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The documentation of design decisions in engineering projects: A study in infrastructure development

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Abstract:

In most design projects, the documentation of design decisions is considered important. Among others, documentation of design decisions contributes to the traceability of decisions that shape a project's development process, helps deal with changes in the project and prevents the recurrence of old discussions. Yet, little attention is given to documenting design decisions in the engineering literature. In this study, a theoretical framework for the key elements of this documentation process was developed. Four infrastructure projects were studied and compared to this framework by means of pattern matching. This method compares theoretical and empirical patterns and determines whether they match or do not match. The findings demonstrate that accessibility of documentation for all involved project parties and the division of documentation tasks are in accordance with the literature. However, the documentation of design decisions and their rationale is not done as completely as is recommended in theory. Literature states that the documentation of interrelations and context of decisions should be described thoroughly, but that is barely done in practice. In addition, the findings show that neither immediate documentation nor periodical monitoring of documentation is applied. Based on these findings, this research proposes a strategy for improving the documentation of design decisions.

Keywords:

design decision; civil engineering; documentation strategy; infrastructure; project management; information systems.

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1. Introduction

The documentation of design decisions in complex projects is of great importance as it, among others, improves the ability to trace decisions, provides more insight in which decisions have been decisive in the project development, and prevents the occurrence of old discussions.

Civil engineering projects often have a long duration and are dynamic in nature [1]. A project consists of multiple phases that have to be completed for the design of new infrastructure, or for redesign or modification of existing infrastructure. The execution of different phases requires the involvement of different specialized parties. Information is not only transferred between different involved parties, but also from one phase to another. Documentation is of great importance as it is the main means to transfer information from party to party and from phase to phase. However, problems concerning the documentation of design decisions have been identified at these transitions [1]. For example, a clear baseline for the project is not always established, as the documentation provided during these transitions is often incomplete or missing in many projects [2]. Moreover, the quality of input-documentation appears to be a problem, even for a phase itself. Project disciplines do not receive the information they require, or the documentation is provided too late [3]. Finally, design decisions are not always communicated with those involved in the project organization [1],[4]. Hence, being dependent on the documented information of others, different teams cannot continue their work activities or have to make assumptions which may turn out to be wrong [5],[6].

Approaches and formats differ per organization or team, which makes tracing information a tedious and time-consuming task and prone to errors [2],[7]. In addition, a high level of effort is also required for managing and controlling changes in project scope and requirements [8]. It is hard for stakeholders, or for members of the project organization, to determine which design decisions have been made earlier in the process, and how these affect or are affected by, the changed parameters [3]. Moreover, a lack of procedures sometimes results in ambiguities about people's responsibilities for both making and documenting design decisions [6]. This not only results in miscommunication between the different involved parties but also between individuals of the same team. Finally, discussions in projects are repeated multiple times as no documentation can be provided based on which the discussion could be closed [1]. To solve these problems, the development of a strategy for the documentation of design decisions in civil engineering projects is relevant.

The documentation of design decisions is required to provide both the project organization and different stakeholders with a reference throughout the project [7]. Documentation allows clients, project members and stakeholders to keep track of project changes and ensures a good traceability [1],[9]. By doing so, knowledge and practices from previous phases could be reused, and reoccurring discussions can be prevented [8],[10]. This increased efficiency enables a timely completion of the different project tasks [11]. Moreover, documentation of design decisions could also be beneficial for communicating within the project organization as well as for allowing an understandable representation of the design for different stakeholders [3].

The objective of this study is to develop recommendations in the form of a strategy for the documentation of design decisions in civil engineering projects by investigating current practices. A literature review has been done, current practices have been studied in four projects, and a concept strategy has been developed. The findings of this study can help determine how to deal with the process of documentation to improve the traceability of design decisions.

In this study, the two research questions are: what are important elements for the documentation of design decisions in civil engineering infrastructure projects? And how can these elements be implemented in civil engineering infrastructure projects to improve the documentation of design decisions?

Section 2 presents the theoretical framework that has been developed based on previous research on design decisions, documentation and information management. Section 3 presents the methodology used to achieve the research objective. Section 4 focuses on the analysis and explanation of the findings of the case studies and Section 5 describes the recommendations of this research, followed by the conclusions and limitations (Sections 6 and 7).

2. Theoretical background

To determine the elements for the documentation of design decisions, a literature study has been carried out. Literature on documenting design decisions in civil engineering has been reviewed. However, current research on documentation of design decisions in civil engineering projects appeared to be scarce. Therefore, literature in other disciplines was reviewed as well. In literature, why-, what-, who-, when-, where- and how aspects of documentation could be distinguished. In this section, we present a review of the literature.

2.1 Literature study

What

Literature addresses the specifics of what should be documented concerning design decisions. First, the design decision itself should be included explicitly in documentation because it describes the specific consideration made [12],[13],[14],[15]. In addition, not only a design decision itself but also the rationale behind the decision should be documented [6],[7],[16]. The rationale comprises the justification and process that has led to a design decision [17],[18]. This rationale is required to determine why a decision has been made, even after a long period of time or if the decision-maker has left the project [19]. Literature also suggests to additionally document the dependencies and interrelations between design decisions [20],[21]. This will provide project members with more insight in the cohesion of the entire system [22]. To further extend this system overview, Babar & Gorton [23] and de Lange et al. [24] propose to document a decision's context as well. The design objects and systems that are affected by a design decision are thus included explicitly in the documentation. The context will provide clarity on different project teams' involvement for a decision, guiding the communication and reflection between them [25].

Who

A documentation strategy is not complete without assigning responsibilities for both documentation and monitoring tasks [7]. To ensure a continuous and structured documentation of design decisions, the responsibility for this should be given to a specific person [1],[11]. Defining clear responsibilities prevents discussion on who is responsible for performing specific documentation tasks. This clarity will also improve the communication about design decisions, as it is clear for project members who should be contacted concerning a specific decision [26]. Furthermore, the responsibility for monitoring and checking the documentation should also be assigned clearly, to ensure verification on the existence and quality of documentation [2]. To prevent errors and inconsistencies, only project members responsible for documenting a specific decision are given rights to do so, similar for the rights to check and approve the documentation which should only be given to those who have these responsibilities [27],[28].

When

To ensure adequate documentation of design decisions, agreements on the moment of documentation should be made. It is stressed in literature that design decisions should be documented continuously during the project, preferably immediately after making decisions [10],[29],[30]. As Lee & Kruchten [31], Weinreich et al. [32], Tyree & Akerman [33] and Babar et al. [34] point out, immediate documentation is required to prevent the loss of information and knowledge. In addition, this documentation should then be evaluated and reviewed periodically [13]. The periodical review will ensure that documentation tasks are executed, and additionally the quality is monitored [35]. Farnham & Aslaksen [2] also suggest reviewing previous documentation at the start of a new project phase to provide the project members with a clear baseline. This baseline provides insight in what documentation is present and what information still needs to be retrieved.

Where

Literature states additional requirements for the documentation conditions concerning the location of documentation. As many parties are involved in civil engineering projects, the transfer of information should be considered [4]. Easily sharing documentation is considered very important in a project organization [1],[36]. However, in order to safeguard sufficient traceability and smooth transition of documentation across phases and people, good accessibility of the

documentation is essential [4],[35],[37]. Involved project parties should therefore be provided with good access to the latest documentation at all times [6],[38],[39]. Often a web interface or software application is recommended as storage and retrieval location for documentation, sometimes complemented by a repository or database [10],[40]. Within such an environment, the use of a pre-defined template or query could present structured and uniform documentation and improves retrieval, but it also supports the user in documenting decisions [2],[35],[37].

How

The first four aspects of documentation describe the content and conditions, but theory also addresses the format in which the documentation could be captured. Anumba et al. [10], Mena et al. [37] and Kruchten [41] suggest documenting design decisions and their dependencies in the form of an ontology. This is a network in which all properties and relations of design decisions are documented [24],[42],[43]. Another possibility to visualize the decisions is to connect them to their context. This could be visualized by placing design decisions in conceptual drawings or models [6],[44]. By doing so, a decision is shown directly connected to the objects in the design that it affects [27].

Implementing a strategy for the documentation of design decisions

Existing literature focused on civil engineering points out that difficulties might be encountered when implementing a strategy for the documentation of design decisions. Documentation requires time and effort of the project members, while benefits often cannot be perceived immediately [1],[2],[6]. Furthermore, a new approach might require training for the project members, however proper guidance is currently often not guaranteed [1],[37]. Additional difficulties occur because of the project-oriented, short-term and task-focused work culture of the civil engineering sector [6],[35]. The level of collaboration is generally low, while the number of involved parties is high [2]. On top of that, Van der Meer et al. [6] add that the documentation provided by the client at the start of the project is often uncertain and incomplete.

2.2 General overview

This literature review combines theory of the civil engineering discipline and of other disciplines. Therefore, it provides new input that is required to solve long-existing problems concerning the documentation of design decisions in civil engineering projects. First of all, it is important to not only document design decisions, but also their rationale, interrelations and context. This will provide a justification of why a decision has been made, but also shows the decision in relation to other decisions and its context. Because of this, project members will have more insight in the cohesion of the entire system. The responsibilities for both documenting and monitoring this documentation should be given to a specific person, so that all design elements are accounted for. Uniform documentation should be ensured by using a documentation environment in which the user can document in a pre-defined template. Civil engineering projects have many involved project parties, thus good accessibility to documentation for all parties is very important. To ensure continuous and complete documentation, design decisions should be documented immediately and this should be monitored by periodical reviews. At the start of each project phase, an assessment of previous documentation should be done to provide a baseline of all available information.

2.3 Theoretical framework

By means of this literature study, a theoretical framework has been developed that was used as a reference for both data collection and analysis. The theoretical framework is summarized in Table 1. As literature did not offer one conclusive framework for the documentation of design decisions, the framework has been developed with separate elements from different sectors. As coherence was not present in literature, case study research should be used to determine if cohesion between the elements of the theoretical framework could be found in practice. The relevance and existence of these elements in current practices should also be determined in the case studies. At last, the case study research should provide a better understanding of the different elements of the theoretical framework.

Table 1. Theoretical framework

Framework	Theoretical patterns	Sources
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	[6], [7], [12], [13], [14], [15], [16], [20], [21], [23], [24]
Who	There should be clear responsibilities assigned for the documentation	[1], [2], [7], [11]
	There should be clear responsibilities assigned for monitoring the documentation	[2]
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	[10], [29], [30], [31], [32], [33], [34], [35]
	There should be an assessment of all available documentation performed at the start of a new project phase	[2]
Where	There should be a documentation environment in which the user should document in a pre-defined template	[2], [4], [6], [10], [35], [37], [38]
	There should be good accessibility of the documentation for all involved project parties	[2], [4], [35], [37]
How	There should be a visualization of the design decisions and interrelations in their context	[6], [10], [27], [37], [41], [44]

3. Method

A theoretical framework has been established by performing a literature review. To be able to develop a strategy for the documentation of design decisions, this framework has been compared to current practices at project level. To establish a clear description of current practices, in which the contextual conditions play an important role, case study research was used [45],[46]. This type of research strategy has been chosen considering the three conditions for using a case study. First, the research question addressing the elements of documentation of design decisions is of exploratory nature, as the goal is to investigate current practices and to develop propositions in the form of a strategy. Furthermore, the projects studied are contemporary and the researchers have no control over the events [46].

This study on the documentation of design decisions has been performed in four civil engineering road infrastructure projects. Data were collected from these projects by means of interviews and document analysis. To ensure data triangulation, both these sources were used for cross verification of the collected data. The case studies have been compared to the theoretical framework by means of pattern matching. Patterns of similarities and differences have been modelled based on this reflection. Pattern matching was used in this research as it is recommended as strategy for qualitative analysis for case studies, as it will provide critical understanding of the subject [46],[47],[48]. This in-depth understanding was needed to define the improvements that are necessary in current practices. This enabled answering the second research question addressing the implementation of the documentation elements. This question is of prescriptive nature and based on the case study findings, recommendations in the form of a concept strategy are proposed. In this strategy, different elements concerning the documentation process are integrated. Also the manner in which those elements should be applied in practice is discussed.

3.1 Case studies

Four projects in the Netherlands were studied. The projects all focus on road infrastructure, more specifically national highways. The projects have been selected following the principle of *ceteris paribus*, in which multiple variables affecting a dependent variable are remained constant as much as possible. The cases were selected in such a way that the discipline, client, use of Systems Engineering (SE) and project objectives and sizes are as similar as possible. This enables an in-depth view on different practices concerning documentation of design decisions in projects with similar contexts and conditions. In all projects, Rijkswaterstaat (RWS) was the client and therefore SE was mandated because

RWS prescribes SE in all its engineering projects [49]. RWS is the executive body of the Dutch Ministry of Infrastructure and Water Management, and is responsible for water management and the construction and maintenance of public works, including waterways and roads. These four cases together provide a clear insight in the current practices of the documentation of design decisions in different stages of development in road infrastructure. For Dutch public road infrastructure, project organizations are obliged to follow the phases as described in the MIRT phasing and Transport Infrastructure Planning Act [50],[51]. MIRT is the multiple year program for infrastructure-, spatial planning- and transport projects of the Dutch government, provinces and municipalities. The Transport Infrastructure Planning Act describes the obligatory procedure for the development of road infrastructure. The projects are:

- Project A: extension of a station and widening of a highway, requiring the construction of two tunnels for the road. The phases studied were the Plan Development Phase, the Development and Contracting Phase, and the Realization Phase;
- Project B: widening of a highway and separation of traffic flows. This project was studied in the Development and Contracting Phase;
- Project C: widening of a highway, construction of a switch lane and development of a sunken road construction. This project was studied in the Plan Development Phase, and the Development and Contracting Phase;
- Project D: widening of a highway, with the ambition to develop a smart and sustainable road through extensive innovation. This project was studied in the Plan Development Phase.

This research focused on the involved project members of both the client and an engineering consulting firm that supported the client. Some of these project members have been involved in the projects in all phases, while others have only contributed to a specific phase, or part of a phase.

3.2 Data collection

During the case studies, current practices concerning the documentation of design decisions were compared with the theoretical framework that is described in Section 2. To collect data, interviews were conducted amongst team members of the four projects, supported by a documentation analysis. The theoretical framework was used as an outline for the interview format so that descriptive data on current practices were gathered for identical elements. These elements describe the what, who, when, where and how characteristics concerning the documentation of design decisions in the case studies. All participants were interviewed following a structured outline, but with addition of some probing questions if more information was required. Examples of the questions used are “was there a standardized procedure for the documentation of design decisions?” and “what are the major limitations of the current method for the documentation of design decisions?” The interviews were conducted in a one-on-one setting of participant and researcher and had a duration of one hour. Data have been collected from in total 29 participants; six for project A, six for project B, eight for project C and nine for project D. These participants have been selected for interviews based on their roles and responsibilities. Among others, technical managers of both the client and engineering consulting firm were interviewed for all projects. Furthermore, both people focusing on SE activities and those responsible for the design products have been interviewed. Several designers, technical advisors and design leaders representing different disciplines of both client and engineering consulting firm completed the list of interviewees.

3.3 Data analysis

The qualitative, descriptive data of the case studies consist of a documentation analysis and interview transcripts. Empirical patterns were formulated for each of the previously defined elements [45]. This condensed set of data was confronted with the theoretical framework by means of pattern matching. This method compares theoretical and empirical patterns and determines whether they match or do not match [29],[46],[47],[52]. The theoretical framework serves as the ‘theoretically ideal pattern’, the collected set of data is the ‘observed pattern’. The theoretical pattern thus describes how the documentation of design decisions should be done according to literature, while the observed pattern provides insight in how it is actually done in practice.

The confrontation either results in matches, partly matches or mismatches between the expected and observed patterns. These matches are assigned values on a three-point scale, a minus (-) indicating that the patterns do not match entirely, a zero (o) indicating a slight overlap and a plus (+) indicating a complete match. For each of the elements of the framework, the matches and mismatches were evaluated and explained, which provides an enhanced interpretation of the data.

The pattern matching analysis has been performed cross-case to compare the different projects and their confrontations with the theoretical framework [46]. Based on these findings, and explanations for the findings, recommendations for improving documentation of design decisions were proposed. These recommendations were formulated in the form of a concept strategy.

4. Results: case studies

This section summarizes the background of the four case study projects from which the empirical patterns are derived. These patterns resemble the elements as used for the theoretical patterns. Analysis of the results explains the differences and resemblances between theory and practice.

4.1 Case study results

Pattern matching was used to confront the theoretical framework and current practices [48]. Table 2 shows the summarized results of the pattern match between theoretical and empirical patterns for all projects. The confrontation was scored per element and is indicated by a three-point scale (-/o/+). By adding up the scores of all projects, the elements were ranked from best match to worst match. The explanations of the initial scores were used to determine the ranking if the combined score was equal for multiple patterns. Background data on matches for each separate project can be found in Appendix A, Tables 1, 2, 3 and 4.

Table 2. Summarized results of the pattern match for all projects

Element	Description	Project A	Project B	Project C	Project D	Rank
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	o	-	o	o	5
Who	There should be clear responsibilities assigned for the documentation	+	-	o	+	3
	There should be clear responsibilities assigned for monitoring the documentation	+	-	+	+	1
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	-	-	o	o	8
	There should be an assessment of all available documentation performed at the start of a new project phase	-	o	-	+	7
Where	There should be a documentation environment in which the user should document in a pre-defined template	o	-	+	+	3
	There should be good accessibility of the documentation for all involved project parties	+	-	+	+	1
How	There should be a visualization of the design decisions and interrelations in their context	-	o	o	o	5

- patterns do not match, o patterns match partly and + patterns match. The ranking indicates the correspondence of the pattern with literature, from best matches (1) to worst matches (8). Some patterns (1), (3) and (5) have a similar correspondence with literature and are thus ranked similarly.

4.2 Ranking the results

As the pattern match (Table 2) indicates, large differences between the results of the different projects emerge. Project D seems to score best on most of the patterns, and project B never performs up to the theoretical standard. The results were ranked from high to low, in correspondence with literature. Considering this ranking, the following most important conclusions can be drawn:

- Both good accessibility of documentation is considered (see Table 2-‘Where’- ranking 1) and clear responsibilities for monitoring documentation are assigned in three projects (see Table 2-‘Who’- ranking 1). Only in project B, no match between theory and practice could be observed for both these patterns. Two projects (A and D) are in keeping with theory concerning the division of responsibilities for documenting itself, and one is partly (C), see Table 2-‘Who’-ranking 3. The use of a documentation environment with pre-defined template is applied in projects C and D and for a part of the aspects of the documentation process in project A (see Table 2-‘Where’-ranking 3).
- Project B is the only project that does not document any of the aspects as suggested in literature (see Table 2-‘What’-ranking 5). For the visualization of design decisions and interrelations in their context, project A is the only project without any correspondence with theory (see Table 2-‘How’-ranking 5);
- Only in project D, a match between theory and practice could be observed concerning the documentation assessment. The other projects are only partly (B) or not in keeping with literature, see Table 2-‘When’-ranking 7. Immediate documentation and periodical monitoring were performed in some situations in projects C and D, but none of the projects showed practices comparable to theory (see Table 2-‘When’-ranking 8).

Based on the data, we could explain the findings. It appeared that good accessibility of documentation is currently considered in practice as long as clients require the use of a specific environment that contributes to traceability and structure in handling large SE projects (cases A, C, D). The analysis also indicates that assigning responsibilities for both documenting and monitoring this documentation is done because it is considered as common practice to handle the projects’ complexity. A pre-defined template for documenting design decisions is used to improve the quality of documentation sometimes, but users are given much freedom in completing it. The findings also show that the client plays an important role because documentation appeared to be more complete when the client puts emphasis and focus on documentation. The documentation of design decisions and rationale is considered in current practices, but the context of and interrelations between design decisions are not documented. The design decisions have been visualized in their context in some projects (cases B, C, D), however this could be further improved by additionally developing a visualization of the interrelations. The largest differences between current practices and literature are identified regarding performing a documentation assessment. It appeared that assessing previous documentation, which is provided by the client, is considered difficult because of the difference in power position between the client and the engineering consulting firm. As the client procures the project assignment, the engineering consulting firm is considered to meet the client’s requirements and report regularly on their progress. Even though they are able to assess the documentation of the client, they cannot demand effort of the client to improve or complement the documentation if this is not sufficient. Furthermore, a difference between literature and current practices is observed in performing periodical monitoring and immediate documentation. Currently, hardly any strict procedures for the moment of documentation are applied resulting in postponement of these tasks due to time-pressure.

4.3 Additional findings

In the interviews performed during the case studies, additional data were collected that were not used in the pattern matching analysis. These data provided a better understanding of the specific approaches that are already used or are absent in current practices. First of all, the project members stressed that guidelines for when a design decision needs to be documented are required because these are not present yet. Besides stressing the need for adequate documentation, the findings show that discussing the documentation during meetings is still needed to ensure that everyone becomes

familiar with the contents: documentation alone is not enough. Furthermore, project members indicated that often, based on experience, an overview of design decisions that will need to be made in a project phase could be developed already at the start of that phase. This enables a better overview of the design decisions and dependencies in terms of project schedule, and provides structure for those responsible. In addition to documenting, this structure could be used for planning and dividing the periodical monitoring tasks.

5. Towards a strategy for the documentation process

This section describes the recommendations. These have the form of a concept strategy, which is based on the findings of the cases. The concept strategy aims to improve the documentation process of design decisions in the civil engineering infrastructure sector. The proposed concept strategy describes what should be documented, who is responsible, when it should be documented, where it should be documented and how it should be documented. The pattern match of each case shows an overview of the similarities and differences between theoretical and empirical patterns. The case studies thus provide insight in the elements already covered in current practices, and those which could still be improved. Also, the findings indicate the relevance of and cohesion between these elements in practice.

This paragraph describes the specifications of the concept strategy, of which the visualization is shown in Figure 1. The extensive descriptions of the elements in the different levels are based on the data collected in the case studies. The different strategy levels are visually presented in Figure 2.

Because of the extent of the improvements following from the case studies, it is considered difficult to implement this in a project organization at once. Therefore, recommendations are described in the form of a concept strategy in which the elements are assigned to different levels that should be implemented subsequently. The base level describes the current practices at the engineering consulting firm being good accessibility of documentation and division of responsibilities. In the first level, the documentation of design decisions and their justification, the use of a pre-defined template, immediate documentation and periodical monitoring are explained and suggestions for their implementation are provided. The second level addresses the documentation of interrelations and context of design decisions, and possibilities for visualizing these aspects. The third level considers an assessment of all available documentation at the start of a new project phase. The levels should be implemented subsequently in that specific order. In each level, the depth of the documentation increases as the required elements have a higher complexity. The subsequent levels improve the documentation by adding relations and visualizations, but in order to do so the basic documentation level has to be acquired. The third level requires much insight of project members, to which execution of the previous levels contributes.

5.1 Current practices

The three elements that are generally included already in current practices, good accessibility (see Table 2; where; ranking 1) and responsibilities for both documenting and monitoring this documentation (see Table 2; who; ranking 1 and 3), are addressed in the base level. The concept strategy stresses the importance of a shared documentation environment. Furthermore, it describes the possibility of applying different user restrictions based on involvement in specific activities and project phases. Second, the importance of assigning responsibilities for monitoring documentation is stressed. As the results indicated, performing the monitoring is considered necessary. Third, also the distribution of responsibilities for documenting itself is described. The concept strategy suggests a distribution of responsibilities for different documentation activities that were identified in the case studies.

5.2 Level 1

First addressed in this level is the documentation of design decisions and rationale, because these elements are already partly implemented (see Table 2-‘What’-ranking 5), however also because these elements form the foundation required for the implementation of all other strategy elements. As documenting all design decisions is considered not desirable, indications for when a design decision needs to be documented are described. Furthermore, at the start, all known design decisions that will have to be made during the project have to be documented already. Secondly, the pre-defined

template in which these design decisions and rationale should be documented is addressed. The specifics of this template are suggested, based on the documentation elements described in the concept strategy. Finally, immediate documentation and periodical monitoring will have to be acquired in this level even though its performance is a large step from current practices (see Table 2-‘When’-ranking 8). The concept strategy distinguishes documentation during design activities and during meetings.

5.3 Level 2

Defining the interrelations and documenting these requires a better understanding of the project system by the user than is required for a design decision itself. Because of this, relations are introduced in the second level of the strategy. Justification of the relation is required as the findings demonstrated it is often unclear why decisions are related and how one affects another. Similar steps are included for defining and documenting the context of a design decision. Second, these new aspects of documentation should be visualized. The settings for these visualizations are to be accounted for by the software manager, so the description focuses on the implications for the project members and how the visualizations could be used in practice.

5.4 Level 3

The assessment of all available documentation at the start of a new project phase is addressed. This is included in the last level as findings indicate that performing this effectively could only be achieved if the assessors have a good understanding of what documentation should be available and what quality this should have. It is important that all design activities are postponed until the assessment is finished.



Figure 1. The concept strategy, showing all elements

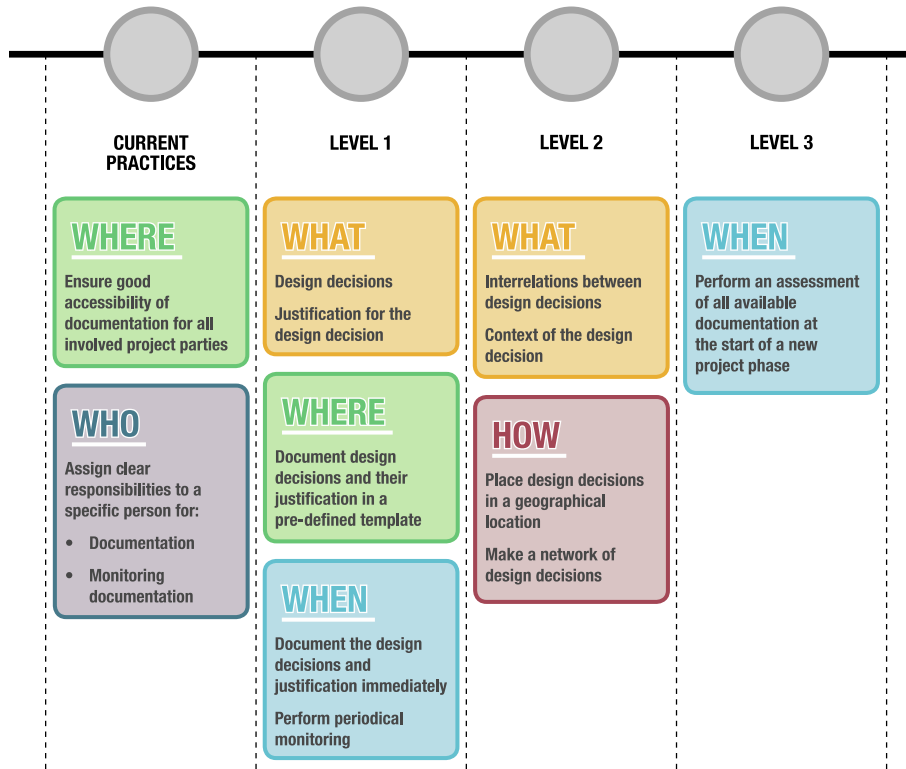


Figure 2. The strategy levels of the concept strategy

6. Conclusion

The documentation of design decisions is important as it provides insight in which decisions have been significant during the development of a project. However, in several studies, problems concerning the documentation of design decisions are mentioned, especially at the transitions between project phases or between different involved parties. For example, project members do not receive the required information, or it is provided too late, delaying work activities. Furthermore, approaches and formats to capture and manage information differ per organization or team, which makes tracing information a tedious and time-consuming task. Moreover, discussions in projects are repeated multiple times as no documentation can be provided based on which the discussion could be closed. Although these documentation problems are acknowledged in several disciplines, little attention is paid in literature to these problems in the context of civil engineering.

To identify the important elements of the documentation of design decisions in a civil engineering context, this research was conducted. It aimed to develop recommendations for improving the documentation process in civil engineering road infrastructure. These recommendations were proposed in the form of a documentation strategy. Coherence was not present in literature, so the case studies were used to determine if cohesion between the elements of the theoretical framework could be found in practice.

The relevance and existence of these elements in the case studies contributed to theory building on the documentation of design decisions and also helped formulate practical recommendations. Since the case study approach only allowed for theoretical generalization, we encourage other researchers to test and expand the theory in other contexts.

The findings demonstrate that good accessibility of documentation for all involved project parties is already considered in current civil engineering practices. This is mainly because of the requests made by the client for the use of a specific environment that contributes to ensuring structure and traceability in large SE projects. Furthermore, the division of responsibilities in practice for both documenting and monitoring this documentation are in keeping with theory. Project members explained these results by indicating that assigning these responsibilities was required to be able to handle the projects' complexity.

The documentation environments used in practice do provide pre-defined templates to document design decisions, but these templates leave more freedom to the user than those described in literature. Design decisions are documented in some of the projects studied, but often incomplete and without rationale that explains why the decision was made. These aspects were most complete in the project that started most recently. Project members who also participated in some of the other case study projects, indicated that they learned from previous experiences of those projects. Interrelations between design decisions and a decision's context, as described in literature, are missing in current documentation processes in practice. The suggestions that were provided in literature for visualizing the decisions in their context are observed in practice, but this could be complemented by additionally developing a visualization of the interrelations.

Assessing all previous documentation at the start of a new project phase is only done in the project that started most recently. Based on previous experience, this project team persisted in performing this assessment to prevent redoing activities. Other projects indicated that the assessment is considered difficult in practice because of high time pressure and the difference in power position of the client and engineering consulting firm. The moment of documentation is not in keeping with theory, as documenting is not done immediately. Also, no periodical monitoring is performed in practice that could ensure this immediate documentation.

Recommendations for the documentation of design decisions

To ensure successful application of the recommendations, barriers that could obstruct the implementation should be deducted or studied further. Tight project schedules form a threat to a successful implementation of the strategy. For example, performing the assessment of documentation would be obstructed, as deadlines require the design activities to commence already. Future research should study the influence of such an assessment on the project performance, so that the reclassification of time could be argued. Furthermore, the attitude of the designers in a civil engineering infrastructure project is considered a possible barrier. They might perceive the documentation process described in the strategy as an administrative burden, which distracts them from their design tasks, and thus obstructs them from performing it. Therefore, the added value and benefits of documenting design decisions also for them should be proven in practice. This will have a more positive effect on their incentives to document than requiring so from a managerial position.

7. Limitations and further work

This research has some limitations that should be pointed out. First, we compared current practices relative to a normative theoretical framework, but did not relate the documentation process to performance in terms of budget, client satisfaction or compliance to the schedule. It was not the intention to study the relation between the degree of documentation and project outcomes. The intention was to identify potential improvements in the documentation of design decisions and to develop a strategy for that. Nevertheless, it is a recommendation for future research to study the relation between the degree of documentation of design decisions and project outcomes.

Second, the projects used for the case studies were all large road infrastructure projects in the Netherlands in which the same engineering consulting firm and client were involved. Moreover, only four projects were studied. This reduces the generalizability of the findings for different types of projects and other organizations involved. Therefore, it is suggested to further study a broader variety of projects to improve and further refine our proposed documentation strategy.

Finally, related to the issue of generalizability, we suggest to address implementation of the strategy with attention and caution. Although we have validated our proposed strategy for documenting design decisions with several experts, it still is the first time that a documentation strategy has been developed for civil engineering infrastructure projects. The strategy should be further tailored to, and validated with, the specific situation and context where it is supposed to be implemented. Most likely, the context of other situations is different compared to the context in which we carried out the research.

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References

- [1] S. T. A. van den Houdt and J. L. M. Vrancken, "Rolling out Systems Engineering in the Dutch Civil Construction Industry. Identifying and Managing the Factors leading to Successful Implementation," *retrieved from repository.tudelft.nl*, pp. 1-9, 2013.
- [2] R. Farnham and E. W. Aslaksen, "Applying Systems Engineering to infrastructure projects," in *INCOSE Spring Conference*, Nottingham, UK, 2009.
- [3] L. Luo, Z. Liu, and M. Xie, "Comprehensive information management model of construction projects based on System Engineering methodology," in *International Conference on Construction and Real Estate Management*, Guangzhou, China, 2017.
- [4] B. Elliot, "Overcoming barriers to transferring systems engineering practices into the rail sector," *Systems Engineering*, vol. 15, no. 2, pp. 203-212, 2012.
- [5] S. Bathallath, Å. Smedberg, and H. Kjellin, "Managing project interdependencies in IT/IS project portfolios: a review of managerial issues," *International Journal of Information Systems and Project Management*, vol. 4, no. 1, pp. 133-145, 2015.
- [6] J. van der Meer, A. Hartmann, A. van der Horst, and G. Dewulf, "Challenges of using systems engineering for design decisions in large infrastructure tenders," *Engineering Project Organization Journal*, vol. 5, no. 4, pp. 133-145, 2015.
- [7] J. M. Chachere and J. R. Haymaker, "Framework for measuring the rationale clarity of AEC design decisions," *Journal of Architectural Engineering*, vol. 17, no. 3, pp. 86-96, 2011.
- [8] R. S. de Graaf, R. M. Vromen, and J. Boes, "Applying systems engineering in the civil engineering industry: an analysis of systems engineering projects of a Dutch water board," *Civil Engineering and Environmental Systems*, vol. 34, no. 2, pp. 144-161, 2017.
- [9] R. S. de Graaf, J. T. Voordijk, and L. van den Heuvel, "Implementing Systems Engineering in Civil Engineering Consulting Firm: An Evaluation," *Systems Engineering*, vol. 19, no. 1, pp. 44-58, 2016.
- [10] C. J. Anumba, R. R. A. Issa, J. Pan, and I. Mutis, "Ontology-based information and knowledge management in construction," *Construction Innovation*, vol. 8, no. 3, pp. 218-239, 2008.
- [11] P. Pirzadeh and H. Lingard, "Understanding the Dynamics of Construction Decision Making and the Impact on Work Health and Safety," *Journal of Management in Engineering*, vol. 33, no. 5, pp. 1-11, 2017.
- [12] R. Capilla, F. Nava, and J. C. Duenas, "Modeling and documenting the evolution of architectural design decisions," in *International Conference on Software Engineering*, Minneapolis, US, 2007.

- [13] H. Deng, Y. Wang, and J. Deng, "Study on decision information management and application during complex engineering system development," in *International Conference on Comprehensive Product Realization*, Beijing, China, 2007.
- [14] M. Küster, "Architecture-centric modeling of design decisions for validation and traceability," in *Software Architecture*, vol. 7957, K. Drira, Ed. (LNCS: Springer, Berlin, Heidelberg, 2013, pp. 184-191.
- [15] O. Zimmermann, J. Koehler, F. Leymann, R. Polley, and N. Schuster, "Managing Architectural Decision Models with Dependency Relations, Integrity Constraints, and Production Rules," *Journal of Systems and Software*, vol. 82, no. 8, pp. 1249-1267, 2009.
- [16] A. Jansen, J. S. van der Ven, P. Avgeriou, and D. K. Hammer, "Tool support for architectural decisions," in *The Working IEEE/IFIP Conference on Software Architecture*, Mumbai, India, 2007, no. 4-4: IEEE.
- [17] M. Bhat, K. Shumaiev, and F. Matthes, "Towards a framework for managing architectural design decisions," in *11th European Conference on Software Architecture: Companion Proceedings*, Canterbury, UK, 2017, pp. 48-51.
- [18] J. S. van der Ven, A. G. J. Jansen, J. A. G. Nijhuis, and J. Bosch, "Design Decisions: The Bridge between Rationale and Architecture," in *Rationale Management in Software Engineering*, A. Dutoit, R. McCall, I. Mistrik, and B. Paech, Eds.: Springer Berlin Heidelberg, 2006, pp. 329-348.
- [19] U. Zdun and R. Capilla, "Sustainable Architectural Design Decisions," *IEEE Software*, vol. 30, no. 6, pp. 46-53, 2013.
- [20] P. D. Borches Juzgado, "A3 Architecture overviews. A tool for effective communication in product evolution," Design, Production and Management, Faculty of Engineering Technology, University of Twente, Enschede, 2010.
- [21] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, *Engineering design: A systematic approach*. Springer-Verlag London, 2007.
- [22] A. MacCalman, H. Kwak, M. McDonald, and S. Upton, "Capturing experimental design insights in support of the model-based System Engineering approach," *Procedia Computer Science*, vol. 44, pp. 315-324, 2015.
- [23] M. A. Babar and I. Gorton, "A tool for managing software architecture knowledge," in *Sharing and Reusing Architectural Knowledge - Architecture, Rationale, and Design Intent*, Minneapolis, USA, 2007: IEEE.
- [24] J. de Lange, E. J. Oude Luttikhuis, and E. Lutters, "Networked Design Decisions in Balanced Life Cycles," *Procedia CIRP*, vol. 21, pp. 230-235, 2014.
- [25] T.-M. Hesse, A. Kuehlwein, and T. Roehm, "DecDoc: A tool for documenting decisions collaboratively and incrementally," in *1st International Workshop on Decision Making in Software ARCHitecture*, Venice, Italy, 2016: IEEE.
- [26] H. Dogan, M. J. Henshaw, and G. Ragsdell, "The risk of information management without knowledge management," *Journal of Information & Knowledge Management*, vol. 10, no. 4, pp. 393-408, 2011.
- [27] A. Tang, M. A. Babar, I. Gorton, and J. Han, "A survey of the use and documentation of architecture design rationale," in *5th Working IEEE/IFIP Conference on Software Architecture*, Pittsburgh, USA, 2005: IEEE.
- [28] R. Weinreich and G. Buchgeher, "Integrating requirements and design decisions in architecture representation," in *Software Architecture*, vol. 6285, M. A. Babar and I. Gorton, Eds. (LNCS: Springer, Berlin, Heidelberg, 2010, pp. 86-101.
- [29] R. D. Galliers and D. E. Leidner, *Strategic information management: challenges and strategies in managing information systems*, 3th ed. Oxford, UK: Butterworth-Heinemann, 2014.
- [30] U. van Heesch, V.-P. Eloranta, P. Avgeriou, K. Koskimies, and N. Harrison, "Decision-centric architecture reviews," *IEEE Software*, vol. 31, no. 1, pp. 69-76, 2014.

- [31] L. Lee and P. Kruchten, "A tool to visualize architectural design decisions," in *Quality of Software Architectures. Models and Architectures*, vol. 5281, S. Becker, F. Plasil, and R. Reussner, Eds. (LNCS: Springer, Berlin, Heidelberg, 2008, pp. 43-54.
- [32] R. Weinreich, I. Groher, and C. Miesbauer, "An expert survey on kinds, influence factors and documentation of design decisions in practice," *Future Generation Computer Systems*, vol. 47, pp. 145-160, 2015.
- [33] J. Tyree and A. Akerman, "Architecture decisions: Demystifying architecture," *IEEE Software*, vol. 22, no. 2, pp. 19-27, 2005.
- [34] M. A. Babar, I. Gorton, and B. Kitchenham, "A framework for supporting architecture knowledge and rationale management," in *Rationale Management in Software Engineering*, A. H. Dutoit, R. McCall, I. Mistrík, and B. Paech, Eds.: Springer, Berlin, Heidelberg, 2006, pp. 237-254.
- [35] M. F. Noordin, L. A. Burhanuddin, and A. Kanaa, "The current state of information management and knowledge management in the Malaysian construction industry," *Australian Journal of Basic and Applied Sciences*, vol. 6, no. 6, pp. 138-145, 2012.
- [36] R. Maier and T. Hädrich, "Knowledge management systems," in *Encyclopedia of Knowledge Management*, D. G. Schwartz, Ed.: Springer Berlin Heidelberg, 2005, pp. 442-450.
- [37] Á. Mena, F. López, J. M. Framiñan, F. Flores, and J. M. Gallego, "XPDR project: Improving the project documentation quality in the Spanish architectural, engineering and construction sector," *Automation in Construction*, vol. 19, no. 2, pp. 270-282, 2010.
- [38] A. Jansen, J. Bosch, and P. Avgeriou, "Documenting after the fact: Recovering architectural design decisions," *Journal of Systems and Software*, vol. 81, no. 4, pp. 536-557, 2008.
- [39] J. Varajão, "The many facets of information systems (+projects) success," *International Journal of Information Systems and Project Management*, vol. 6, no. 4, pp. 5-13, 2018.
- [40] C. S. Greeven and S. P. Williams, "Enterprise collaboration systems: addressing adoption challenges and the shaping of sociotechnical systems," *International Journal of Information Systems and Project Management*, vol. 5, no. 1, pp. 5-23, 2017.
- [41] P. Kruchten, "An ontology of architectural design decisions in software-intensive systems," in *2nd Groningen Workshop on Software Variability Management*, Groningen, The Netherlands, 2004, pp. 54-61.
- [42] Z. Ming *et al.*, "Ontology-based representation of design decision hierarchies," *Computing and Information in Engineering*, vol. 18, no. 1, pp. 1-12, 2016.
- [43] E. J. Oude Luttikhuis, J. de Lange, E. Lutters, and R. ten Klooster, "Evolving Product Information in aligning Product Development Decisions across Disciplines," *Procedia CIRP*, vol. 29, pp. 573-578, 2015.
- [44] F. F. Brussel and G. M. Bonnema, "Interactive A3 Architecture Overviews," *Procedia Computer Science*, vol. 44, pp. 204-213, 2015.
- [45] M. B. Miles, A. M. Huberman, and J. Saldana, *Qualitative Data Analysis: A Methods Sourcebook*. Thousand Oaks, USA: SAGE, 2013.
- [46] R. K. Yin, *Case Study Research: Design and Methods - Second Edition* (Applied Social Research Methods). London, UK: SAGE, 1994.
- [47] G. Cao, S. Clarke, and B. Lehaney, "The need for a systemic approach to change management: a case study," *Systemic Practice and Action Research*, vol. 17, no. 2, pp. 103-126, 2004.
- [48] T. Hak and J. Dul, "Pattern matching," in *Encyclopedia of Case Study Research*, A. J. Mills, G. Durepos, and E. Wiebe, Eds. Thousand Oaks, USA: SAGE, 2009.

- [49] Rijkswaterstaat, "Procesbeschrijving Systems Engineering voor RWS Projecten. Version 2.1.3," 2017.
- [50] Ministry of Infrastructure and Water Management, "Spelregels van het Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT)," 2016.
- [51] *Tracéwet*, 2017.
- [52] D. T. Campbell, "Degrees of freedom and the case study," *Comparative Political Studies*, vol. 8, no. 2, pp. 178-193, 1975.

Appendix A. Background data on matches for each separate case study project

Table 1. Pattern match Project A

Framework	Theoretical patterns	Empirical patterns	Match	Explanation
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	There is limited explicit documentation of design decisions and rationale is only implicitly documented. No interrelations or context of design decisions are documented	o	Design decisions and rationale are documented implicitly in specific reports as this was requested by client. There were no requirements set for explicit documentation in a digital online documentation environment, so due to time pressure and short-term deadlines this was not done to a large extent. Interrelations are regarded as logical derivatives of design activities, thus were not documented specifically
Who	There should be clear responsibilities assigned for the documentation	Responsibilities for documentation are assigned to specific people	+	Responsibilities were assigned to prevent elements of the project not being accounted for. However, this responsibility was for the documentation in the final reports
	There should be clear responsibilities assigned for monitoring the documentation	Responsibilities for monitoring the documentation are assigned to specific people	+	Responsibilities were assigned to prevent elements of the project not being accounted for. However, this responsibility was for monitoring the documentation in the final reports
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	Documentation is not done immediately and no periodical procedure for monitoring was used	-	Designers perceive the immediate documentation as administration without obvious benefits, so they are not willing to change to that new manner of working even though management would prefer it. No hard rules for moment of documentation are set
	There should be an assessment of all available documentation performed at the start of a new project phase	No assessment of all available documentation was performed at the start of a new project phase	-	An assessment of all documentation has not been performed as the engineering consulting firm is considered not to be in the position to set requirements for the client at that moment
Where	There should be a documentation environment in which the user should document in a pre-defined template	The design decisions are documented in a digital online documentation environment in a template, and in free form in meeting minutes and reports	o	Administrators of the digital online documentation environment decided to specify several fields in the template to ensure uniform documentation. However, user is free to leave parts of template open. In reports, users could document in his own manner as this is considered most easy for them
	There should be good accessibility of the documentation for all involved project parties	The digital online documentation environment ensures good accessibility of the documentation for all project parties	+	The digital online documentation environment is considered as standard in the industry for management large SE projects, so its use was prescribed by the client
How	There should be a visualization of the design decisions and interrelations in their context	Design decisions are not placed in context but only documented as derivative of meetings or implicitly in text, interrelations are not documented at all	-	Textual documentation was considered sufficient to determine to which element of the design the decisions belong

Table 2. Pattern match Project B

Framework	Theoretical patterns	Empirical patterns	Match	Explanation
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	There is only implicit documentation of design decisions and rationale is missing. No interrelations or context of design decisions are documented	-	The project team was not focused on traceability of information in the early phases of the project and thus did not document extensively. Interrelations and context are regarded as logical derivatives of design activities, thus were not documented specifically
Who	There should be clear responsibilities assigned for the documentation	Responsibilities for documentation are not clearly assigned to specific people	-	Because documentation was considered less important in design phases no responsibilities were assigned. In the contract development, actions do have responsible persons but these are not focused on documentation
	There should be clear responsibilities assigned for monitoring the documentation	No responsibilities are assigned for monitoring the documentation	-	In the contract development, focus is on delivering specifics contract and thus not on documentation and monitoring
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	Documentation is not done immediately and no periodical procedure for monitoring was used	-	Designers do not think the benefits of immediate documentation outweigh the effort and time it takes. No hard rules for moment of documentation are set
	There should be an assessment of all available documentation performed at the start of a new project phase	Standard RWS procedures are used for assessment of some documentation at the start of a new project phase	o	The RWS procedures (gates and KAd ¹), focusing on the most important design documents, are considered sufficient for assessing necessary documentation according to management
Where	There should be a documentation environment in which the user should document in a pre-defined template	The design decisions are documented implicitly and in free form in memos and meeting minutes	-	In memos and meeting minutes, users could document in his own manner as this is considered most easy for them
	There should be good accessibility of the documentation for all involved project parties	Not all required documentation could be traced by project members	-	As traceability of information was not considered in early project phases, this documentation is missing or hard to trace by current project members
How	There should be a visualization of the design decisions and interrelations in their context	A selection of design decisions is captured in posters of objects in context, interrelations are not documented at all	o	To structure the project and gain overview, posters are made for each object in which the most important decisions are discussed

¹ KAd (Kwaliteitsborging Aanbestedingsdossier) is the formal review performed by a dedicated team of Rijkswaterstaat to ensure the quality of the tender documentation.

Table 3. Pattern match Project C

Framework	Theoretical patterns	Empirical patterns	Match	Explanation
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	There is documentation of design decisions and rationale. No interrelations or context of design decisions are documented	o	The traceability of design decisions and rationale was not considered in the design project phases, so documentation is done at a later moment as justification of the design was required by client. Interrelations and context are regarded as logical derivatives of design activities, thus were not documented specifically
Who	There should be clear responsibilities assigned for the documentation	Responsibilities for documentation are assigned to specific people for a large part	o	Responsibilities were assigned to prevent elements of the project not being accounted for. However, some elements do not have a specific responsible person for documentation because of lack of discipline
	There should be clear responsibilities assigned for monitoring the documentation	Responsibilities for monitoring the documentation are assigned to specific people	+	Responsibilities were assigned to prevent elements of the project not being accounted for. However, this responsibility was generally for monitoring the documentation in the final reports as the documentation was not fully explicit
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	Documentation is not done immediately, but documentation is monitored by discussion in design meetings	o	In two-weekly design meetings, design decisions have to be discussed and are at least documented then, documentation is not done immediately because of lack of discipline and time
	There should be an assessment of all available documentation performed at the start of a new project phase	No assessment of all available documentation was performed at the start of a new project phase	-	An assessment of all documentation has not been performed as the engineering consulting firm is considered not to be in the position to set requirements for the client at that moment and feels they should be able to trust the client in this
Where	There should be a documentation environment in which the user should document in a pre-defined template	The design decisions and rationale are documented in a pre-defined template of lines of reasoning	+	For the lines of reasoning a template was discussed to ensure that all elements were documented at the same level. However, the exact completion of the templates was different for each discipline as else it would require too complex alignment
	There should be good accessibility of the documentation for all involved project parties	Procedure for storage documentation ensures good accessibility for all project parties	+	Communication between different project parties was considered very important, so focus was put on good accessibility of all documentation
How	There should be a visualization of the design decisions and interrelations in their context	Design decisions are connected to the contextual geographical location, interrelations are not documented at all	o	Design decisions are connected to the location in design drawings to create insight in the context of the decision

Table 4. Pattern match Project D

Framework	Theoretical patterns	Empirical patterns	Match	Explanation
What	There should be documentation of design decisions and their interrelations, context and the rationale behind decisions	There is documentation of design decisions, rationale and context. No interrelations of design decisions are documented	o	Design decisions, rationale and context are documented explicitly as traceability was in the project focus from the beginning due to the level of innovation required in the project. Interrelations are regarded as logical derivatives of design activities, thus were not documented specifically
Who	There should be clear responsibilities assigned for the documentation	Responsibilities for documentation are assigned to specific people	+	Responsibilities were assigned to prevent elements of the project not being accounted for. The explicitness of documentation improved assigning responsibilities
	There should be clear responsibilities assigned for monitoring the documentation	Responsibilities for monitoring the documentation are assigned to specific people	+	Responsibilities were assigned to prevent elements of the project not being accounted for. The explicitness of documentation improved assigning responsibilities
When	There should be immediate documentation of design decisions, rationale, interrelations and context which should be ensured by periodical monitoring	Documentation is done immediately during meetings, during design activities it is not. No periodical procedure for monitoring was used	o	Meetings are directly documented in a digital online documentation environment to prevent additional documentation activities afterwards. For other documentation, designers perceive the immediate documentation as administration without obvious benefits, so they are not willing to change to that new manner of working even though management would prefer it. No hard rules for moment of documentation are set
	There should be an assessment of all available documentation performed at the start of a new project phase	An assessment of all available documentation was performed at the start of a new project phase	+	Management instructed that the design could not start until all required documentation was collected and assessed, to prevent unnecessarily redoing activities
Where	There should be a documentation environment in which the user should document in a pre-defined template	The design decisions are documented in a digital online documentation environment in a template	+	Administrator of the digital online documentation environment decided to specify several fields in template to ensure uniform documentation. However, user is free to leave parts of template open
	There should be good accessibility of the documentation for all involved project parties	The digital online documentation environment ensures good accessibility of the documentation for all project parties	+	The digital online documentation environment is considered as standard in the industry for management large SE projects, so its use was prescribed by the client
How	There should be a visualization of the design decisions and interrelations in their context	Design decisions are connected to the contextual geographical location, interrelations are not documented at all	o	Design decisions are connected to objects in the digital online documentation environment which are visualized in the GIS viewer ¹ to create insight in the context of the decision

¹ GIS (Geographical Information System) is an information system in which (geographical) data is captured, stored, analyzed and displayed.

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