, P7, P8, P10 and P11. However, after reading the description again, P4, P7 and P11 understood it correctly, therefore seven participants could apply its information for moderating trust.

Finally, the content of the raw data was confirmed as useful by two users, P5 and P7, through the provided access. Therefore, trust was moderated, while P5 and P10 directly used this information from the initial floor plans for generating the suggestion as a kind of personalised "Grundrissfibel" (P10), which is categorised as 'supporting'.

Table 5
Seeked explanations by the architects.

PARTICIPANT	Seeked explanations	Effect	Ratio
P1, P3, P4, P5, P6, P7, P8, P9, P10, P11	area size, dimensioning	> **SUPPORT**	10/11 Pr
P2, P3, P8	technical information/ supply lines	> **SUPPORT**	3/11 Pr
P4, P6	simulation information/ ventilation, aerodynamics	> **SUPPORT**	2/11 Pr
P10, P11	circulation	> **SUPPORT**	2/11 Pr
P10, P11	furniture	> **SUPPORT**	2/11 Pr
P1	more detailed access to floor plans	> **MODERATED TRUST**	1/11 Pr
P2	building context information/ surrounding buildings	> **REPRESENTATIVE BIAS**	1/11 Pr
P5	building context information/ climate zones	> **REPRESENTATIVE BIAS**	1/11 Pr
P11	building context information/ occupants	> **REPRESENTATIVE BIAS**	1/11 Pr
P5	leave out building context information/ material	> **MODERATED TRUST**	1/11 Pr
P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11		> **SUPPORT**	11/11 Pr.
P2, P5, P11		> **REPRESENTATIVE BIAS**	3/11 Pr.
P1, P5		> **MODERATED TRUST**	2/11 Pr.

After discussing the mind map of the applied explanations, the participants' requested explanations are presented in Table 5, as well as their deduced purpose. It illustrates that every architect within the study seeked further support for the design requirements. Except for P2, every participant wished for area size and dimensioning. On the contrary P2, like P3 and P8, wished for more advanced technical information, such as supply lines. P4 and P6, who originate from South-East Asia and the Middle East, even wanted to have access to detailed ventilation and aerodynamics of 'What if?' scenarios. Nevertheless, both advanced technical topics were questioned by the participants themselves, as it might be too early for this stage.

P10 and P11 asked for suggestions for furniture layouts and circulation possibilities, because, as P11 elaborates, modern floor plans often are open-plan and therefore, the furnished floor plan is the most interesting. P1 requested detailed access to the individual floor plans used for creating the suggestion, e.g. tooltips with the categorisation of the individual floor plans, when the raw data is accessed.

P2, P5 and P11 were rather interested in further 'building context information', mitigating representative bias: surrounding buildings, 'Climate zones' instead of or additionally to the 'Location', and the specifications of the occupants, e.g. married couple or shared flat, especially in relation to the requested furniture. Finally, P5 suggested to simply leave out 'Material', as it was deemed too irritating during the design process and therefore distracting, increasing mistrust.

Thus, the findings for the explanations are fully discussed and the findings for their respective representation as visualisations within the paper prototype are presented in the following.

Explanation visualisation

Within this section, the usability of the explanation visualisation is examined, as it is translated into a mind map, shown in Figure 5-3, which can also be viewed in full size in 11.15 of Appendix (p. 87). It is based on the same hierarchy as the mind map of the explanations, divided into the mitigation of the heuristic biases, support and the moderation of trust. The connections within the mind map are categorised as useful, for visualisations explicitly 'liked' by the participants, and failed, deduced from expressed confusion or observed misinterpretation, while the line weight visualises the amount of participants for the respective visualisation type. They are interconnected with their purpose and then their success is determined based on the connection type.

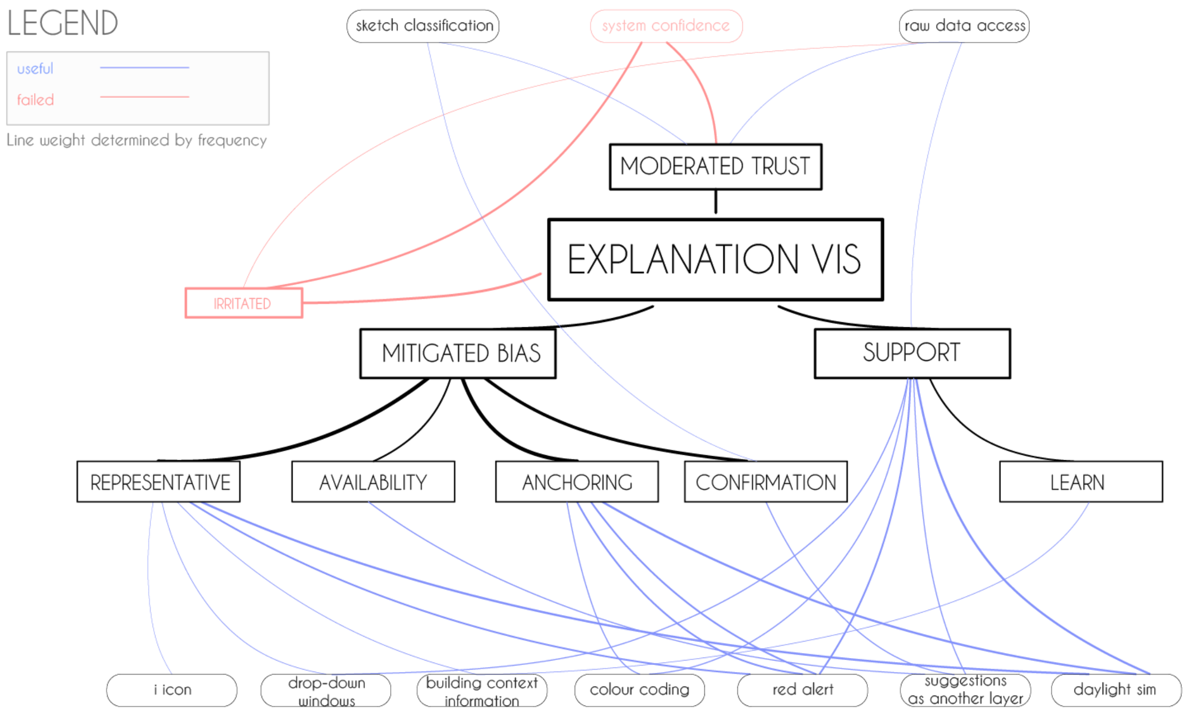

Figure 5-3: Mind map for explanation visualisations.

The visualisations in general were described as "very clear" by P1, P6 and P10 and "clean" by P6 and P8. P4, P5 and P6 further noted their user-friendliness because of their simplicity. P7 even mentioned that the "sketch-y" roughness of the program befits the sketching purpose of the application, intended to be used during the schematic design phase. P8 pointed out the dense content of additional information provided by the explanation visualisations without "messing up the window".

Seven participants specifically enjoyed the daylight simulation, mitigating representative and anchoring bias and supporting counterfactual and transfactual reasoning, while receiving the lighting information "with one glance" (P1).

Further, the red alert of divergent 'building context information' as an immediately perceivable information, supporting contrastive reasoning, is noteworthy for P1, P5, P7, P8 and P11. Colour coding for the different visualisations is expressively liked by P1, P4 and P9 in general, further supporting counterfactual and transfactual reasoning, i.e. for support and mitigating anchoring bias.

P2, P5 and P7 liked to see the suggestions as another layer, mitigating confirmation and availability bias, referencing the looks of sketch paper for emphasis on the visibility of choice, as P5 expresses: "It just gives me options, so this is just a suggestion".

The visibility of the textual 'building context information' is specifically enjoyed by P2 and P10 for both mitigating representative bias, as well as a basis for further studying, while P8 enjoys its universal 'i' icon as the access button. However, the raw data of the used floor plans in a second step irritated P3, because of its full-screen presentation overlaying the sketch. Therefore, the original floor plans could not be directly compared to the sketch for contrastive reasoning.

Even though all participants agreed that the visualisations were easily readable and helpful, observations showed that misinterpretation occurred. The progression circle of the 'confidence of the system', moderating trust, e.g. for P1, was often misinterpreted. Architects, like P2, P4, P7, P8, P10 and P11, aimed for achieving 100%, even after reading the description again P2, P8 and P10 still read the visualisation incorrectly. Therefore, the visualisation of the 'confidence of the system' is deemed as failed.

Table 6
Seeked explanation visualisations by the architects.

PARTICIPANT	Seeked explanation visualisation/ seeked tweaks	Specific visualisation technique	Categorisation	Ratio	Ratio2
P1, P3, P5, P7, P9, P10	area size/ sense of scale	textual square metres	**> ADDITION**	6/11 Pr.	10/11 Pr
P4, P8, P10, P11		furniture	**> ADDITION**	4/11 Pr.	
P8, P9		textual dimensions	**> ADDITION**	2/11 Pr.	
P6		textual percentages of overall area	**> ADDITION**	1/11 Pr.	
P9		textual square metres with reference to optimal size	**> ADDITION**	1/11 Pr.	
P5	area size/ sense of scale	ruler' tool for dimensions	**> ADDITION**	1/11 Pr.	
P4, P11	circulation	furniture	**> ADDITION**	2/11 Pr.	
P2	facade, height	elevation	**> ADDITION**	1/11 Pr.	
P2	supply lines	different layers for tiny sketch	**> ADDITION**	1/11 Pr.	2/11 Pr.
P3		thickened wall for installation in separate tab of tiny simulations	**> ADDITION**	1/11 Pr.	
P4	ventilation	arrows	**> ADDITION**	1/11 Pr.	2/11 Pr.
P6		heat map	**> ADDITION**	1/11 Pr.	
P11	contrastive reasoning	more difference alerts for the visualisations from suggestion to suggestion	**> ADDITION**	1/11 Pr.	
P5, P10, P11	faster understanding of vis	group vis: in sidebar	**> WITHIN GUI**	3/11 Pr.	5/11 Pr.
P8, P10		title different visualisations	**> WITHIN GUI**	2/11 Pr.	
P3		group vis: separate sketch and suggestion/ daylight simulation with sketch	**> WITHIN GUI**	1/11 Pr.	
P2		group vis: sketch and building context information classification	**> WITHIN GUI**	1/11 Pr.	
P7, P8, P10	more information	more detailed daylight simulation	**> CHANGE**	3/11 Pr.	
P10	faster overview of raw data	raw data references in mini like taskbar	**> CHANGE**	1/11 Pr.	
P10	less distraction/irritation	minimise the percentage numbers, especially confidence of the system	**> CHANGE**	1/11 Pr.	
P8	understanding of specific visualisation	overlap as two different schematic floor plans overlapping	**> CHANGE**	1/11 Pr.	
P7	differentiation between inside-outside sketch	different font for room labels than program font	**> CHANGE**	1/11 Pr.	

After the examination of the explanation visualisations, in the following visualisations, requested by the participants, are presented. They are separated into three different categories (see Table 6): additions, GUI-specific requests and changes. It is started with the additions.

As previously mentioned in the explanations, all participants, except for P2, asked for area size or a visualisation to create a sense of scale. Therefore, they were asked by the researcher about the visualisation preferences: most participants preferred textual square metres. P4 and P11 also asked for furniture visualisation for further use of visualising circulation on a "micro-scale" (P4), meanwhile P10 wanted to see square metres first and only later furniture. P8 and P9 requested length dimensions, which P9 wanted to see enriched with references to optimal or standard lengths. P6 wished to have the percentage of square metres from one room to the total square metres referenced. P5, additionally to square metres, asked for a digital ruler tool, as already in use within a mobile application for tablets at their office. Others requested additions for explanation visualisation aim for support of technical planning, like supply lines. These are imagined in both the actual suggestion or as additional pictograms, similar to the small daylight simulation. Only P11 mentioned more alerts for divergence in-between the different suggestions.

The GUI-specific requests, in Table 6 referred to as 'within GUI', were all intended for faster understanding of the explanation visualisations. It involved different grouping of the visualisation, e.g. P5, P10 and P11 would group them on the blue suggestion sidebar. While P3 would group the daylight simulation with the sketch-specific visualisations, P2 wished to see the sketch and 'building context information' classification next to each other for swift comparison. P8 and P10 recommended titling the different visualisations for quick understanding without the need to check the tooltips and to avoid interpretation, i.e. titling the 'confidence of the system' with "Confidence".

The requested changes included a more detailed daylight simulation for more differentiated understanding of the simulation by P7, P8 and P10, i.e. more colours and a legend for the colours. P8 asked for the 'Overlap percentage', currently represented with a health bar, completely to be changed completely into two schematic floor plans overlapping each other, visualising the similarity. P10 imagined the individual floor plans for generating the suggestion, the raw data, to be permanently and directly accessible as small pictograms. Further, the same participant wished the numbers within the visualisations, e.g. percentage of 'confidence of the system', to be minimised to be less prominent and thus, less distracting. Lastly, P7 would rather have the font used within the GUI changed for better differentiation of the suggestions and the application, "inside-outside sketch".

After clarifying these findings for the explanation visualisations, the last question section is presented: the user perception.

User perception

The mind map of the user perception (see Figure 5-4) is available as a full page in 11.16 (p. 88) of the Appendix. The user perception is defined as the personal perception of the study participant, as well as the resulting emotional involvement with the explanations and the own design decision, and the trust in the hypothetical application WHITE BRIDGE. The visualised mind map is divided into these same three categories. These questions were asked by using descriptive questions of 'How do you feel?' during the semi-structured interviews. The subsequent mind map is constructed by the use of these descriptive words, which are then connected to their impact. The connection type is divided into successful or failed, while similar to the previous mind maps, the line weight shows the amount of participants using the word or synonym. Each question is further illustrated using the word clouds created from the exact wording of the participants, which shows the frequency of the word through font size and transparency, while the colouring is random. It is started with the user perception of the explanations.

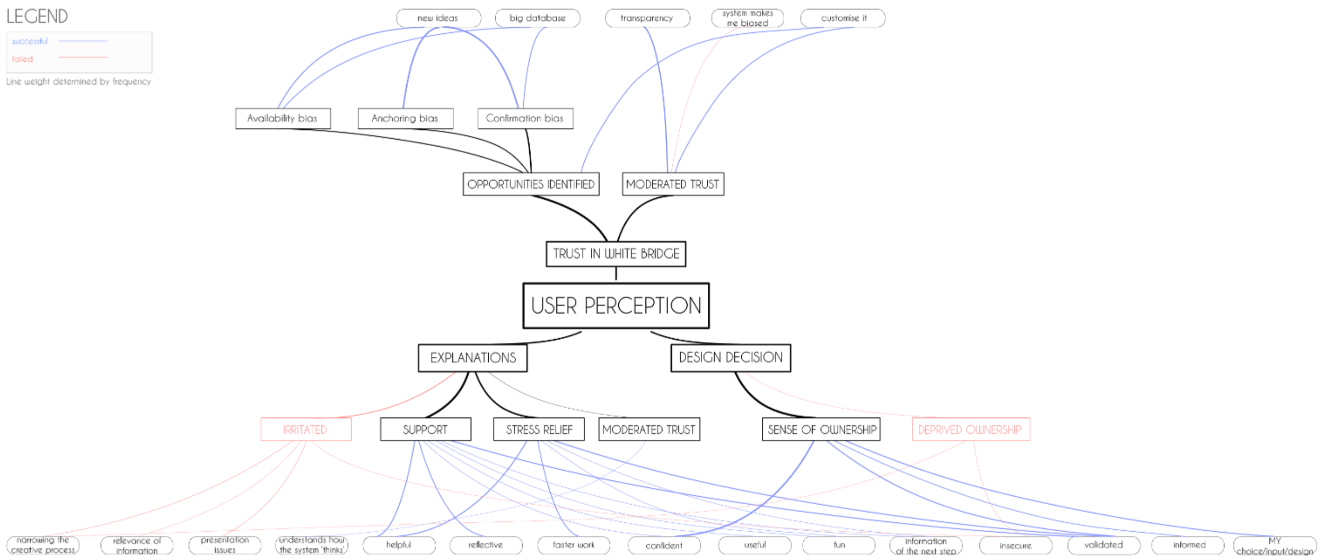

Figure 5-4: Mind map for user perception.

The wording of six participants expressed irritation, such as "narrowing the creative process" (P9), often specifically referring to the 'Material' categorisation. On the other hand, P2 questioned the relevance of the explanations in general for the user.

Figure 5-5: Word cloud for user perception of explanations.

Nevertheless, for ten participants support was identified, as they used the words 'helpful', 'useful' and 'reflective', as well as stress relief through 'faster work' by having the "information of the next step provided" (P3, P6). The moderation of trust seemed to be only moderated for P1, because it was uttered that it could be followed "how the system thinks". As illustrated in Figure 5-5 (see full-page in Appendix 11.17, p. 89), the most used word is 'Help', the words 'Good' and 'Nice' are also quite large and therefore high up in the hierarchy. The whole word cloud suggests a positive impression of the explanations. The frequent usage of 'Know', 'Give' and 'More' indicates the successful application of the explanations for 'Generalise and learn' of the explanation goals within architects' design requirements (see sub-chapter 3.2).

Figure 5-6: Word cloud for emotions towards on design decision.

Within the question asking about the own design decisions, the visible 'confidence' (see Figure 5-4) achieved through 'validation' and an 'informed' decision, as well as the explication of "my input" (P4 and P9), "my choice" (P4 and P10) and "my design" (P11) expressed the sense of ownership the architects have of their design decision. Only P2 articulated insecurity and a deprived ownership due to "the system [making the user] biased" towards the own ideas. However, as seen in Figure 5-6 (see for full page 11.18, p. 90), the expressions of the participants convey the positive perception: very often 'More' was used to express the surplus of information they receive from the application, as well as 'suggested', as the intelligent design assistant simply offers without any definitiveness of the further design steps.

Figure 5-7: Word cloud for trust in WHITE BRIDGE.

Finally, when asked about the feelings towards the whole hypothetical application of WHITE BRIDGE, the participants found the trust well moderated, based on the 'transparency' of the intelligent design assistant and possible future manual debugging. Solely P2 showed increasing mistrust. Furthermore, most architects themselves identified the opportunities, the 'More' (see Figure 5-7 and for full size 11.19, p. 91) WHITE BRIDGE has to offer. They themselves identified possible biases they had, which the intelligent design assistant may mitigate. They expressed how the big data base and suggestions of WHITE BRIDGE could support them in getting rid of old habits (P2, P5, P8, and P10). Thus, the participants themselves identified the opportunity to overcome availability, anchoring and confirmation biases with the support of an intelligent design assistant, as it 'Knows' more. P4 and P11 even explicitly expressed the wish to use the application. Lastly, P3, P4, P5, P7 and P9 even identified the opportunity to customise the intelligent design assistant through the personal input and requested manual debugging of the floor plans used to incorporate specific buildings they would reference or to change the sketch classification for maximised moderation of trust and scrutability of WHITE BRIDGE.

Summarising the findings of the study, explanations were applied by the architects of the study as intended. Through different application techniques the explanations served an even greater variety of purposes than initially anticipated by the researcher, including both supporting the design requirements and mitigating biases. Explanations which were deemed 'too early' to be determined within this design phase and therefore not useful were rather irritating to the user and would be recalled throughout the session with negative connotations, i.e. the 'Material' categorisation of the 'building context information'. Almost all of the architects requested the addition of area sizing or an explanation for a sense of scale for further support. The visualisations of the explanations were widely positively received and the participants only wished for minor "tweaks" (P4) for even faster working. However, the visualisation for the 'confidence of the system' was misinterpreted seven times and therefore could not be used to its full potential by all participants, which led to irritation and distraction. The whole concept and experience was evidently very positively perceived by all the participants concerning the explanations, their own design decision and the hypothetical application of WHITE BRIDGE, except for one architect, who expressed increasing mistrust and insecurity due to deprived ownership over their own design process. Thus, the Chapter 5 concerning the conducted study is complete. Finally, the whole thesis is summarised in the following and last chapter.

6 SUMMARY

This chapter summarises the thesis through a discussion of the conducted research and study with regard to the research questions and 'metis' developments, drawing up an agenda for future work and presenting the overall contribution of the thesis to the field within a conclusion.

6.1 Discussion

This thesis aims for a pragmatic perspective on supporting architects in their design decision making process and understanding the suggestions of an intelligent design assistant. Therefore, the main objective of the thesis is to design a concept of what kind of information is needed and how to communicate this information to an architect in order to understand the suggested design steps of an intelligent design assistant. Such an intelligent design assistant, like WHITE BRIDGE, intends to reduce the cognitive workload of design decisions on the architect in the early design stages.

The methodology of triangulation was applied to identify the cognitive limits of architects and strategies to expand these. The first part consisted of theoretical research, utilising the framework by Wang et al. (2019) and a diverse literature review of architects' design decision making processes, workflow and architectural evaluation assessment for clarifying architects' reasoning goals and biases. The second research method of the triangulation was a study with the prospective user group utilising a paper prototype, created from the findings of the theoretical research. This triangulation was especially useful, as the conducting researcher is an architect with prior domain knowledge and therefore has a biased point of view. Due to the previously conducted empirical research on a theoretical basis, cognitive limits were identified while successfully creating a paper prototype for a hypothetical theory-driven intelligent design assistant without relying on unvalidated guidelines for design and evaluation, purely based on the researcher's experience and domain knowledge.

The theoretical research showed that architects apply an AHP with MCDM for design decision making when translating their abstract ideas into sketches during the early design stages. They use existing reference buildings as sources of inspiration, design conditions, tools for evaluation of their own design, a medium for communication, and source of explicit information. Due to the wrong application of reference buildings and incorrect prioritisation of criteria within the AHP, the four main heuristic biases can occur during the architectural design process. These biases are representative bias, availability bias, anchoring bias, and confirmation bias. In order to mitigate these heuristic biases, moderate trust between an intelligent design assistant and support the contrastive, counterfactual and transfactual reasoning of architects within the AHP, a digital paper prototype was drafted for WHITE BRIDGE, integrating visualisations to answer to these needs. The expansion of cognitive limits was tested in a study with architects in order to evaluate its success and the influence of the visualisations on it. The findings of the study led to feasible further steps for drawing up an agenda for future work, which aims to provide precise work steps and general future research points based on the insights of this thesis to guide and inspire other researchers. The results are summarised to directly answer the initial research questions:

Explanations expanding architects' cognitive limits

At the beginning of this thesis, the possibility of the expansion of architects' cognitive limits for the decision making during the early design phases through explanations for design impulses, suggested by an intelligent design assistant like WHITE BRIDGE, was questioned. In order to answer to this, the cognitive limits of architects needed to be defined. Through literature research the limited amount of criteria that can be processed at the same time was found to be three different criteria for human simulatability during the architectural design process, identified as an AHP with MCDM methods. Further, the four main heuristic biases of representativeness, availability, anchoring and confirmation limit the architect's capabilities of making design decisions when working with buildings as references for inspiration, design conditions and as a tool for evaluation. Finally, misplaced absolute trust, when relying on an intelligent design assistant, was identified as a possible weakness within the decision making of an architect.

The theoretical research revealed that the accessibility to additional and already processed information, including consequences, through explanations, enable architects to make faster decisions or double-check their decisions within the same timeframe, as was confirmed within the study proceedings. The explanations can contain information that is generally not considered within this early phase, e.g. daylight simulation. Subsequently, information of the next step is already taken into consideration within the schematic design phase, omitting the revision of the sketch to focus on the lighting situation. Thus, expanding the cognitive limits of the AHP with MCDM is considered successful. The explanations provide direct access to enriched information, formed from processed criteria for contrastive, counterfactual and transfactual reasoning of architects. In this way, the amount of criteria is reduced, as multiple criteria and their relations are pre-processed into less, and architects are able to make the same design decision earlier.

Furthermore, during the study the successful mitigation of the different biases through the intended explanations was observed, providing further cognitive support for the architects. However, it also became apparent that, depending on the application techniques of the explanations by the participants, either actively, like 'use', or passively, such as 'validated by' and 'influenced by', it was also valuable input for the mitigation of other biases or even instead as support for fulfilling the architect's design requirements. By the end of each session, every participant of the study was able to identify the opportunities for mitigation, biases and faster work for themselves, often seeing the biggest support in being offered ideas by WHITE BRIDGE that were outside of their regular architectural process – expanding their cognitive limits. Nevertheless, if the information conveyed within a visualisation was deemed not relevant for this stage, in this case the 'Material' categorisation within the 'building context information', this disruption of the visualisation was constantly recalled as irritating. Thus, this information even evoked suspicion of the entire application for few participants, as it disrupted the personal design decision making process.

Finally, the moderation of trust for overcoming the weaknesses of analytical 'System 2' of the human thinking was addressed through explanations. However, it was the most difficult information to understand for the architects to cognitively utilise. One questioned the relevance of this information for the user as it disrupted the personal creative process, while most architects identified and welcomed the transparency of the system, hoping for future manual debugging and scrutability.

Summarising, the explanations used within WHITE BRIDGE expanded the cognitive limits of all participants within the study, even in ways that were not priorly anticipated, e.g. confirmation bias was found to be mitigated through the multitude of suggestions. However, if the information did not seem useful, i.e. explanations for moderation of trust, it may seem irritating to the architect.

Visualisation effects on architects for understanding explanations

Thus, the expansion of architects' cognitive limits for the design decision making process through explanations for the suggestions of an intelligent design assistant was shown. Following, the effects on the fulfilment of this goal due to the presentation and visualisation of the explanations is presented.

Many architects of the study emphasised on how they enjoyed the minimalistic GUI, as they were able to focus on the drawing process, as well as the design decision making. This was achieved through a clear view of the drawing surface with the suggestions layered on top because the explanations were not disrupting but instead offered information for quick understanding of the suggestions. Further, colour coded alerts as an immediately visible notification for difference, supporting contrastive reasoning, were enjoyed by most of the architects in order to process the information even faster.

However, the visibility of non-useful information disrupted the flow of the design decision making process, which some even referred to as 'narrowing the mind'. Thus, the visualisation of the information had the opposite effect than intended of expanding the cognitive limits. Finally, if the explanation visualisation was not correctly understood, it led to confusion and developing of goals into the wrong direction by the user, e.g. the 'confidence of the system' was read as percentage of optimisation of the sketch with 100% as the goal to achieve. Thus, the misinterpretation of a visualisation needs to be avoided at all costs, as it misdirects the focus of the cognitive efforts and design decision making process of the architect.

To conclude, the usability of the explanations is significantly correlated with their visualisations for the visually driven target group of architects. Therefore, their perceptions, positive and negative, can affect the perception of the entire application in the same way.

Limitations

After answering the two research questions, the limitations of the study have to be addressed. My results show that the designed paper prototype and its explanations as well as the explanation visualisations used within a user study facilitates early identification of mistakes and misconceptions of the researcher. Thus, the applied methods are useful for the creation process of designing explainability for an intelligent design assistant for architects. Further, a clear indication for useful and failed features can be observed within the limited study setting. The preliminary material for the participant and set-up of the study is deemed successful to prepare the architect and create an immersive design situation close to reality. Finally, the established workflow of data collection and data analysis through multiple steps of generating processed secondary data is effective in producing results for consumption.

Nevertheless, the study included a quite limited number of participants. Therefore, this study and its results are not of definitive scientific significance. Further, all the architects are quite young and are used to working with CAAD programs on a daily basis. An intelligent design assistant, suggesting further design steps, needs to be considered a concept this selected group can quite easily adapt to and envision. It seems likely that aged architects, who probably mainly rely on hand-drawings, are less comfortable with working with such an application. Finally, the acquaintance of the participants with the researcher has to be addressed. The limitations of the study therefore include the possibility that participants might not have freely expressed their negative opinions due to the relationship with the researcher. The word 'sorry' could be quite often observed within the transcripts when they offered their opinion, especially if they explicated negatively connotated answers. Finally, some participants had trouble during the last three questions concerning user perception, as they only experienced a narrated video instead truly interacting with the paper prototype. Because of the determined choreography of the video, presentation tooltips and their containing description were not accessible at all times. This lead to a misinterpretation, i.e. 'confidence of the system', which could only be resolved by re-reading the tooltip after the entire video.

'metis' developments

Finally, the developments within the 'metis' projects, funded by the DFG, need to be addressed. As this digital paper prototype was designed for the hypothetical application WHITE BRIDGE, based on the methods of 'metis', changes within 'metis' affect the implementation of such an application. Currently, the digital drawing device for an intelligent design assistant is not decided on. Both a paper-like tablet with a digital pen, as well as a version of sketching on paper with pens expanded through augmented reality (AR) by using a head-mounted device are discussed and their implementations are being tested. It has to be mentioned, though, that P3, P5 and P6 of the study (see Chapter 5) enjoyed the idea of using a tablet for sketching due to the instant digitalisation of their ideas and easy access at later times, as well as its portability and possible sketching on-site. In the architecture office where P5 is working, the use of sketching on tablets for everyone to see and view with a projector is already a common practice.

Thus, the results, limitations, and changing circumstances for creating explanations and their visualisations, including their consequences on the cognitive processes for architects during the early design stages for an intelligent design assistant, are discussed. Following, the future work, deduced from this discussion, is presented.

6.2 Future work

The future work describes an agenda of precise steps for the explanations and explanation visualisations in reaction to the findings of the user study as well as topics for future research including roughly outlined approaches.

Explanations

As requested by the study participants, the explanations are to be expanded by more support for the architects' design requirements. Thus, more processed information is provided to the user. This especially includes the area sizing and dimensioning within the sketch in order to create a sense of scale for the sketching architect. Further, in order to improve the understanding of the explanations, they need to be better clarified to the user as well as their purpose and usefulness, using the language and knowledge of architects. Finally, information that is not deemed useful during the early design phases is to be removed, as it has the opposite effect on expanding architects' cognitive limits, like the 'Material' of the 'building context information'.

Explanation visualisations

The area size and dimensioning are to be visualised as square metres of the rooms, possibly with furniture layouts in the later stages of the sketch within separate suggestions.

The comprehension of the different explanation visualisations is achieved through titling the different visualisations for a swifter understanding. These headlines are constantly visible to avoid misinterpretation, while keeping the space occupied by the explanation visualisations to a minimum. Further, the improvements to understand the explanation visualisations include providing a legend for the daylight simulation in the tooltip, as well as more detail with up to five levels of light. Additionally, in order to support fast understanding of the explanation visualisations, the grouping of the explanation visualisations for the suggestions should be tested as being grouped on the suggestions sidebar. It remains to be seen whether the main space for the drawing space is still central and large enough for the sketch or if the explanation visualisations seem to push the sketch aside. This needs to be avoided, as the sketch of the architect is the focal point, while the explanation visualisations only have a supportive role.

Finally, the 'Material' category of the 'building context information' is to be removed in order to avoid irritation and disruption of the architect and the architect's design process.

Future research

After presenting the precise steps to be taken for explanations and the explanation visualisations of WHITE BRIDGE, a broad agenda for future research is outlined.

As previously addressed within Limitations, the study is not of true scientific significance. The amount of participants as well as the selected age group are quite limited. A large group of participants might change the results of the study. Further, it stands to reason that architects of a more diverse background may interact, react and perceive the paper prototype as well as the hypothetical application WHITE BRIDGE differently.

Thus, another user study utilising an updated paper prototype is to be conducted, based on previously described steps for changes as well as the successful methods and workflow for data collection and analysis established within this thesis. For the study, a large group of participants needs to be recruited, which consists of members with a more diverse background, i.e. a wider age range, and who have no personal connection to the researcher. Further, it would be preferable to conduct the next study in person in order to gain more - and different - data through the observation of the architects when actually interacting with the prototype. It is necessary to find out how the perception of the explanations and explanation visualisation changes if the user is able to freely use the paper prototype, as well as how it changes the perception of the hypothetical application, e.g.: 'Do less misinterpretations of visualisations occur if the architect can access tooltips at any given moment?'.

In case of a change of digital device, the GUI of WHITE BRIDGE is to be adapted. If the device changes from the currently assumed tablet with a pen, the GUI, as well as the gestures, need to respond to the specific type of device for optimal usability. Especially a switch to AR using a head-mounted device results in different gestures for the application and a possibility to use the three-dimensional space, e.g. the explanations can be vertically positioned instead of framing the drawing surface in order to facilitate fast differentiation between sketch and explanation visualisations, creating a front-facing sidebar when looking up from the drawing board. In further research, the possibilities, limitations and common practices for a GUI for a head-mounted device for AR would need to be examined, guidelines formulated and finally, a new digital prototype for user studies drafted.

Thus, the future work, formulated as precise next steps for improving the explanation and explanation visualisations, broader research points for considering necessary adaptations because of developments of 'metis' as well as for increasing the quality and significance of data through conducting a larger study, was drawn up in an agenda. Finally, within the following and last sub-chapter, the whole thesis will be concluded.

6.3 Conclusion

The framework by Wang et al. (2019), including their building blocks for adapting it to a specific user group, is found to be applicable for designing explanations for an intelligent design assistant, which suggests further design steps for architects during the early design phases. It is useful for creating explainability methods for an intelligent design assistant, whose suggestions are based on the use of reference buildings as a source of inspiration, source of design conditions, a tool for evaluation of the own design, a medium for communication and a source of explicit information, derived from the common practice of architects. The thesis contributes an established methodology for the design of the explanations and explanation visualisations, and their integration into paper prototype for a case study to the research field. Further, it provides a successful workflow for data collection and analysis. Thus, it offers a functional approach for creating and visualising explainability for an intelligent design assistant for architects used during the early design stages, which is transferable to other fields of the construction industry as well as other fields.

The theory-driven explanations, deduced from the framework and buildings blocks (Wang et al. 2019), seem to expand architects' cognitive limits during the early design stages. This is achieved through the support of the architects in fulfilling the design requirements within the architectural design process, mitigation of the four main heuristic biases, and moderation of trust, while the visualisation of the explanations heavily affects the fulfilment of these goals for this visually driven user group. A pleasing visualisation is essential for architects. The positive or negative perception of one visualisation or a part of a visualisation affects the perception of the entire application.

Possible heuristic biases of representativeness, availability, anchoring and confirmation occurring during the complex design decision making process, incorporating a multitude of criteria of different priorities, are even recognised by the architects of the study themselves. Further, they identify the opportunity to overcome these biases through the support of an intelligent design assistant. Even more support for the own design decision making process is the most requested feature for WHITE BRIDGE in order to generate high quality architecture. The architects of the study enjoy the provided suggestions with additional information during the schematic design phase of sketching. The choice of these suggestions or the decision to design further on their own is highly important to them to maintain a sense of ownership over their own design. Finally, the explanations make the architects informed and confident about their own design decision, as claimed by the participants. Therefore, they can make the single design decisions faster, through both contrastive reasoning and validation, speeding up the entire process of an architectural design. Thus, the participants' express reduced stress and relief.

As mentioned in the very beginning, quick work, while maintaining and even increasing architectural quality, is essential for the future of the growing demand on the construction industry. As architects shape space on a micro-scale in apartments, they are designing the urban space. Thus, the hypothetical intelligent design assistant WHITE BRIDGE aims to support them in their architectural design decision making process in the early design stages through suggestions, enriched through explanations. The intelligent design assistant intends to help architects to be able to meet the increasing demand of high quality architecture, while the architects themselves are able to focus on the creative aspects of the design process.

Finally, I hope that my work may inspire and guide future research for supporting architects in designing with confidence and in more informed ways early on, in order to create high quality architecture more efficiently.

7 GLOSSARY/ABBREVIATIONS

AHP Analytical Hierarchy Process. *Tree-like chain of analyses.*

AR Augmented Reality.

CAAD Computer-Aided Architectural Design.

CBD Case-Based Design. *Adaptation of Case-based Reasoning for design by assuming stance of solving current design problem based on solutions for similar past design case.*

CBR Case-Based Reasoning. *Process of solving current problem based on solutions for similar past case.*

CONA Cultural Objects Name Authority (CONA). *Project for controlled vocabulary of cultural objects used for e.g. cataloguing architectural buildings.*

DFG Deutsche Forschungsgemeinschaft.

DQI Design Quality Indikator. *Toolkit by the Construction Industry Council based on the Vitruvian Principles to measure, evaluate and improve the design quality of buildings in the early design phases.*

GUI Graphic User Interface. *The graphical looks and interaction point for the interface between user and system.*

HCI Human-Computer-Interaction. *Research field, studying the interactions between human user and computers, often focusing on interfaces as a connection and drawing from different fields, like computer science, psychology, philosophy and design theory.*

'metis' *Artificial intelligence methods for auto-completion of designs based on semantic building information (BIM) to support architects in early design phases. Used as a basis for the hypothetical application WHITE BRIDGE (see below).*

MCDM Multi-Criteria Decision Making. *Multiple ranked criteria within one decision making process weighed against and next to each other.*

NDA Non-disclosure agreement. *A legal confidentiality agreement that outlines the material, knowledge, subjects, and information that is shared between at least two parties, but to be otherwise kept from being shared with others.*

UCD User-Centred Design. *Design approach with focus of the design on the users and their needs for optimised user experience and usability for the specific target group, specified within the ISO 9241-210.*

UX User Experience. *How the user subjectively experiences a product or service, based the personal perception of the utility, usefulness, usability, efficiency and resulting feeling, e.g. satisfaction.*

WHITE BRIDGE *Hypothetical intelligent design assistant based on methods developed within the projects of 'metis' (see above).*

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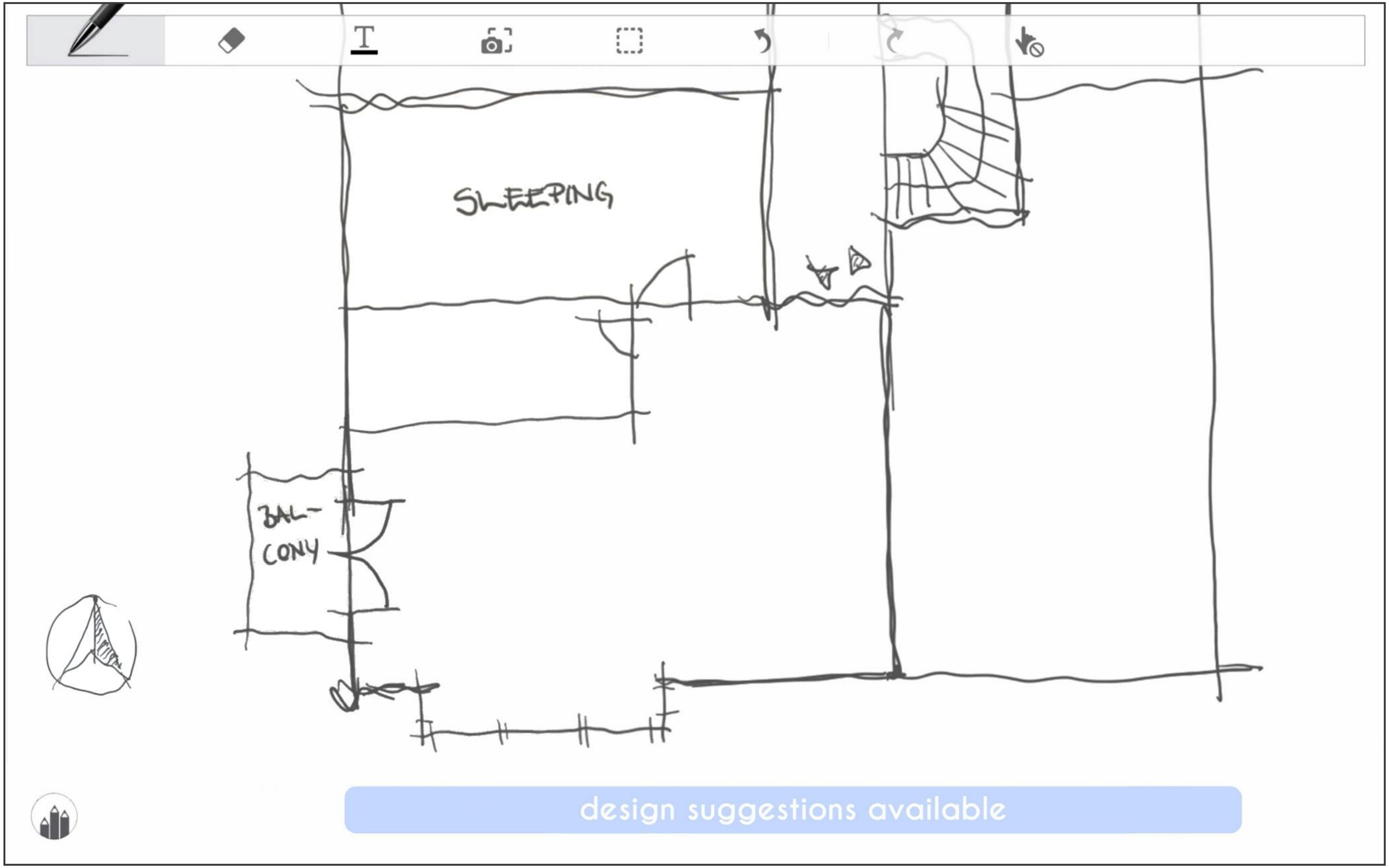
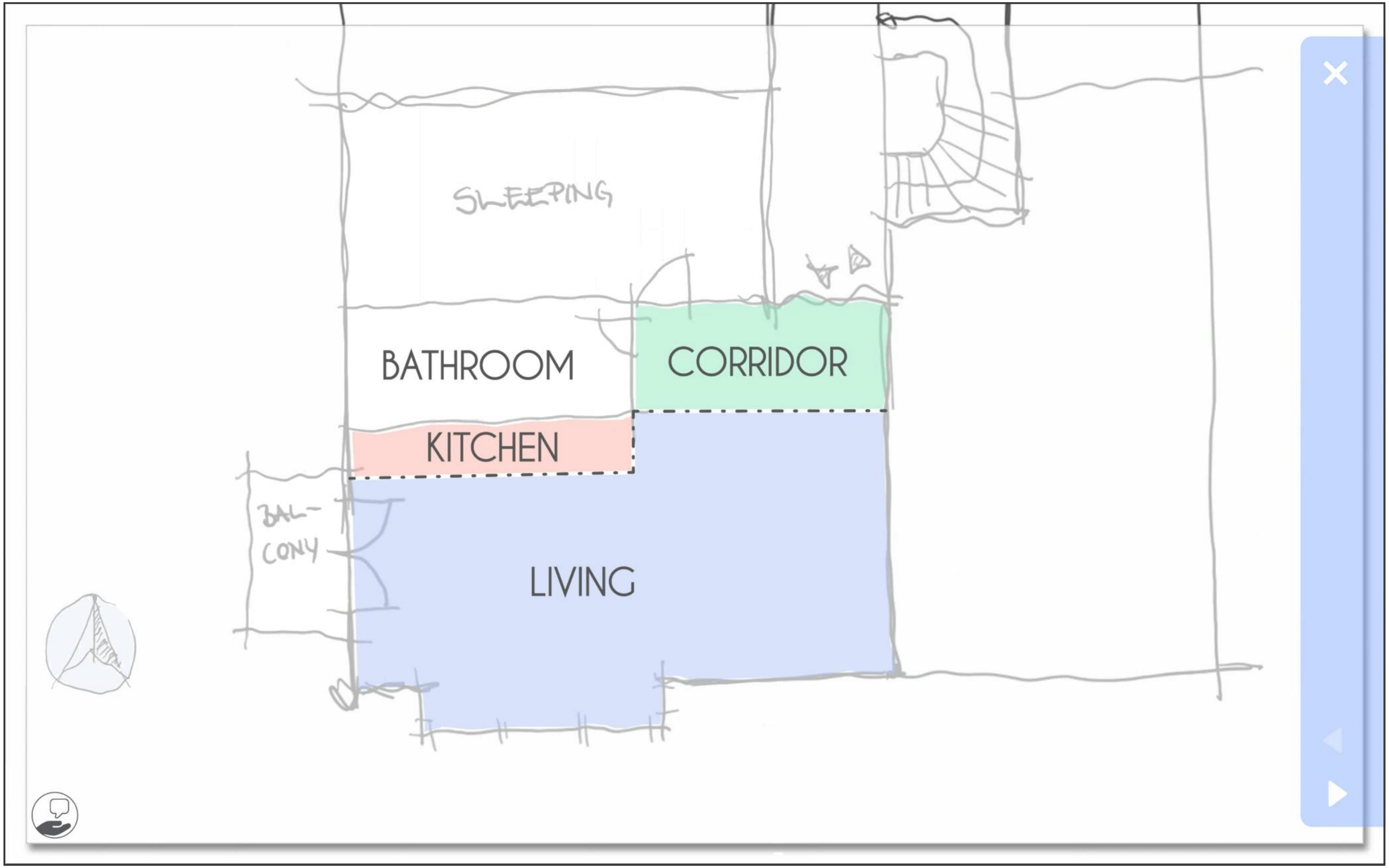
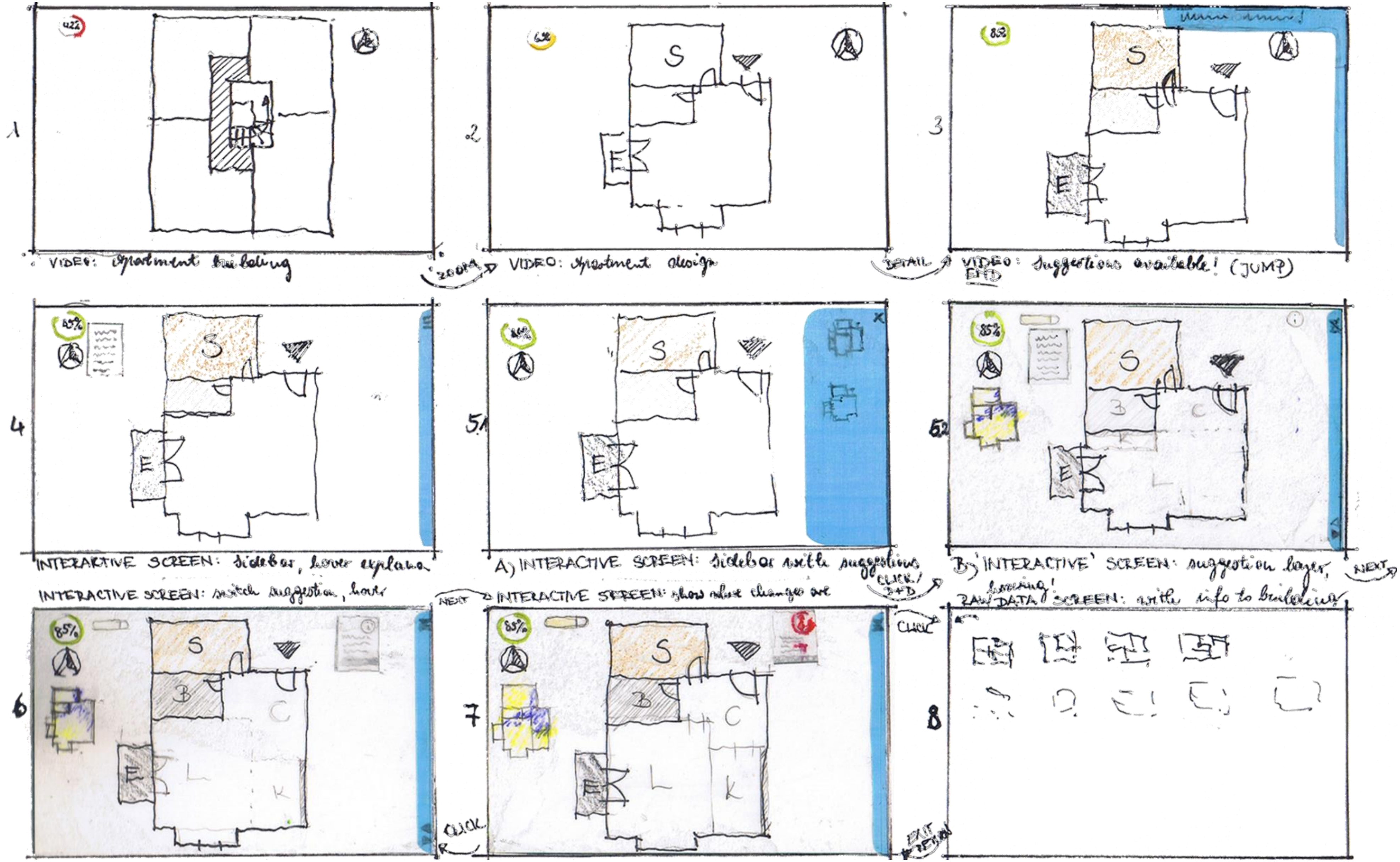


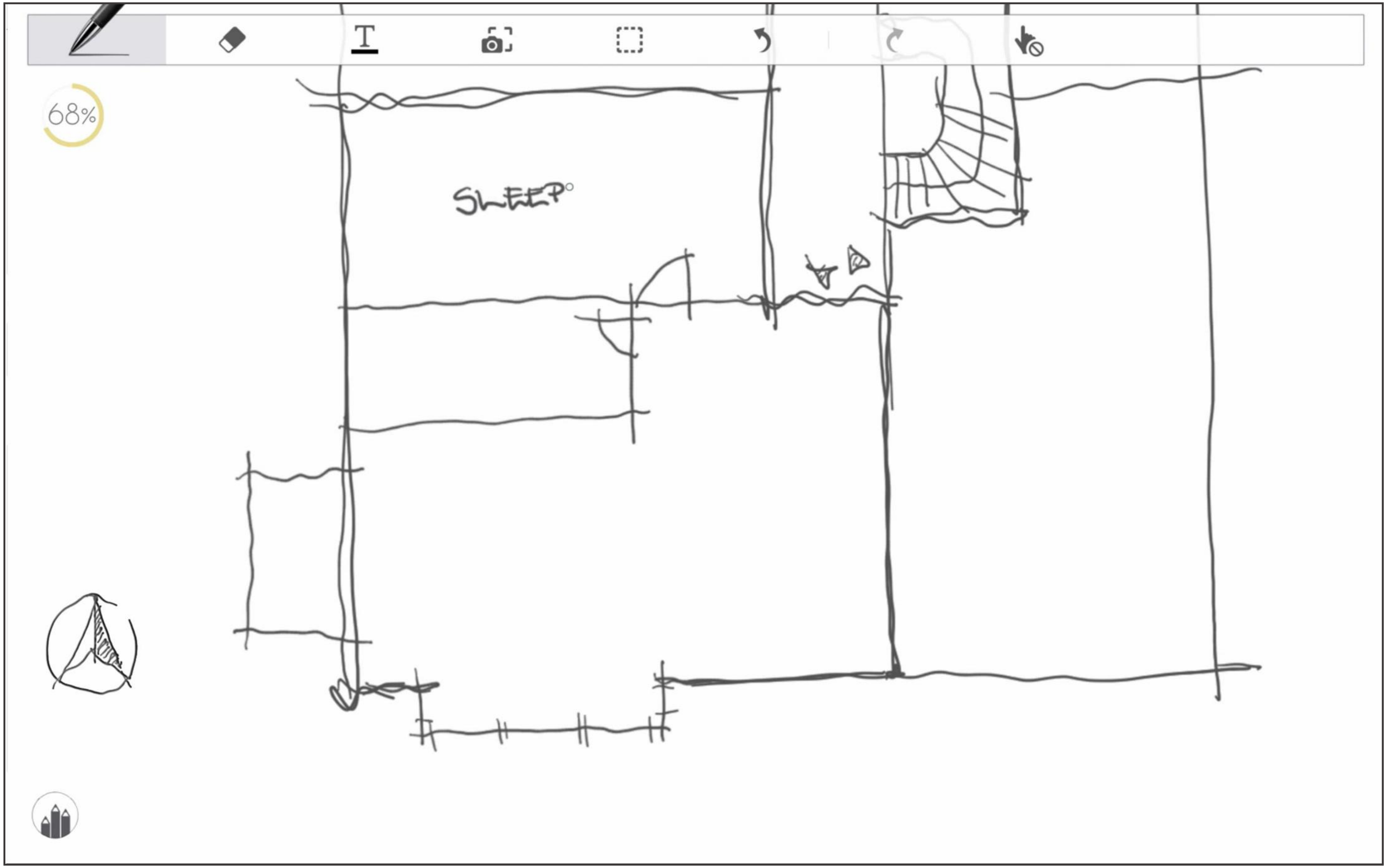
11.2 Paper Prototype, layered suggestion view (without explanations)



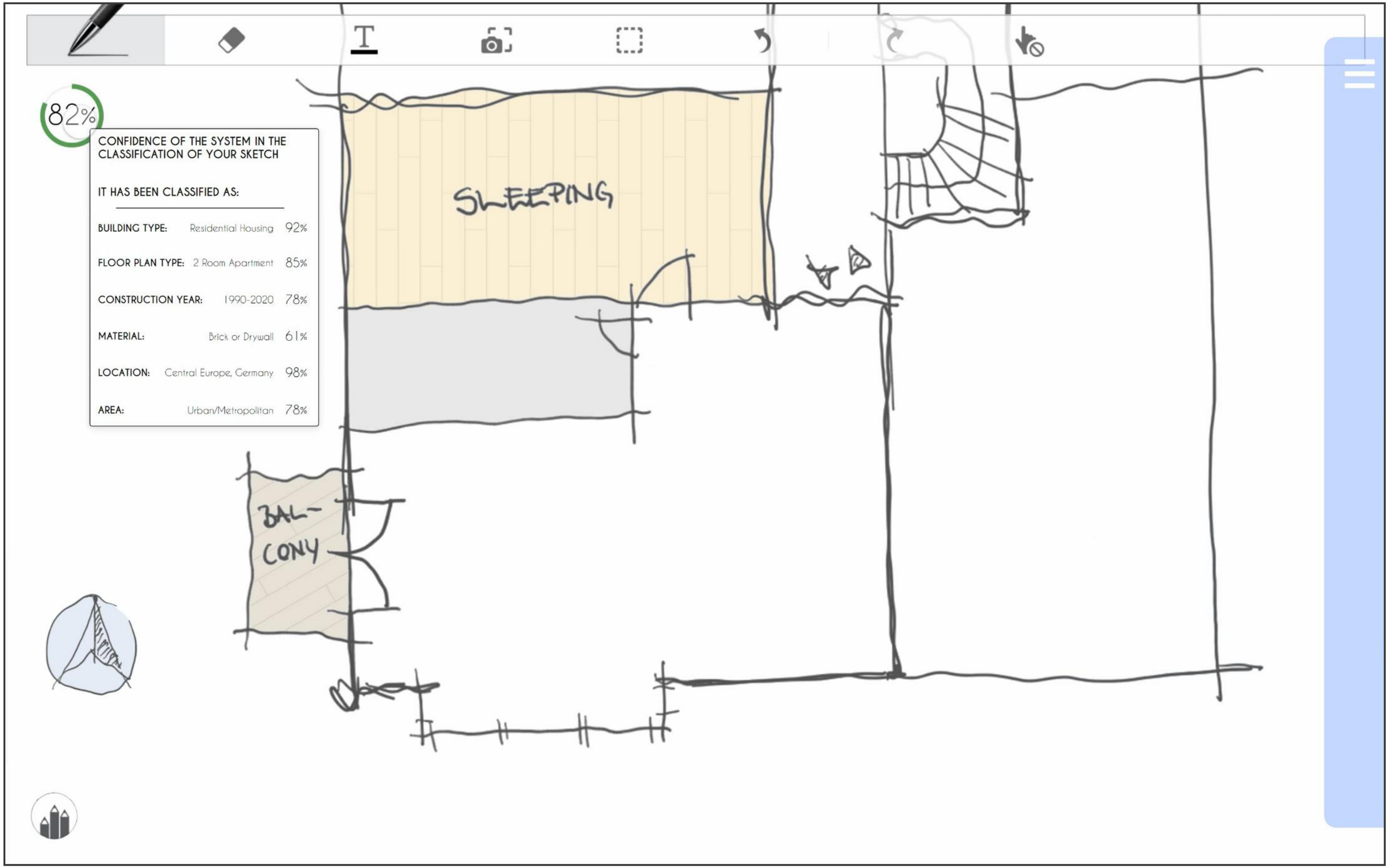
11.3 Hand sketches of wireframes and their transitions



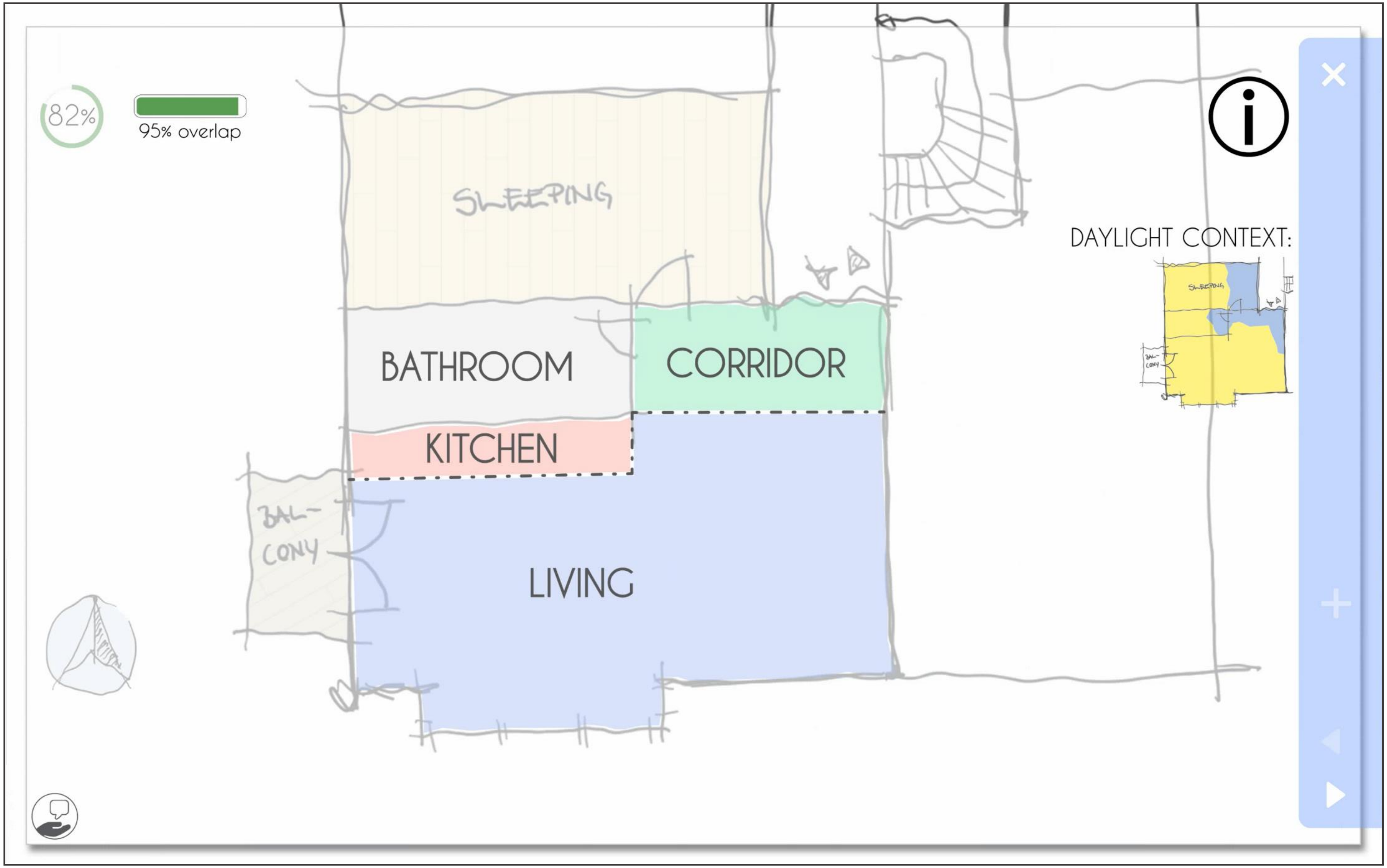
11.4 Paper Prototype, drawing view



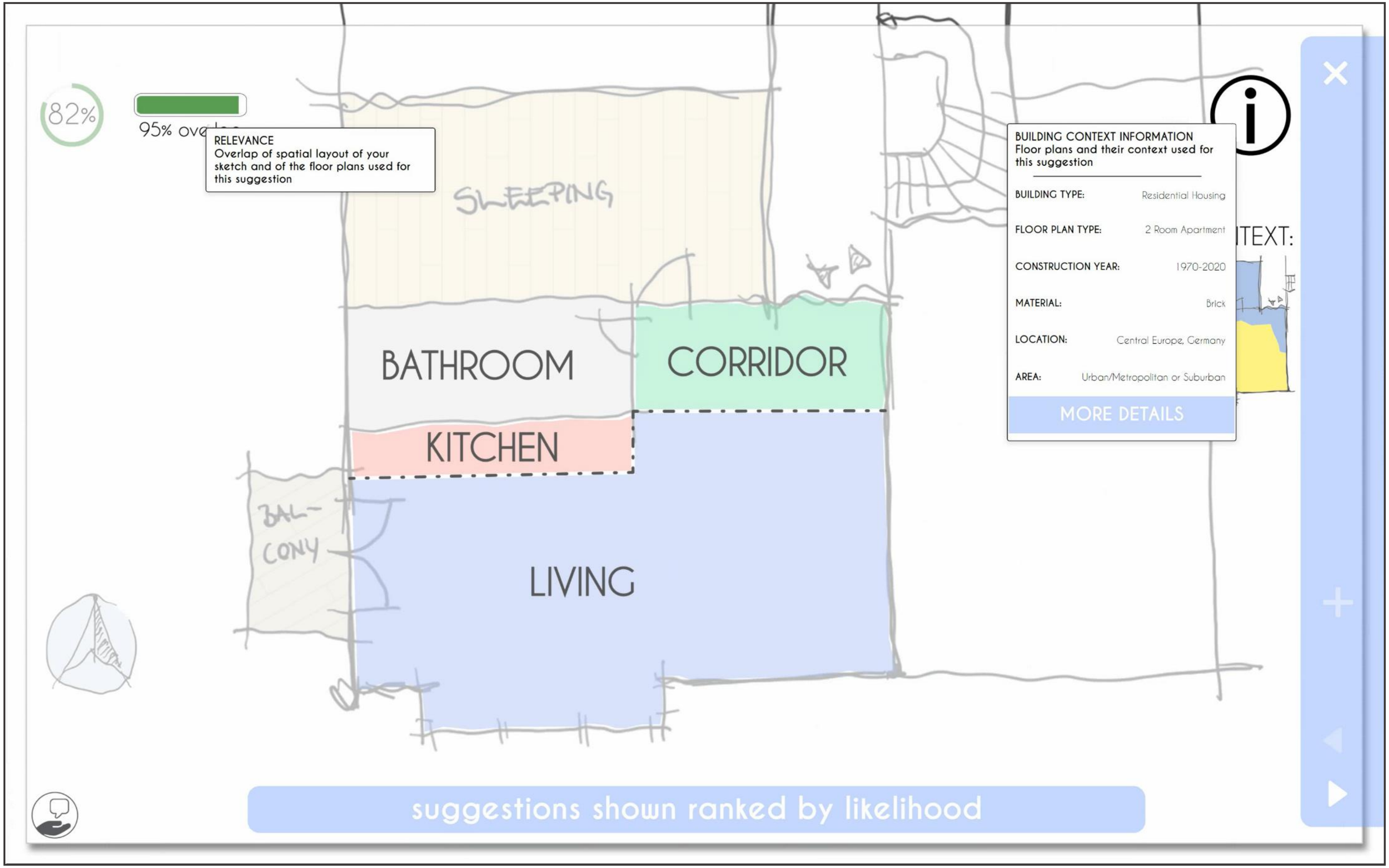
11.5 Paper Prototype, drawing view/ tooltip



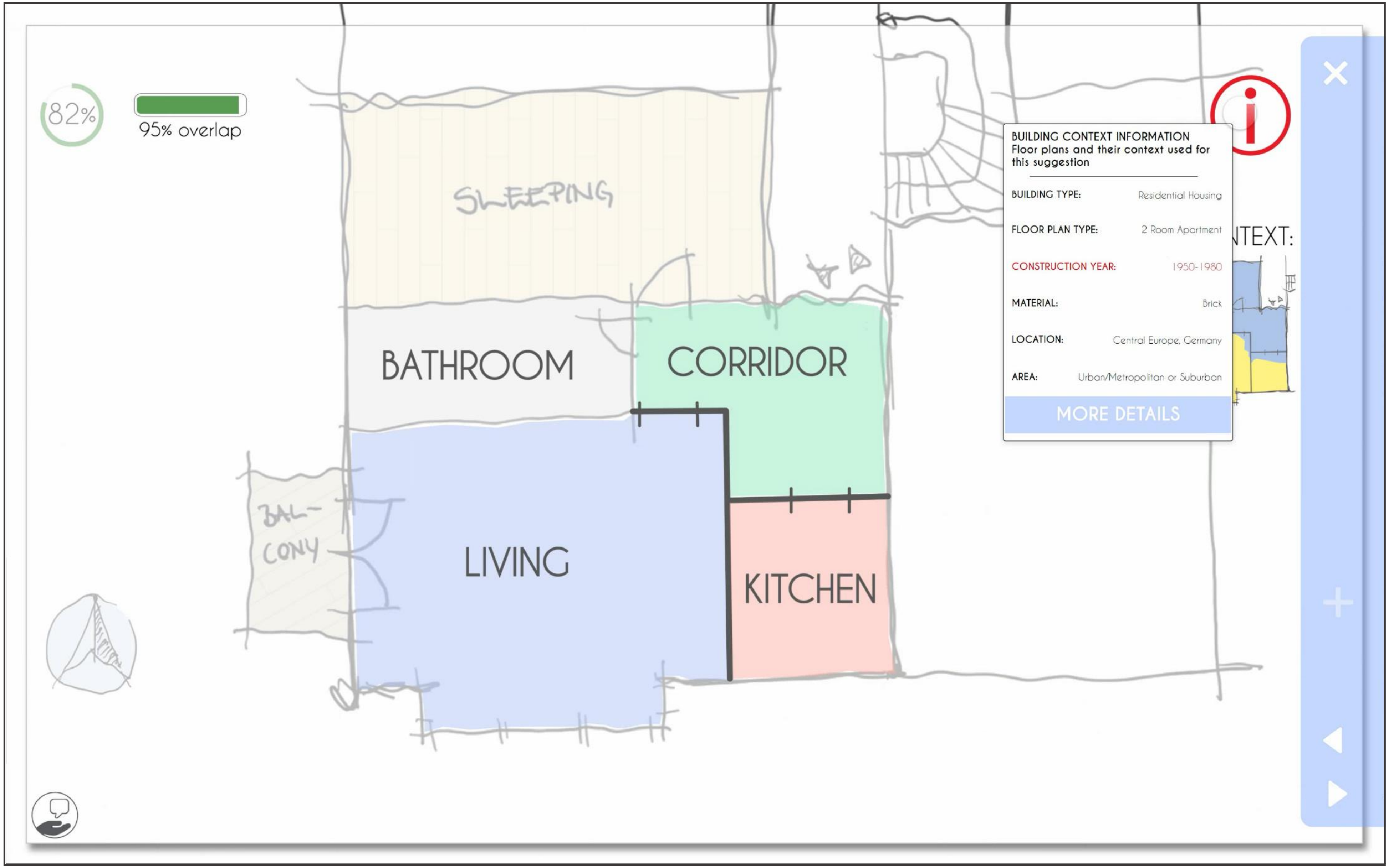
11.6 Paper Prototype, suggestion view



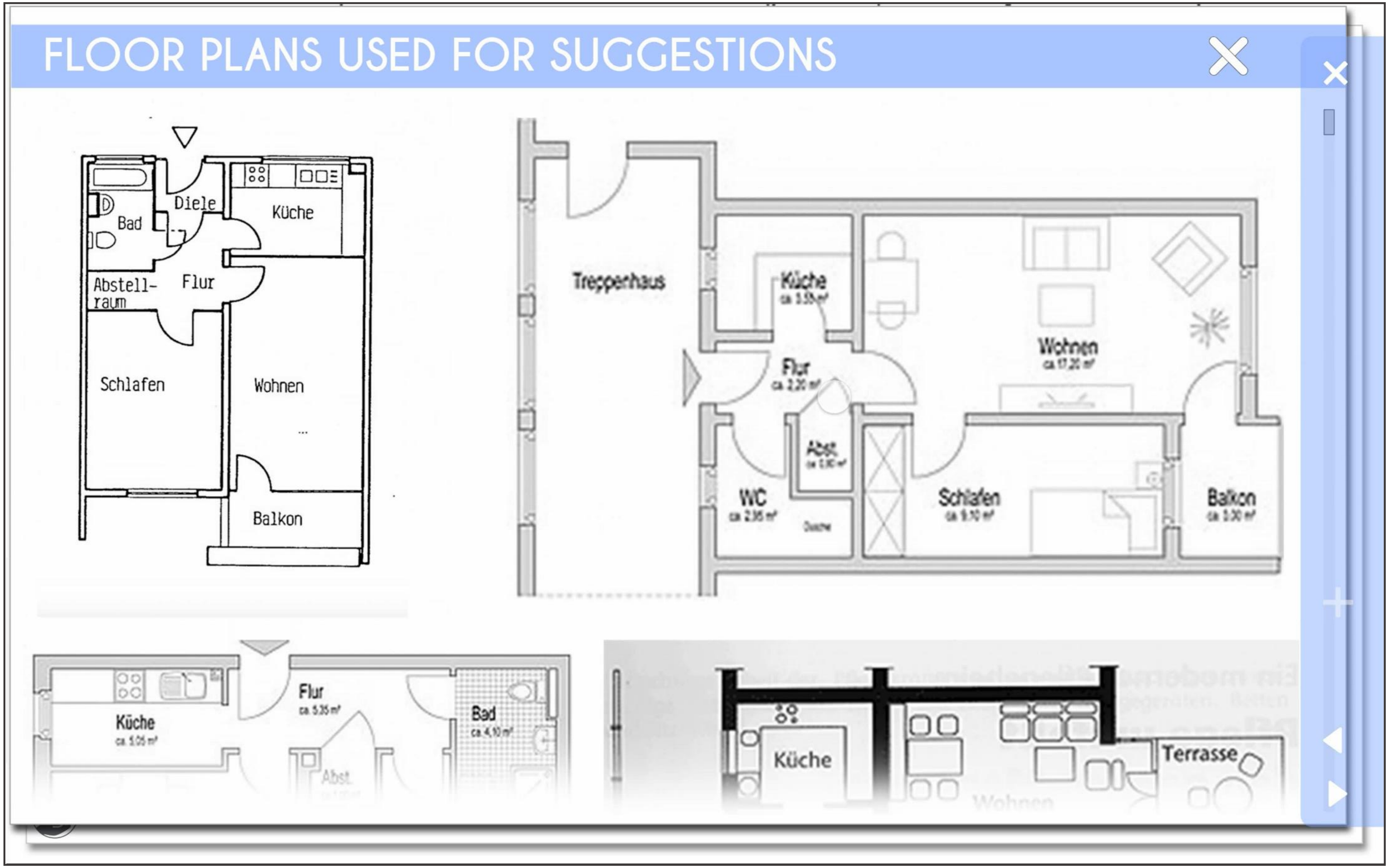
11.7 Paper Prototype, suggestion view/ dropped down



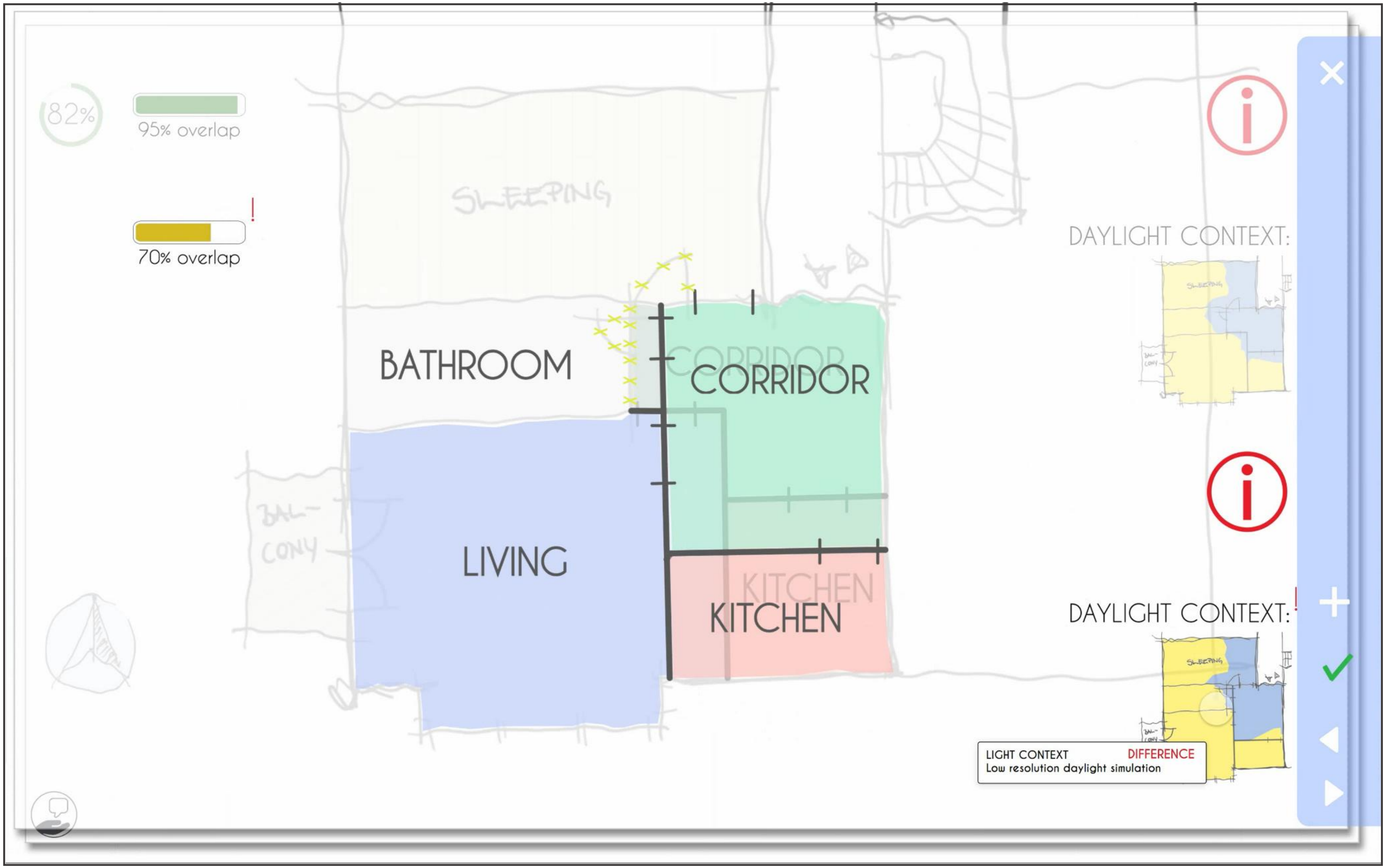
11.8 Paper Prototype, suggestion view/ alert



11.9 Paper Prototype, layered raw data view



11.10 Paper Prototype, layered suggestion view/ dropped down



11.11 Storytelling Canvas WHITE BRIDGE

Topic:
What is the story about?
intelligent design assistant WHITE BRIDGE

Audience:
Who is your story's audience? What are their needs?
- working architects, who are stressed and swamped with work
- need support for fast and high quality designing in early design stages

Goal:
What do you want to achieve with this story?
- show and explain the uses/support of an intelligent design system like metis II

Before:
What does your audience think, feel, know, want, before they have experienced your story?
- intelligent systems on TV and auto-completion of keyboards
- probably suspicious of AI
-relatively little knowledge except for TV
- submit quality building desings > become renowned?

Beginning

Start with Why:
Why is it useful? (Connect to daily job) Why is it relevant? Why is it worth being excited about?
- take off work/pressure
- implications for AEC future because of growing population

Common ground:
What from your past do you have in common: memories, historical events, interests? Where are you headed in the future? What types of outcomes are mutually desired? Why are you uniquely qualified to be their guide? What similar journey have you gone on with a positive result?
- time pressure, often overtime working and being overworked
- increase of workload in the future > ~10 Bil. people by 2050, most of them in dense urban areas

One big idea:
How is the big idea conveying your unique perspective? How is the big idea communicating what's at stake? Articulate the big idea in one complete sentence.
what if there was a tool to support you in your design with access to a huge database?

Middle

Simplicity:
What is the key point? How do you support that key point? Why care?
- metis II as an intelligent design assistant
- future implication on building industry because of growing population, fast and efficient buildings neceassary

Unexpectedness:
Surprise, curiosity, pose questions, create gaps and fill in later or guide audience to fill them, take people on a journey
- curiosity?
- how? SUPPORTING architect through suggestions as design impulses

Concreteness:
Real examples, concrete images, metaphors (my topic is like..., being in... is like...), analogies (Alien = White Shark in space ship)
- analysis by system
- auto-completion of texting by smart keyboard

Credibility/Truth:
4 truths (teller, audience, moment, mission), social proof, statistics, personal stories
- reference buildings = common practice in architectural design process for inspiration/evaluation/deriving design conditions/communitaion > but metis II offers huge ready-to-use database

Emotions:
Images/visuals, personal, labels, negative (painful problem, fear), positive (relief from problem, benefit, imagine a better future)
- relief of the user > take off work and memory load
- reduced stress, YAY!

Storylines:
Explanation (step-by-step), Pitch (overcoming a challenge), Drama (down to bottom, up to top)
- PITCH
- huge amount of work already > sharp increase in future > support for achievement and high quality designs

S.T.A.R. moment:
Memorable dramatization, repeatable sound bite (strong labels, alliteration), evocative visuals, shocking statistics
intelligent design assistant for fast and well-informed decisions of early design stages, which significantly influences design quality of finaly building!

End

Call to action:
What are you asking the audience to do? Clearly state how you want the audience to take action. What type of decision do they have to make?
- use metis II! ‚check it out'
- ‚don't be afraid of an AI'
- ‚see for yourself, how it influences your design decisions!'

Reward:
How will they personally benefit from adopting the idea of your story? What's in it for them emotionally or materially? How will this help their sphere of influence such as friends, peers, and direct reports? How can they use it with those they influence? How will this help the humans or the planet?
- relief: faster work, but keep high quality
- be able to focus on creative aspects, while system analysis for you in the background
- shape future desingin and the face of the world!

After:
What does your audience think, feel, know, want, after they have experienced your story?
- motivated to try
- informed about the general metis II
- curious (about study)
- re-assured that metis II and AI in general won't steal their jobs, but are there to support them

11.12 'WHITE BRIDGE – an intelligent design assistant'

WHITE BRIDGE

an intelligent design assistant

WHITE BRIDGE made my life a lot easier, in both the past and in the present. Its support is helpful, but not intrusive. Whenever it presents me with suggestions for further design steps, I'm positively surprised to see the variations I get of my own sketches, see the ideas existing in my head confirmed in front of me or what different design directions the design assistant has for me.

What is **WHITE BRIDGE**? I think the best way to describe it, is as a support system for your own design process. Like the auto-completion of a keyboard, instead of letters and words WHITE BRIDGE suggests further design steps. It often amazes me, how it can so fast generate suggestions from my early sketches. I am always glad, when I can see my own thoughts confirmed by WHITE BRIDGE, before proceeding with my sketching. From time to time the suggestions take me out of my comfort zone and direct my thoughts in new ways or points out context and reasons I wouldn't have thought of before in this early stage. Especially, since design decisions of these early phases have shown to be highly significant for the overall quality of the final building, reflecting and re-evaluating your design choices is important.

How is **WHITE BRIDGE** supporting you? I guess to answer that I have to go a bit further back. I started using WHITE BRIDGE after leaving university, right at my first job. Until that, I've never even heard of it before. I was supposed to be a full-fledged architect right after university, taking up the responsibility of designing houses – houses that are for actual people to live in. I was very insecure and asked my supervisor a lot for meetings, feedback and so on. Because of the sharp increase of needed living space in the urban area in the past few years, he had very little time, the office was swamped with work and at one point he told me to just use WHITE BRIDGE if I was that unsure of my own designs.

When he told me that it was an artificial intelligence system that supports me in designing I didn't believe my ears: is this program going to do my work? Is he mocking me that an AI would do a better job than me? Basically, my thoughts went straight to Sci-Fi and how the artificial intelligence is going to hog my designs, take away the soul of my designs, and my personal touch and creativity will be lost. He laughed a bit, he could clearly see all these thoughts on my face. When he showed me the simple sketch interface of WHITE BRIDGE I was (positively) surprised. It was your typical hand-sketching tool, everything I knew from my studies, the old-school way of designing. My supervisor explained to me that WHITE BRIDGE is simply a support system and reassured me that in no way it is going to take away my work, just make it a bit easier – but that I would still need to work, he said with a little wink.

make it a bit easier – but that I would still need to work, he said with a little wink.

After my first sketches, the design assistant intuitively led me through its suggestions and I was amazed by the whole tool. It basically uses a huge database of buildings to generate these suggestions, the same way you learn to use existing buildings as inspiration at university.

In these first, probably like, two years of working, WHITE BRIDGE supported me in my design decisions by giving me confidence through the confirmation of my own ideas or pointed to more important factors that I hadn't considered before. WHITE BRIDGE helped me learn and grow while I was already working, so that I could submit quality work. I actually believe that, what would normally take many many years of experience within the workforce, like how to prioritise the criteria during the schematic design phase, I achieved much faster through the constant feedback and dialogue with WHITE BRIDGE .

Nowadays, after working with it for years, I use WHITE BRIDGE rather for being fast. Like I mentioned before, it is a bit like the suggestions of a keyboard. In the same way, my WHITE BRIDGE learned from me and now knows my personal style and suggests accordingly. So overall, at this moment in time it speeds up my sketching process, which is really helpful in these stressful times – and according to the numbers there is more and more work to come for us architects in the future. It's a relief to see that I can work this fast, while keeping such high quality. It allows me to absolutely focus on the creative aspects of designing, while the system analyses, considering all kinds of factors, for me in background to support me.

Can you recall of any other benefits of **WHITE BRIDGE** ? Recently, my former supervisor, now colleague, also told me, that it helps him keeping his knowledge of new technologies, materials and construction methods up-to-date. The database for the suggestions gets regularly updated and so WHITE BRIDGE can create suggestions based on the latest designs for maximum efficiency and style. Which brings me back to the fact, that the current world population is pushing the 10 Billion mark soon, of whom most are living in dense metropolitan areas. So we need to create buildings that are long-lasting and efficient, but also flexible and answering to the context around it. WHITE BRIDGE, being the intelligent design assistant that it is, is simply a tool to support me in making fast and well-informed design decisions during sketching, so that I can meet my high work demand with ease, while focusing on the architectural design process.

by Tilman Filger

20.03.2042

11.13 Interview Guidelines

GUIDELINES FOR SEMI-STRUCTURED INTERVIEW

Benutzerstudie von
Jessica Bielski

Im Zuge der
Master Thesis des Wintersemesters 20/21
Lehrstuhl für Architekturinformatik

TECHNISCHE UNIVERSITÄT MÜNCHEN

1. So, this was a lot right now, for a small downing

    1.1 How are you feeling after seeing this paper prototype?

    1.2 Could you follow the presentation of the paper prototype?

    1.3 Do you have any questions that we need to discuss right away, before we start the questions of the study?

2. Ok, now let's talk about the paper prototype. I have some questions for you, which are concerning the content of the additional information WHITE BRIDGE is offering you, additionally to the suggestions. Afterwards, there are questions specifically for the visualisation of the different kinds of information.
To give you a short idea what I mean here: it's the additional information, so the content, you get from the tiny graphics – or visualisations - in the upper part of the video, like classification of your sketch, the relevance/ overlap percentage…

    2.1 Was the additional information gained from the graphics helpful for you to understand and follow why you got this suggestion?

    2.2 I don't know if you had the time actually check out the suggestions made to you as the user. If so, which one would you have chosen and did you use the additional information for your decision? If so, which one(s)?

    2.3 Did any of this additional information make you think of something you haven't considered, while checking out the different suggestions? Like pointing to something that has been out of your scope before?

    2.4 Did you want any other information to support you in your design process, different and/or additional?

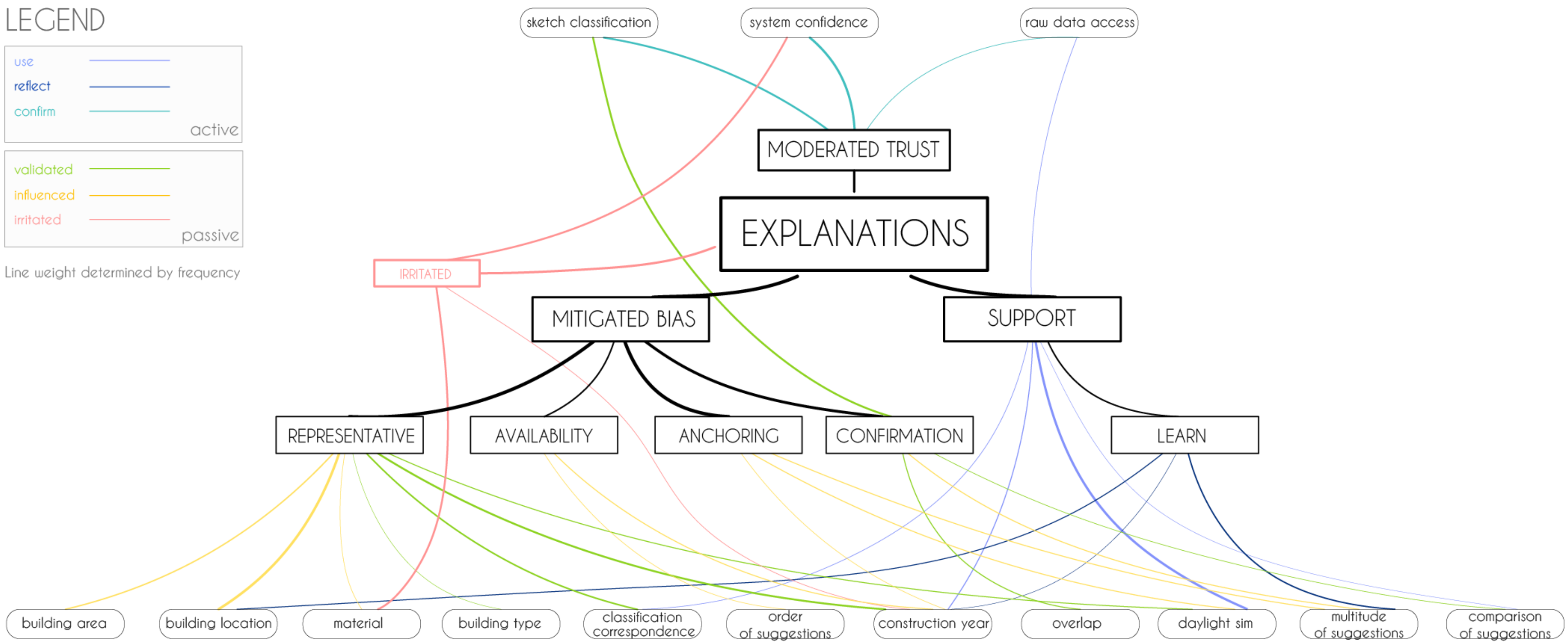
3. Great, thanks. Like I said, after talking about the content or the additional information gained, we go on now to the visualisations, so the tiny graphics which show the information:

   3.1 Were the visualisations easily readable and helpful to get and understand the conveyed information?
   3.2 Were the visualisations as you expected them to be for the content?
   3.3 Did you want any other visualisations, different and/or additional? If so for which information?

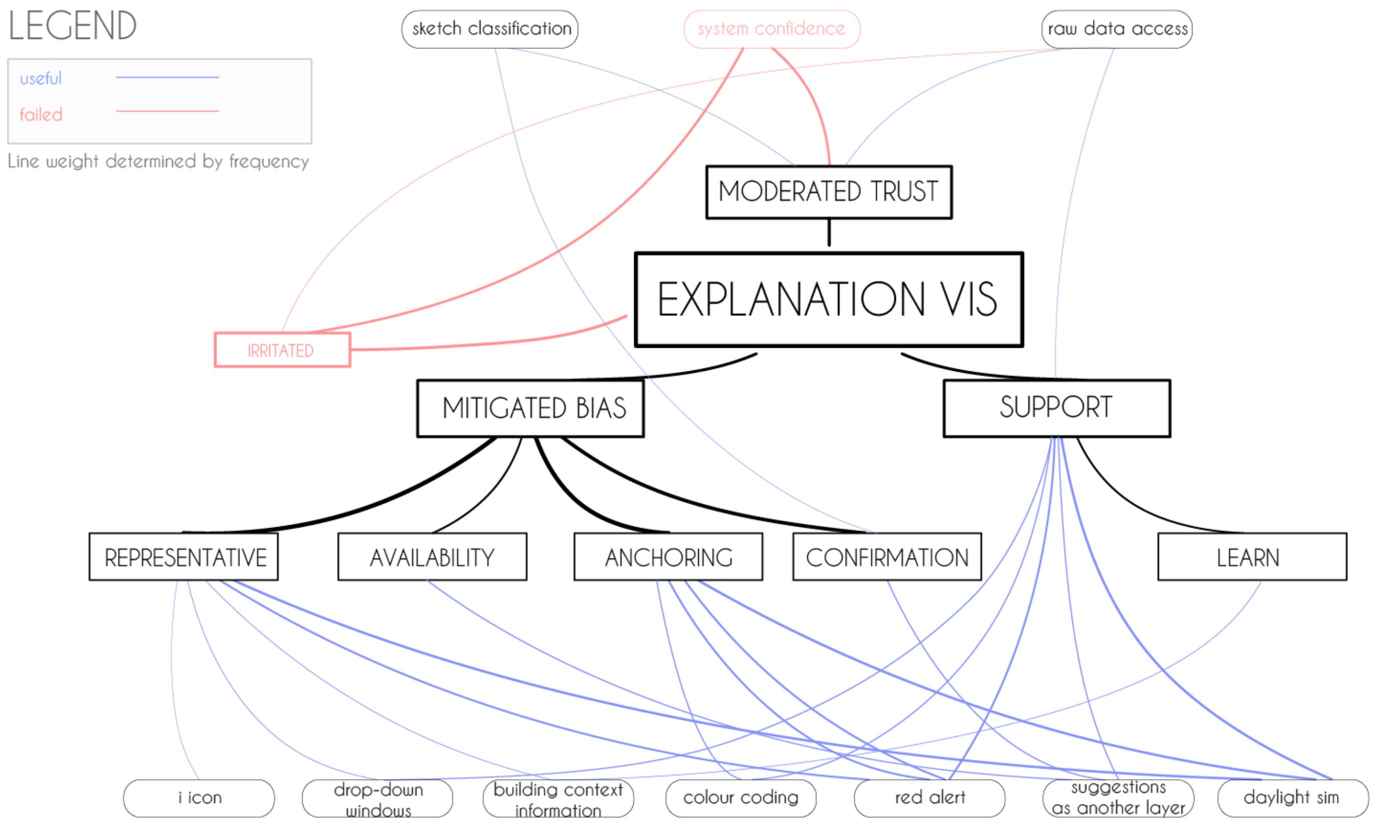
4. To conclude, I would like to ask you a reflect one last time:

   4.1 How did the additional information make you feel?
   4.2 How did the additional information make you feel about the design decision you've taken?
   4.3 How did the additional information make you feel about the intelligent design assistant 'WHITE BRIDGE'?

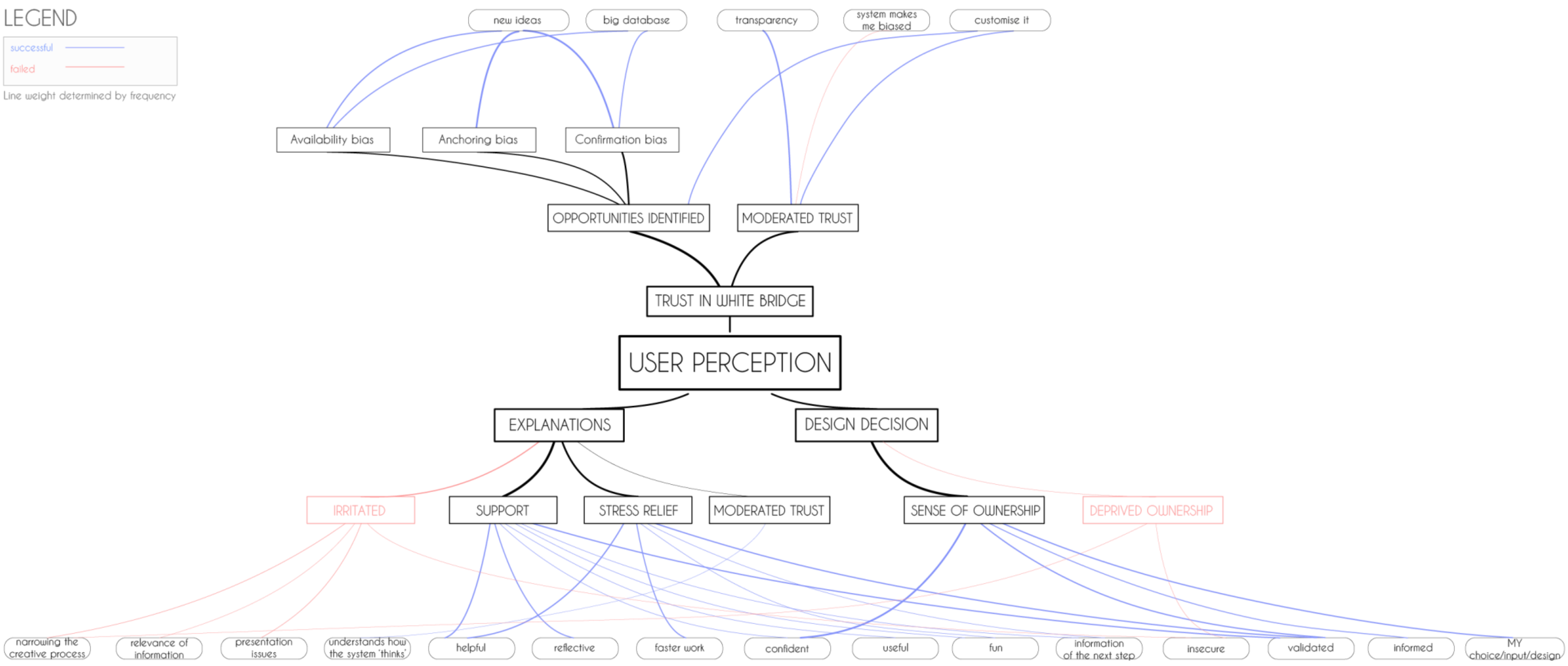
11.14 Mind Map, explanations



11.15 Mind map, explanation visualisations



11.16 Mind map, user perception



11.17 Word cloud, perception of explanations

11.18 Word cloud, emotions towards own design decision

11.19 Word cloud, trust in WHITE BRIDGE