Design rationale documentation and exchange in the Danish AEC industry

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Abstract
This paper examines how design intent and rationale are described in the Danish architectural, engineering and construction (AEC) industry, providing the description needed to investigate how design rationale is documented and which tools can be utilised to do so. Through semi-structured interviews, a need for capturing and exchanging design rationale between project participants was identified. It was, furthermore, revealed that design rationale is rarely captured and that documentation of design rationale is usually only found implicitly in CAD and Building Information models or in emails, documents, handwritten notes or minutes of meetings. Most design rationale is, however, never documented which can lead to information loss and re-working of already functional design solutions. Lack of design rationale can additionally lead to model-changes being discarded, as the argument or rationale for the solution or change is not accessible.

Keywords: Design Rationale, Design Intent, Information Management, Building Information Management

1 Introduction

Throughout the past century, the complexity of buildings has increased due to the development of new materials, methodologies and technologies in the building industry. Legislation and building owner as well as end-user demands for how buildings must perform has additionally grown in recent years, in addition to the amount of stakeholders and specialists who are involved in the design and building process (Zou and Tang, 2012). This has led to an increased need for information and an enhanced focus on digitalisation and use of technology to solve design and constructional problems (Boligstyrelsen, 2019). Focus has furthermore been extended to improving building quality (Molio, 2018; Neve and Wandahl, 2018), and reduction of construction time and cost (Zou and Tang, 2012; Bryde, Broquetas, and Volm, 2013).

Design information flowing efficiently, is according to Zou and Tang (2012), the foundation for a successful construction project. Hence, tools and methodologies for developing, storing and exchanging data has been introduced to the Architectural, Engineering and Construction (AEC) industry, to facilitate this efficient information flow.

Examples of such tools and methodologies are Computer Aided Design (CAD) and Building Information Management (BIM), which today, are common-practice in the AEC industry in many countries, due to the benefits the tools provide by facilitating development, collaboration (Epstein, 2012), storing and exchange, as well as use and re-use of building information (Sacks, Eastman, Lee, and Teicholz, 2018). However, another reason for BIM adoption can according to Ayinla and Adamu (2018) be found in peer pressure from competing companies or that a company does not want to lose patronage in the BIM-market.

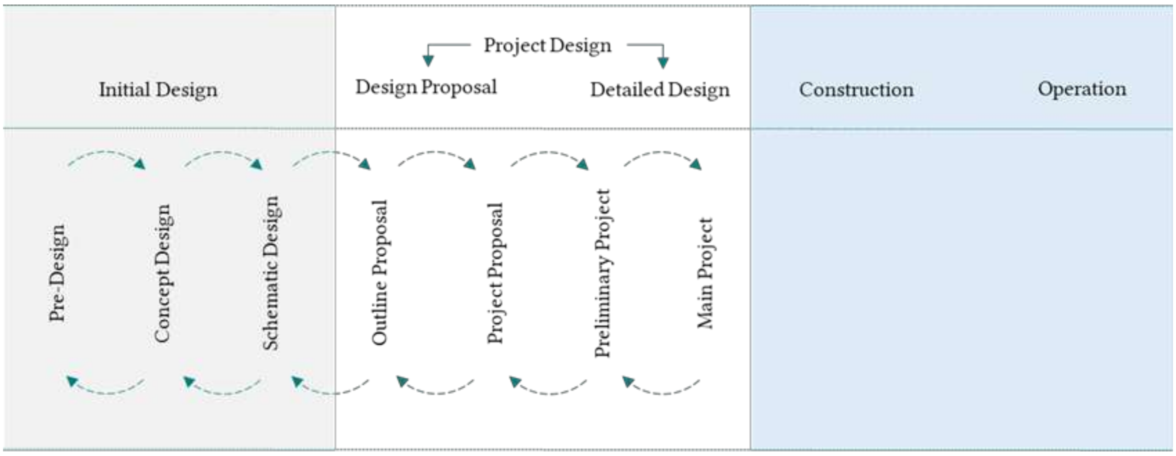

Figure 1 The design, construction and operational phases and their milestones (FRI and Danske ARK, 2012; Landgren, Jakobsen, Wohlenberg, and Jensen, 2019)

In this paper, we use the definition by Penttillä (2006) defining BIM as a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle (Succar, Sher, and Aranda-mena, 2007).

Use and re-use of building information on a project can be hard to do, as building information is often developed based on a poor modelling strategy (Alducin-Quintero, Rojo, Plata, Hernández, and Contero, 2012), are fragmented and exchanged as well as stored in multiple analogous and digital representation formats during the various phases of a design project. Information and knowledge gained from a project are furthermore rarely retained and re-used on later projects (Bryde, Broquetas, and Volm 2013).

In contrast to both good and poorly documented design information, some information is never documented in CAD, BIM nor anywhere else, but exist only in the memory of the developer of the information. This can lead to information loss in the project organisation between phases and when project participants are substituted. Even if the person using the memory as documentation-platform for building information does not leave the design-team during the project's lifecycle, information-loss can occur, as "the memory" is not a reliable storage for building information.

The design and building process can be divided into four primary phases, initial design, project design, construction and operation, whereas the project design phase can be divided in two parts, 1) the design proposal and 2) detailed design (FRI and Danske ARK, 2012; Landgren, Jakobsen, Wohlenberg, and Jensen, 2019). The phases include the milestones shown in figure 1, as described by Landgren, Jakobsen, Wohlenberg, and Jensen (2019). The process of completing said milestones is, however, an iterative process, in which designers must go back and forth between the milestones to complete the information development needed, in order to achieve approval from the building owner, and attain building permit from local government.

In most design projects, the use of CAD and BIM begins in the initial design phase. At this point specifications are usually translated from the written description of the demands for the building, set by the building owner and other stakeholders to the project, into drawings and models using CAD and BIM tools. According to Zou and Tang (2012) it is essential that a designer proposes more than one solution to how design should be solved to facilitate the demands set by the building owner in the early design phases, which entails collaboration between the designer and various specialists in order to reach a design which is suitable for construction.

Most building information stored in CAD and BIM repositories, both in the initial and in the design proposal phase, are concerned with the geometry of a building, and the properties of the objects attached to said geometry. In addition to information documented in CAD and BIM tools, a description of building information is typically also utilised on design projects in Denmark.

Building information found through CAD and BIM tools often makes an implicit or explicit documentation of the design intent of a design; however, often the rationale for a design is not documented in any reliable format.

Design intent is a special kind of design knowledge (Chen, He, Lv, and Cai, 2019), There is, nonetheless, currently no consensus for how design intent should be defined (Camba and Contero, 2015).

In a study about design intent in 2D CAD, Iyer and Mills (2006) describe design intent as, "the insight into the design variables (design objectives, constraints, alternatives, evolution, guidelines, manufacturing instructions and standards) implicit in the structural, semantic and practical relationships between the geometrical, material, dimensional and textual entities present in the CAD representation".

Chen, He, Lv, and Cai, (2019) define design intent in the context of efficient clean-sheet or re-use CAD-modelling as, "a description of the collaboration process, a coordination procedure of design intents from every participant and an optimal design solution as a result of a collective intelligence". The task of design intent capturing, is furthermore described as, a recording of how different project participants generate the form of a product and why the form is generated in the way it is.

According to the International Organisation for Standardisation (ISO) "Design intent is captured in the schemes of parameterization and constraints imposed upon models during their construction"(ISO, 2005a), and is the "intentions of the designer of a model with regard to how it may be instantiated or modified" (ISO, 2005b).

Based on analysis by Otey, Company, Contero, and Camba (2018) the design intent primarily provides behaviour and function, but does also make design requirements explicit and eases communication, and is according to Camba and Contero (2015) directly related to CAD quality.

On the other hand, Otey, Company, Contero, and Camba (2018), describe design rationale as the explicit documentation of the reasons behind the decisions made when designing, which provides the argument or rationale which supports and helps understanding the choices made (MacLean, Young, and Moran, 1989). Lee (1997) adds that well-structured design rationale can help designers track the issues and the alternatives being explored sand their evaluations, and can be represented as both informal, semi-formal and formal. Informal rationale can entail unstructured descriptions in natural langue, audio/ video recordings and raw-drawings, whilst a system can read and manipulate a formal representation, using formal operations. Semi-formal representation of design rationale consists of both informal and formal (Lee, 1997), and relates well to the construction industry, which is already utilising semi-formal representation in the design process.

Interpreted by Otey, Company, Contero, and Camba (2018), Peña-Mora, Sriram, and Logcher (1993) states that the AEC industry can benefit from explicit design intent representation in four ways.

1. Changes in complex projects require certain design decision to be modified during the development process. When the justifications defined during the initial stages are lost, they need to be recreated, which has a negative impact on project costs and development times. The ability to store, process, and retrieve this information can significantly improve productivity.
2. When design intent information is represented explicitly and is easily available for review, the overall quality of the product increases.
3. Explicit communication of design intent leads to a more intelligent use of resources and knowledge.
4. Efficient communication of design intent is essential for integrating solutions and transferring design knowledge.

In the same paper Peña-Mora, Sriram, and Logcher, (1993) describe design intent as equivalent to a set of design requirements, and the design rationale as the reasoning that shaped the design.

In this paper we focus on design rationale documentation in the Danish construction industry, defining design rationale as the argument which supports and helps understanding choices made, in a semi-formal representation, utilising both informal and formal representation of design rationale as suggested by Lee (1997). We furthermore distinguish between design intent and design rationale, defining design intent as the design knowledge harbouring not only geometrical, but also non-geometric aspects of the design, including product information and design process information.

Through five semi-structured interviews with respondents from small and medium-sized companies in Denmark, this paper identifies how design rationale is documented and exchanged on design projects. In the third section of the paper, the results from the interviews are presented, followed by a discussion in section four, identifying similarities and discrepancies between our results and existing literature, to understand 1) if and how design rationale is documented and exchanged and 2) identify which tools AEC companies currently use to document and exchange design rationale. Finally, section six presents a summary and conclusion of the research.

2 Methodology

The data collection for this paper was divided in two parts. Firstly, a small systematic literature review and secondly, an empirical data collection using semi-structured interviews. Interviews were mainly conducted during an interdisciplinary learning event in Northern Denmark, called the Digital Days. At the Digital Days, students from different educational levels and programmes, as well as industry representatives, works together in teams of 10-15 people. The event is held annually and took place online in 2021. Most of the interviews were therefore conducted using online meeting platforms and the telephone.

2.1 Literature review

Literature was collected using the keywords: design rationale, design intent, information management, building information modelling and decision-making in the Web of science and Scopus databases. To ensure a broader documentation of the state of the art, backwards snowballing was performed on key-references found using the keyword searches. Non-AEC literature was not excluded.

2.2 Empirical data collection

Empirical data was collected using semi-structured interviews, based on the recommendations of Tanggaard and Brinkmann (2015). Using semi-structured interviews provides the interviewer the ability to ask both pre-determined questions, as well as spontaneously arising questions. The use of semi-structured interviews furthermore allows respondents to speak in a narrative, which can provide information about process and context. One interview with two persons from an architectural company was conducted, in person, whilst the rest of the interviews were conducted during the Digital Days 2021, using an online meeting platform or the telephone.

In all, five respondents from both architectural and engineering companies were interviewed as shown in figure 2.

2.3 Data Analysis

The qualitative datasets collected from semi-structured interviews were sound-recorded and transcribed. The transcription allowed coding of the interview data, structured using the keywords from the literature search, in order to facilitate a well-organised presentation and discussion of the data. This allowed direct comparison of the empirical data and the literature and made it possible to highlight similarities and discrepancies between the two data collections.

3 Results

In this section, the results from the semi-structured interviews are presented divided in the four topics, 1) design rationale, 2) design intent, 3) information management and BIM, and 4) decision-making.

3.1 Design rationale

Interviews showed that design rationale can be documented and exchanged using different types of tools including CAD modelling. For most of the respondents, design rationale is not a type of design knowledge they specifically document and exchange, however in some cases design intent and rationale was reported to be present in CAD and BIM implicitly. The degree of information maturity

No.	Gender	Profession	Company employees	Interview-platform
1	Female	Architect	1-10	Telephone
2	Male	Construction Architect	1-5	Telephone
3	Male	Engineer	100-150	Microsoft Teams
4	Male	Construction Architect	25-30	Physical meeting
5	Male	Construction Architect	25-30	Physical meeting

Figure 2 Structure and information about the interviews and the respondents

was nonetheless the primary determinative for if design intent and rationale were accessible implicitly.

Respondent 2 noted that use of visualisation technologies like Virtual Reality (VR) made it possible to inspect models visually and interpret the rationale behind the design decisions made in earlier design phases. Design made by others on the design team was furthermore made easier to understand, as the immersion provided through VR acts as a better platform for communicating design intent and rationale, than 2D and 3D representations of the same design shown through a modelling tool.

Respondent 2 also explained that design decisions made in the early design phases, are often altered throughout later design phases, only to be changed back to the original design before it is handed over for construction. This is due to design-changes not living up to cost-limitations or not fitting with demands for the building when evaluated thoroughly.

Respondent 3 added to this description, by explaining that sometimes a design solution gets updated in the design model, only to be changed back again by another person working on the project, because that person did not understand the reason for the change. The respondent further noted that documentation of design rationale, in this regard, could make a difference.

Three of the respondents described how they utilise “breadcrumbs” in Autodesk Revit, which is a family based collaboration tool (Autodesk, 2021), allowing designers to place notes in a building model. The tool is used to exchange notes among designers on a project, describing what needs to be changed, however, as explained by respondent 3, such notes, exchanged using “breadcrumbs”, rarely include a rationale explaining why a change is needed.

3.2 Design intent

In contrast to the lack of design rationale found in “breadcrumbs” used by some of the respondents, design intent, describing which demands needs fulfilment, are often exchanged between project participants. This is done using a collaboration tool like “breadcrumbs” or through email correspondence or oral communication.

Having regular meetings, facilitating oral discussion of design solutions between project participants were described as essential by respondents 3 and 4, highlighting that such meetings can limit the transferring of issues regarding how, where and what to model in the used CAD and BIM tools, between phases, throughout a project’s life-time.

Respondent 1 revealed that design intent and change-requests to a design-model are based on handwritten post-it notes, or notes inserted into the building description document in her company. However, sometimes information is lost, using such procedures.

Respondent 3 described how his company often has interdisciplinary discussion about how to solve a design problem. The primary factor for which solution is chosen during such discussions are the cost, and the company therefore rarely uses BIM-based analysis tools, to reveal if the design lives up to the demands set for the design, or to provide an argument or rationale for a specific solution.

3.3 Information management and BIM

All respondents’ companies use CAD and BIM tools. However, respondent 1 disclosed that only geometric modelling is utilised in her company, as the competences with respect to parametric modelling are limited in the company.

Respondents 4 and 5 explained how they are trying to connect the design description document, with their 3D model, which would connect a written document the company uses to describe all building components and their intent, with the 3D model, and allow better information exchange between project participants. However, the current process of exchanging information relies heavily on oral communication and email correspondence, stored without being connected to CAD and BIM.

Four of the five respondents reported that they use automatic model checking, at least to some degree, indicating, that tracking of changes is occurring in the companies, documenting changes made to the design intent, however, without capturing the argument behind the changes.

3.4 Decision-making

All respondents explained how they use CAD and BIM in various ways, however; only respondents 4 and 5 described their design models as a means for decision-making. However, the communication of the decisions made based on model scrutiny, relies on documentation, which is not stored through the CAD and BIM tools.

4 Discussion

BIM usage, makes it possible for multiple project participants to collaborate using the same model (Epstein, 2012), and use of BIM seems as a feasible solution for information exchange between parties. It is therefore, of no surprise that all respondents revealed that they use 3D modelling tools. However, as noted by respondent 1, adoption of Autodesk Revit in her company was based on one person's commitment, as the other employees in her company were comfortable using 2D modelling only.

When using 3D modelling in designing, some respondents explained that they use BIM, having the 3D model as a basis for communicating of design on their projects. This is a common practise in the construction industry, and a process which is commonly divided into four phases with specific milestones attached, as described in figure 1 (Landgren, Jakobsen, Wohlenberg, and Jensen 2019). However, based on the results from the interviews, the chronological understanding of the design process does not fit with the description of when information about design intent and rationale must be accessible. Some early design intent and rationale might support decision-making in late phases, and could hinder changes being made to a design solution, which works or might not be changeable due to an underlying rationale.

To provide design rationale to all phases of a design project, it must be documented throughout the full design process, and stored in an accessible representation, format and location, as shown in figure 3. Documentation of design rationale might be most useful if documented through BIM and CAD tools; however, this option cannot be concluded as feasible based on this research alone.

Respondents 4 and 5 explained that planning ahead of modelling is the key to success on their projects, and that issues regarding how to model, what to model, and which modelling tools must be used, can be avoided through such planning. They further noted that communication through BIM-tools alone, is not enough, and that oral discussions about design intent and design rationale are needed throughout the design process to ensure issues does not grow during the various design phases.

Design phases might be divided with respect to which milestone to reach, but they are not divided with respect to information and when design rationale is needed to inform decision-making.

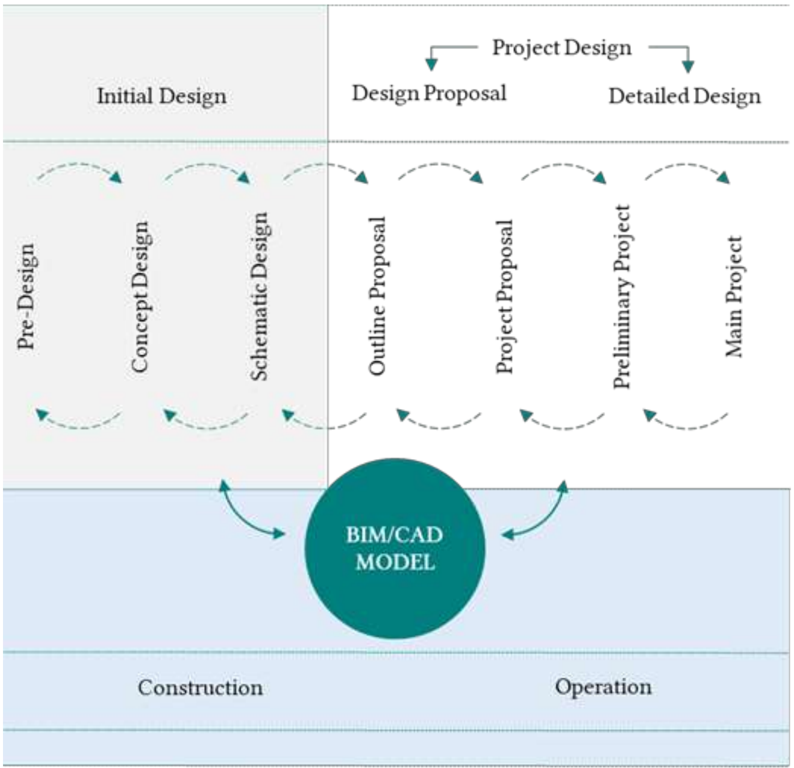

Figure 3 The commonly accepted phases and milestones for a design project, combined with documentation of design rationale information in a BIM or CAD model, allowing accessibility to the information for all project participants, in all phases, as indicated by the full coloured arrows.

Some attempts are already being made to digitise some of the information that might result from oral design meetings, through combining building descriptions and building models, as well as using tools like "breadcrumbs" in Autodesk Revit, to communicate changes. However, rationale needs to be added when using such tools, as design rationale can help designers avoid re-designing a functional solutions, or go back on a change made by another designer, due to lack of understanding for why the change was made (MacLean, Young, and Moran, 1989).

Design rationale is sometimes stored implicitly in a design-model, but only becomes obvious when viewed through another medium than a BIM-tool. This could be virtual reality, as noted by one of the respondents, as the immersive nature of virtual reality through head-mounted-displays, might make it easier for a designer to understand why a design solution is as it is.

When design rationale is not found implicitly in design models, a structured representation of it is necessary, including not only formal, system-readable information, but also informal rationale, which might include handwritten notes and documentation of oral-communication.

As described by Zou and Tang (2012) multiple design proposals should be the foundation for decision-making, ensuring the fulfilment of the design demands set by the building owner. However, as revealed through the interviews, decisions are not made based on selecting a solution from a catalogue of options. Design solutions and changes to a model are often made on an individual level. Such changes can be tracked using automatic rule-checking software applied to a CAD or BIM model, however, the rationale for the changes made by an individual project participant are not traceable in this way, if they are not documented in the model.

Even though some companies strive to preserve the same participants on a project throughout the design process, people along with their knowledge of building rationale are often removed from projects. This has a negative impact on project costs and development time (Peña-Mora, Sriram and Logcher, 1993; Otey, Company, Contero, and Camba, 2018), as well as the ability to contain design rationale on a design project.

5 Limitations and future work

The empirical research data was collected only from small and medium-sized companies in Denmark. Even though Ayinla and Adamu (2018) in their research have concluded that small and large organisations are somewhat similar in sophistication of BIM technology utilised and their adoption speed, the study would have benefitted from interviewing major-sized companies also, to achieve a broader understanding of the documentation and exchange processes related to design rationale.

The generalisability of the study is limited by its local nature and future research should include an empirical data collection with an international scope.

The study did not consider documentation and exchange of design rationale in a building information maturity context, which should be included in future work.

6 Conclusion

This paper presented a small literature review, summarising different perspectives and definitions of design intent and design rationale, resulting in a definition, of design intent and rationale, as the argument which supports and helps understanding choices made, in a semi-formal representation (MacLean, Young, and Moran, 1989; Lee, 1997). We furthermore distinguished between design intent and design rationale, defining design intent as the design knowledge harbouring both geometrical, product information and design process information.

Through five semi-structured interviews, with respondents from small and medium-sized companies in Denmark, it was revealed that no specific processes occur during the design phases capturing design rationale. A need for documentation and accessibility of design rationale was, nonetheless identified.

The design and building process is often divided into four phases, in which the design process contains an initial design and a project design, which includes seven milestones established in the Building and Planning Regulations by The Danish Association of Consulting Engineers and the Danish Association of Architectural Firms (FRI and Danske ARK, 2012). Even though the phases and milestones might be completed in a chronological order, information from one phase is not only informative for decision-making in the following phase. Information of design intent and rationale from the early design phases can inform decision-making in late phases.

Implicit design intent is often present in CAD and BIM, through use of collaboration tools such as "Breadcrumbs" or documented in emails and design briefs.

Design rationale is sometimes documented on design projects implicitly through use of CAD and BIM tools, in emails, documents or handwritten notes, or in minutes of meetings. However, most design rationale is not documented and even if it is, it is rarely shared between project participants in any explicit or reliable representation.

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