MSc. Thesis in Construction Management and Engineering

Boosting fitness for use of configuration management databases by user specific views

Kije Zijlstra

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"Intelligence is the ability to adapt to change"

Steven Hawking

Boosting fitness for use of configuration management databases by user specific views

Research to improve effective and efficient use of CMDB

MASTER OF SCIENCE THESIS

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Kije Zijlstra

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Executive summary

The construction industry is heavily transitting from paper-based systems engineering to Model-Based Systems Engineering, especially in the development phase of large infrastructure projects. The implementation of software is considered by many to be a complex, and for some end-users the implementation of software makes performing their daily tasks harder than before. Nevertheless, the expectation is that software gives the possibility to manage and present information more on point. In more detail, the configuration management database which is considered to be one of the central systems in the Model Based Systems Engineering vision is considered to be not fit for use for all participants. Observations made clear that the implementation of software is lacking in different fields such as: strategy on information management, availability of knowledge on practical processes and participants information needs. As a result, the following main research question has been formulated.

How to improve the fitness for use of configuration management databases used in the development phase of large infrastructure projects?

In order to contribute both academically and practically, a thorough study has been conducted. The design cycle methodology has been used with a focus on the implementation evaluation phase. The implementation evaluation phase consists of the deep dive into the systems engineering methodology in the shape of a context study. Consequently, a literature study has been performed to improve academic understanding of the information needs of engineers. Furtermore, a practical empirical study has been conducted in which the information needs and experiences of the end-users are studied by interviews. With the findings from the implementation evaluation, a set of solutions have been proposed. These solutions have been validated in the last section.

A context study has been conducted in order to identify the systems engineering processes. The systems engineering processes mainly consists of requirements analysis, functional analysis, design synthesis, verification and validation, system analysis and control, and interface management. Based on the Integral Project Model, the technical management department has the biggest stake in the processes in the development phase of large infrastructure projects. The systems engineering information management development is called Model Based System Engineering and consists of several phases. In the as-is situation of systems engineering information management, the information management is done in a relational database that focusses on entities and the relations between entities. However, some aspects of the transition towards more complex Model Based Systems Engineering provides the possibility to manage information in more detail and provide the corresponding level of detail of specialty engineers in the shape of user specific views. The complex information management in Model Based Sytsem Engineering requires the need to formalization of information in order to effectively and efficiently manage information. In addition to the formal structuring of information, different abstraction levels are introduced that consists of different levels with different functions: generic, abstract and conrete. The abstraction level empowers the user to manage objects on both abstract and concrete levels.

The literature study has been performed in order to conceptually understand the information needs of users, activities of engineers, workarounds and the fitness for use assessment. The literature study shows that the information needs of engineering professionals are characterised by the following variables: individual demographics, context, frequency, predictability, importance and complexity. Furthermore, the literature shows that engineers mainly visit information systems for decision-making processes. In addition, the literature also shows that the participants could implement workarounds for their purposes. At last, the experiences of the individual are assessed and structured by a framework that considers the following themes: accessibility, security, relevancy, completeness, consistency, timeliness and logical coherence.

A practical study in the shape of interviews has been conducted to identify the information needs and the corresponding fitness for use. Six interviews have been conducted on the specialty engineer (3x) and the lead engineer (3x) wich are being part of the technical management. These roles are chosen as they are involved in the same processes but have different tasks and responsibilites and therefore different information needs and experiences in the system. The specialty engineer mainly focus is on the design synthesis process in which the specialty engineer has deviating information needs that vary in complexity, frequency, importance and predictability. The fitness for use results show that the specialty engineers have difficulties with using the system in any process whereas the lead engineers predominantly consider the system fit for use. A set of core problems regarding presentation and structuring are listed.

The design of solution chapter focuses on the information needs of the specialty engineer in the design synthesis and system analysis processes as in these processes the system appears to add the most value. The problems observed in the practical study are translated in goals, requirements and solutions. The main solutions consist of physical relations between objects, abstraction levels, conceptual data model, one stop page and custom query. The solutions are elaborated on in more detail. 1) Physical relations are established between physical objects to improve the obtainability of adjacent objects when on a particular object page by adding hyperlinks. Furthermore, the relations make the information model smarter and empower the user to present information in different compositions. 2) The abstraction levels consists of three sub models (generic, abstract and concrete) which all have a different function. At first, the generic model stores and manages the general conceptualisation of particular objects. Second, the abstract level manages the abstract decomposition and the project specific information. At last, the concrete model manages the concrete relations between objects by adding name, code or number. The abstraction levels contribute to the manageability of the information. 3) The approach to a conceptual data model is presented to clarify the management and storage of information in separate sub models. Nevertheless, the sub models are linked by an inheritance relation. 4) The one stop page has direct impact on the work practices of the specialty engineer as object specific information needs to be obtained from these pages. Besides, these pages need to provide the required context on the particular object. The one stop page meets the information needs that are predictable, recurrent and non complex. 5) The custom query empowers the user to retrieve information from the database that is not presented in a fixed composition like the one stop page. The user can develop the query and determine which entities are requried in what composition and quantiy. The custom query meets the unpredictable, new, complex and urgent information needs.

The practical relevance of the solutions has been tested by an use case example of a tunnel project. The use case example proposed a simplified tunnel project in which the information model is developed, the information is presented on the one stop page and a practical example is shown of the custom query. Furthermore, each solution further specifies the practical contributions to the working practices of the users and the improved fitness for use. At last, all solutions have been tested by validation in the shape of an expert panel. Suggestions for small improvements are implemented and bigger improvements are listed in future research.

Samenvatting

De bouwindustrie is onderhevig aan een digitale transformatie, voornamelijk in de ontwikkelingsfase van grote civiele infrastructuurprojecten. Waar de systems engineering methodiek decennia geleden haar intrede heeft gedaan in de ontwerpfase van grote infrastructuurprojecten ligt de focus nu op het koppelen van de losstaande systemen. Deze trend staat bekend als model gebaseerd werken waarin ontwerp informatie in een centrale database gemanaged wordt zodat alle betrokkenen erbij kunnen op ieder moment. Deze digitale ontwikkeling vraagt veel van de gebruikers die in principe opgeleid zijn om objecten te ontwikkelen of hier het management voor uitvoeren. Een van de centrale softwaresystemen is het configuratie managementsysteem waarin ontwerpprocessen zoals eisenanalyse, raakvlakkenmanagement en verificatie activiteiten centraal worden gemanaged. Naast het managen van deze processen, welke worden uitgevoerd door de ontwerpleider, functioneert het systeem ook als bron van de ontwerpinformatie die benodigd is door de technisch specialisten. Desondanks ervaren de technisch specialisten het systeem vaak als gebruiksonvriendelijk en worden alternatieve routes geïmplementeerd om aan de juiste informatie te komen met de nodige gevolgen zoals: gelimiteerde transparantie, inconsistente informatie, veiligheidsrisico's en niet gestroomlijnde doorontwikkelingsprocessen. In dit onderzoek wordt onderzocht wat de functie is van het configuratie managementsysteem, hoe de informatiebehoefte geanalyseerd kan worden, hoe het configuratiesysteem wordt ervaren, waarom men alternatieve routes gebruikt en hoe dit opgelost kan worden. Hiervoor is de onderstaande hoofdvraag geformuleerd.

Hoe kan de bruikbaarheid verbeterd worden van configuratie management databases die worden gebruikt in de ontwikkelingsfase van grote infrastructuurprojecten?

Om zowel een bijdrage te leveren aan de academische als de praktische wereld worden beide onderdelen behandeld. Hiervoor is de design cycle gebruikt als leidende methodiek waarin de focus hoofdzakelijk ligt op de implementatie evaluatie. De implementatie evaluatie is opgedeeld in een context studie, literatuurstudie en praktische studie. Deze opdeling is gemaakt om een goed beeld te krijgen van de context waarin het softwaresysteem gebruikt wordt, wat de literatuur zegt over de behoefte van gebruikers en hoe de ervaring van softwaresystemen geanalyseerd kan worden. Tot slot wordt in de praktische studie de werkelijke informatiebehoefte en de werkelijke ervaring van eindgebruikers geanalyseerd. De problemen die naar voor komen uit de interviews worden opgelost in het hoofdstuk ontwerpoplossing.

De context studie is uitgevoerd om duidelijk te krijgen welke processen er uitgevoerd dienen te worden volgens de systems engineering methodiek. De systems engineering methodiek bestaat voornamelijk uit een eisenanalyse, functionele analyse, ontwikkelen, verificatie en validatie, systeemanalyse en controle en raakvlakkenmanagement. Gebaseerd op het Integral Project Management Model is het technisch management hoofdzakelijk betrokken in de ontwikkelingsfase van een project. Hiernaast is er ook aandacht besteed aan de trend van Model-Based Systems Engineering waarbij de focus is gelegd op de toenemende complexiteit van informatiestructurering en wordt er aandacht besteed aan de mogelijke kansen om de toenemende complexiteit te beheersen aan de hand van maatwerk van informatiepresentatie. In de context studie wordt ingegaan op de bijbehorende structurering, de modules die worden gemanaged en de relaties die

onderling gelegd dienen te worden in het desbetreffende informatiesysteem. Ook wordt er aandacht besteed aan het formaliseren van de conceptualisatie van de inhoud van informatiemodellen door middel van een ontologie. Dit heeft als doel om de subjectiviteit met als gevolg mogelijke communicatieproblemen te vermijden. Tot slot wordt er nog aandacht besteed aan de verschillende abstractieniveaus (generiek, abstract en concrete sub modellen) die ieder een specifieke functie vervullen. De implementatie geeft de mogelijkheid om efficiënter en effectiever informatie te managen.

De literatuurstudie is uitgevoerd met als doel te begrijpen hoe informatiebehoeften geanalyseerd dienen te worden, wat de gevolgen zijn van het onvoldoende dienen van de informatiebehoeften en hoe de ervaringen geanalyseerd kunnen worden. De informatiebehoefte kan geanalyseerd worden aan de hand van de volgende variabelen: individuele demografie, context, frequentie, voorspelbaarheid, belang en complexiteit. Hiernaast stelt de theorie dat als gevolg van het niet voldoen aan de informatiebehoeften als gevolg kan hebben dat tijdverlies optreedt en er mogelijk zelfs alternatieve routes worden gevonden om informatie te verkrijgen buiten het initiële systeem om. Tot slot worden de ervaring van de individuen geanalyseerd aan de hand van het kader waarin de volgende onderwerpen worden behandeld: toegankelijkheid, veiligheid, relevantie, compleetheid, consistentie, tijdigheid en logische samenhang.

In de praktische studie wordt de opgedane kennis gebruikt om informatie op te halen uit interviews. Hiervoor zijn zes interviews gehouden met zowel drie technische specialisten als drie ontwerpleiders, welke beide onderdeel zijn van het technische management. De gekozen rollen zijn over het algemeen betrokken bij dezelfde objecten en processen. Alleen de taken en verantwoordelijkheden verschillen en hierbij dus ook de activiteiten die uitgevoerd worden in het configuratiesysteem. De resultaten van de interviews worden opgedeeld in drie groepen: processen waar men bij betrokken is, de informatiebehoefte die men heeft in deze activiteiten en de ervaring die men heeft in de CMDB. De resultaten van de interviewanalyse laten zien dat technisch specialisten problemen ondervinden in het gebruik van het softwaresysteem terwijl ontwerpleiders het systeem als geschikt voor gebruik beoordelen. Daarnaast laten de eerste twee onderdelen van de interviews zien dat de specialisten hoofdzakelijk betrokken zijn bij het ontwerpproces en de systeemanalyse. Vervolgens kan ook geconcludeerd worden dat de informatiebehoeften van de specialisten verschillen per proces in de variabelen voorspelbaarheid, frequentie, urgentie en complexiteit. Waar de specialist in het ontwerpproces voornamelijk behoefte heeft aan niet complexe informatie zoals een object en de context van het object, is de specialist geneigd om in de systeemanalyse een complexe behoefte te hebben omdat hiervoor verschillende samenstellingen van object informatie gepresenteerd dienen te worden. Daarnaast ervaren de technisch specialisten problemen omtrent effectief en efficiënt gebruik als gevolg van de overvloedige informatiepresentatie, de beperkte structurering van relaties tussen objecten, inconsistente informatie en niet actuele presentatie van informatie. De problemen fungeren als basis voor de aanzet tot conceptuele oplossingen.

De aanzet van de conceptuele oplossingen richten zich op de problemen die naar voren zijn gekomen uit de interviews met de focus op de technisch specialist. De geïdentificeerde problemen zijn getransformeerd naar doelen, eisen en vervolgens naar losstaande oplossingen. Dit heeft geresulteerd in vijf oplossingen: fysieke relaties tussen objecten, abstractieniveaus, conceptuele datamodel, one stop page en de custom query. De oplossingen worden een voor een toegelicht. 1)

De fysieke relaties tussen objecten dienen ervoor om de verkrijgbaarheid van informatie te verhogen vanaf de object pagina omdat er hierdoor links aangebracht kunnen worden. Daarnaast maken de relaties het datamodel slimmer en geven deze relaties de mogelijkheid om data in andere samenstellingen te verkrijgen. 2) De abstractieniveaus bestaan uit drie sub modellen (generieke model, abstracte model en concrete model) die ieder een specifieke functie hebben. Allereest, het generieke model beheert de algemene objectinformatie. Ten tweede, het abstracte model beheert de abstracte decompositie en project specifieke informatie. Tot slot, het concrete model beheert de concrete relaties tussen concrete objecten, dus object met een naam, code of nummer. De abstractieniveaus dragen bij aan de beheersbaarheid van de informatie voor iedere rol. 3) De aanzet voor een conceptueel datamodel is gepresenteerd om duidelijk te maken dat de informatie los beheerd wordt en dat er erfenis relaties zijn geplaatst tussen de sub modellen. 4) De one stop page is direct van invloed op de technisch specialist omdat dit de plek is waar object specifieke informatie verkregen kan worden. Daarnaast moet de informatie en links op deze pagina de gewenste context bieden. De object pagina voorziet in de voorspelbare, terugkerende, niet complexe informatiebehoefte. 5) De custom query geeft de gebruiker de mogelijkheid om informatie te verkrijgen dat niet wordt gepresenteerd in de gewenste samenstelling zoals de hiervoor genoemde object pagina. De gebruiker kan zelf invoegen welke entiteiten en relaties gepresenteerd dienen te worden. De custom query voorziet in de onvoorspelbare, nieuwe, complexe en urgente informatiebehoefte van de gebruiker.

De praktische relevantie van de oplossingen zijn weergegeven in een use case over een tunnel. In het use case voorbeeld wordt een versimpeld tunnelproject behandeld waarin het informatiemodel ontwikkeld en gebruikt wordt. Het ontwikkelingsproces wordt stapsgewijs toegelicht en de informatiepresentatie wordt gedaan aan de hand van de one stop page van een camera en specifieke custom query. Hiernaast wordt per onderdeel ook toegelicht hoe de oplossing in praktijk bijdraagt aan een verbeterde bruikbaarheid van het systeem. Tot slot zijn de oplossingen getest met behulp van een validatie in de vorm van een expert panel waarbij de suggesties voor verbeteringen zijn opgedeeld in twee categorieën: categorie voor suggesties zijn geïmplementeerd in de huidige oplossing en een categorie met verbeteringen voorgesteld voor vervolgonderzoek.

Contents

List of figures

List of tables

Definitions

Abstract decomposition	Decomposition (has part relations) of abstract objects consisting of so called 'object types'
Configuration Management Database	Systems engineering information software system in which up-to-date configuration information is stored, controlled, and managed in a single source of truth
Concrete decomposition	Decomposition (has part relations) of concrete objects which are physical objects in the real-world
Controlled vocabulary	List of terms that have been enumerated explicitly
Plan report	Report that is to be presented to the client, written in addition to design of construction when proposal (Dutch: ontwerpnota)
Fitness for use	Emphasises the importance of taking a consumer viewpoint of quality because ultimately it is the consumer who will judge whether or not a product is fit for use
Governmental authorities	(Semi-) Government organisations such as: Ministry, provinces, municipality, Rijkswaterstaat, Prorail
Entities	Refers to something that has unique and separate existence such as objects, requirements, interfaces, activities, end products
Individuals	An instance referring to an object as an instance of a class,
Interoperability	The ability of effective interaction between enterprises based on the exchange of information' as defined in ISO 11354
Model Based Systems Engineering	Formalised application of modelling to support systems engineering process and corresponding information management beginning in the conceptual development phase and continuing throughout development and later life cycle phases
Ontology	Formal explicit conceptualisation of a problem domain shared by stakeholders
Perspective	View of certain role
Relatics	Information system used in practice in the infrastructure construction industry to manage systems engineering processes

Single source of truth	Practice of structuring information models and associated data schema such that every data element is mastered (or edited) in only one place
Snowball effect	A situation in which an action or event cause many other similar actions or events and increases in size or importance at a faster and faster rate
Specialisation tree	Abstraction mechanism which relates to a concept to other more general and to other less general concepts by an 'Is a' relation
System decomposition	End results of the decomposition process in which a complex problem or system is broken into parts (subsystems) that are easier to conceive, understand, program, and maintain
Taxonomy	Science of categorisation, or classification, of things based on a predetermined system
Viewpoint	Combination of a role, actor, agent or knowledge sources and a view or perspective
Workaround	A goal-driven adoption or other change to one or more aspects of the existing information system to overcome the impact of obstacles to achieve the desired level of efficiency and effectiveness

Abbreviations

CMDB	Configuration Management Database
DO	Definitive Design (Definitief Ontwerp)
ERD	Entity Relationship Diagram
INCOSE	International Council on Systems Engineering
LFV	Logical Function Fulfiller (Logische Functie Vervuller)
MBSE	Model Based Systems Engineering
OTL	Object Type Library
PVR	Minimum clearance outline (Dutch: Profiel van Vrije Ruimte)
SE	Systems Engineering
SMART	Specific, Measurable, Achievable, Realistic and Time
UO	Execution Design (Dutch: Uitvoeringsontwerp)
V&V	Verification & Validation
VO	Preliminary Design (Dutch: Voorlopig Ontwerp)
WBS	Work Breakdown Structure

1 Introduction

Over the last few decades, the development of large infrastructure projects has changed in several ways. Projects have become increasingly complex due to improving sophisticated technical solutions as well as rising management complexities. As a result, systems engineering, a relatively new methodology to manage complex projects, originated from U.S. army and aerospace industry, has been embraced by the industry. Furthermore, with the rise of the internet, digitalisation in information management has increased significantly. This paradigm shift was partially caused by a changed focus of the Dutch government who has repelled several governmental activities since 2000. Due to the major changes in institutions, public opinions and limited financial capabilities, governments increasingly cooperate with private parties in the construction industry. As a result, the Dutch government shifted from a solution-oriented approach towards a problem-oriented approach. Therefore, contractors are not solely responsible for the execution but also for phases such as design, engineering, construction, and maintenance. This directly affects the working practices of both the clients (governmental authorities) and the contractors resulting in a solution in the shape of the systems engineering methodology. Systems engineering focuses on the fulfilment of the clients' requirements throughout the projects' lifecycle. Last decades, systems engineering has been increasingly adopted by all bodies of the Dutch government including projects of Rijkswaterstaat.

Megaprojects such as large infrastructure projects are characterised by a complex web of different objects, phases, processes and activities, contracts, specialised actors, and requirements. The information creation and information exchange that takes place in the complex web of actors is becoming digitalised. As seen in other industries, digital transformations in information management have changed business processes significantly raising the opportunity for innovation and optimisation. Although it took a while for the conservative construction industry to acknowledge the benefits of digital transformation, the industry is in the process of fully embracing the new working methods and technologies. The major trend of linking information systems and aligning systems engineering processes is called Model-Based Systems Engineer (MBSE) (See chapter 2.2 for more information). As part of the MBSE application, the Configuration Management Database (CMDB) (See chapter 2.2.2 for more information) has been introduced in which the particular systems engineering processes are managed. In combination with the continuation of automation and digitalisation in the construction industry, measures are to be studied to improve information management (McKinsey, 2019) (Roland Berger, 2016). This research aims for identifying and understanding the end-users' information needs in the systems engineering processes. This will be done by analysing systems engineering processes in detail, identifying the role specific information needs as well as identifying the role specific experiences in the CMDB. At last, solutions are proposed to improve the fitness for use of the CMDB.

1.1 Problem statement

Developing major infrastructure projects by the systems engineering methodology is characterised by a variety of highly dynamic, iterative, sequential, and dependent processes, which lead to an abundance of complex information throughout the project life cycle. The systems engineering processes mainly performed in the development phase are requirements analysis, functional analysis, design synthesis, verification processes, and system analysis and control. The exploratory study shows that drawbacks are observed in the implementation of systems engineering. Holt and Perry state that the main reasons for drawbacks in systems engineering implementation can be boiled down to complexity, lack of understanding and communications problems (Holt & Perry, 2017). Houdt appoints the availability, quality and alignment of systems engineering tools between stakeholders as an important factor for systems engineering implementation (van den Houdt, 2013b).

The systems engineering information creation and management is predominantly performed in the systems engineering tool (Configuration Management Database: CMDB). The purpose of the CMDB is to offer a single source of truth in a project by storing, sharing and managing project information in a central place (Relatics, 2016). However, the exploratory study shows several problems with the systems engineering tool regarding the fitness for use and the information creation (Appendix A). The fitness for use of a system is considered to be limited when it doesn't serve the users information needs (Rosemann et al., 2004) (Wang & Strong, 1996). Weinschel identified two principal factors that discourage the use of electronic resources: 1) difficult to use and 2) fail in meeting problem oriented information needs (Weinschel et al., 1986). Participants in the development phase of large infrastructure projects need to solve problems and require information that is related to the topic and can be easily obtained. The incremental character of information creation could result in an increasing information load (Pennington & Tuttle, 2007). The burden of a heavy information load will confuse the individual, affect his or her ability to set priorities, and make prior information harder to recall (Schick et al., 1990). As a result, the decision-making performance decreases (Chewning & Harrell, 1990). In practice, Van den Houdt argues that individuals are having a non positive attitude towards the application of SE because: they do not perceive the benefits, potential benefits are not entitled to them and have insufficient information and/or tools to accomplish their SE tasks (van den Houdt, 2013a). In addition, Van Ruijven states that the limited interoperability of systems engineering information between parties leads to ineffective communication (van Ruijven, 2019).

In order to prevent from ineffective communication, measures are implemented such as workarounds in the shape of the traditional communication routes. Alternative systems such as Word or Excel are implemented or experts are requested for information (Azad & King, 2008) (Appendix A). The phenomena of workarounds might go as far as bypassing the formal information system entirely for the intended purpose resulting in lacking information system success (Koopman & Hoffman, 2003) (Delone & McLean, 1992) (Appendix A). There are several critical consequences to the use of workarounds such as security issues, limited transparency, inconsistent data, and negative impact on project organisation processes. The implementation of workarounds maintains the ineffective communication status quo. To finalise, it is observed that a variety of participants in large infrastructure projects experience drawbacks in the fitness for use of systems engineer information management tools as their information needs are not satisfied effectively and efficiently.

1.2 Research objective

The goal of this research is to improve the fitness for use of the CMDB in the development phase of large infrastructure projects by identifying the information needs of the particular users. The objective of this research is to identify the tasks in particular processes, identify the information needs in these processes, and identify the problems that users experience in the fitness for use of the CMDB. At last, conceptual solutions are proposed to improve the fitness for use by meeting the information needs of the particular users.

1.3 Knowledge gap

Systems engineering information management in the CMDB in the development phase of large infrastructure projects is a step in the transition towards fully embracing MBSE. Current studies on the management of systems engineering information in a CMDB focus on macro (organisational) level instead of the micro (individual) level (van den Houdt, 2013a) (van Ruijven, 2019). As a result, there is limited knowledge and information available on the perceptions of the individuals in the systems engineering process. For example, there is no information available on the tasks and responsibilities division of the users, the information needs in the particular tasks and responsibilities and the assessment of the experiences in the information system. Furthermore, there is also limited information on how to assess these for engineers and managers. Therefore, this research focusses on deep understanding of existing systems engineering practices as well as the information needs and experience in the system that is used in practice (Kim et al., 2019). To finalise, this research will also identify solutions on how to solve problems that are observed with the fitness for use of the CMDB.

1.4 Research questions

Research question

How to improve the fitness for use of configuration management databases used in the development phase of large infrastructure projects?

Sub questions

1- How are systems engineering processes managed in a configuration management database?
2- Which aspects of Model-Based Systems Engineering could contribute to fitness for use of the CMDB adopted in the development phase of large infrastructure projects?
3- Which variables characterise role specific information needs of engineering specialists and engineering managers?
4- How to analyse the fitness for use of a configuration management database used in the development phase of large infrastructure projects?
5- What is the perceived fitness for use in the configuration management database used in the development phase of large infrastructure projects?
6- How to incorporate identified role specific information needs to improve fitness for use?

1.5 Methodology

To improve understanding of the artifact and the experiences of the users, an exploratory study has been performed prior to the main research. For the exploratory study interviews have been conducted on the experiences of the different types of users. Based on these results, a more detailed problem evaluation was required on the context which led to the implementation of design science. Design science evaluates and designs an artifact in context by the design cycle. The design cycle represents a subset of the steps taken in the engineering cycle. In Figure 1, the steps of the design cycle are marked with blue arrows consisting of the implementation evaluation/problem investigation, treatment design and treatment validation. The last step: treatment implementation (grey arrow), is excluded from the design cycle. The design cycle consists of two main research strategies: the problem orientation and evaluation research and the solution-oriented research. This research primarily focuses on the problem orientation and evaluation orientation as no knowledge is present on the practical experiences of users and the context in which the information system is used. However, the research will continue with the solution-oriented approach. Below the phases are specified in detail. Explorative study is added to the graphic as explorative interviews are conducted.

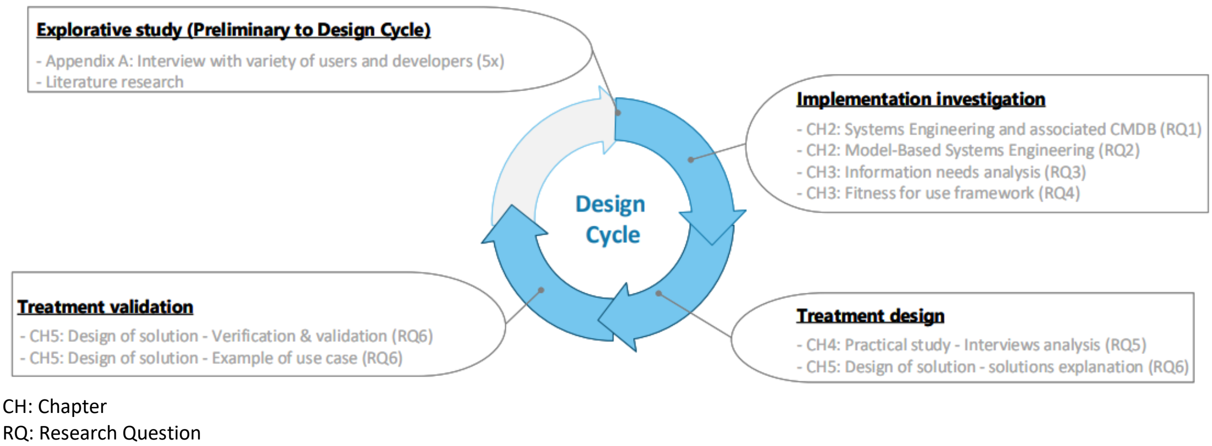


Figure 1 Design cycle (Wieringa, 2014)

Phase 1 – Implementation evaluation/problem investigation

The artifact considered in this research is already implemented for a decade in large infrastructure projects. Therefore, the focus of phase 1 is on the implementation evaluation. The implementation evaluation is subdivided into a context study, literature study and practical study. These chapters cover the processes, stakeholders, information management, information needs and information system assessment. At first, a context study is performed to understand the systems engineering processes, corresponding tasks performed and related users in systems engineering processes. Furthermore, the information management concepts have been discovered by elaborating on the as-is information management as well as the information modelling methods in MBSE. Second a literature study has been conducted on the information seeking process and the information needs variables to analyse the particular information needs. Furthermore, the fitness for use considers the understanding of the general concept, the consequences of not satisfying the information needs and the experience of the end users in the CMDB. Thirdly, the practical study elicits the experiences of the stakeholders by interviews and assess the results by a thematic framework. The results of the interviews are subdivided into three parts: processes, information needs and experience. The results of the interviews are the particular division of tasks and responsibilities per role, the information needs per process per role and the fitness for use per role.

Phase 2 – Treatment design

The desired properties of the treatment are based on the results of the implementation evaluation. The results of the empirical study are summarised in phase 1 and transformed into goals, artifact requirements and solutions. The analysis of the interviews show that the problems are mainly present at the specialty engineer in a particular set of processes. A variety of solutions are proposed ranging form presentation solutions that serve the various information needs to structuring solutions that enable meeting the presentation solutions.

Phase 3 – Treatment validation

The goal of the treatment validation is establishing a design theory of an artifact in context to predict the fitness for use in the original context. The treatment validation is done based on the requirements set in the treatment design. Consequently, the use cases considered are tested by an expert opinion in a panel. The expert panel, which consists of several experts in the role of specialty engineer, assesses the treatment by the framework assessment that is used as well in the interviews. Furthermore, a use case example is presented that shows the benefits for the users.

1.6 Thesis outline

Chapter 1 – Introduction

In the introduction the general composition of the report is considered. The introduction chapter consists of the problem statement, knowledge gap, research question and methodology.

Chapter 2 – Context study

The context study elaborates on the detailed systems engineering processes in the development of large infrastructure projects and the information modelling concepts that are present in Model Based Systems Engineering. The context study focusses on the as-is situation in information modelling as well as on technological developments.

Chapter 3 – Literature study

The literature study focusses on the general concept of professionals that have information needs in performing their tasks. Furthermore, the general concept of experiences of end users in information systems are considered by the fitness for use and the phenomena of workarounds.

Chapter 4 – Practical study

The practical study elaborates on the results of the interviews conducted on the users of the CMDB. The interview results are subdivided into tasks and responsibilities, information needs and fitness for use. The interview data is analysed by the information needs characteristics and fitness for use dimensions. At last, the results are presented by clarifying the core problems.

Chapter 5 – Design of solution

The design solutions chapter focusses on the specialty engineer in the process of design synthesis and system analysis. The core problems identified are considered as input for the development of the solutions. The design of solution presents the design process and solutions as well as a use case example and verification validation

Chapter 6 – Discussion

The discussion chapter elaborates on the practical and theoretical implications, limitations, and practical recommendations and future research.

Chapter 7 – Conclusion

The conclusion presents a summary of the sub questions as well as an answer to the main research question. The ends with a practical and theoretical contributions.

2 Context study

Systems engineering and systems engineering software are relatively new developments in the conservative construction industry. The systems engineering processes are managed in a CMDB, which is part of the transition towards Model Based Systems Engineering (MBSE). In this chapter the systems engineering processes are explored as well as the current information management software and the concepts of model-based information management and exchange.

SQ 1 *How are systems engineering processes managed in a configuration management database?*

SQ 2 *Which aspects of Model-Based Systems Engineering could contribute to fitness for use of the CMDB adopted in the development phase of large infrastructure projects?*

2.1 Systems engineering

Systems engineering is a methodology that is broadly implemented in the engineering disciplines of organisations in various engineering industries. The aerospace and military industry initially developed the methodology back in the 50s to solve complex engineering issues. After other industries such as automotive followed suit, the Dutch construction industry hitched on as well from 2000. Despite a general understanding of the methodology, discrepancies remain on the implementation of systems engineering between industries. The concept of systems engineering appears to be ambiguous as it can be defined as a process, profession or perspective (Ramo, 2006) (Eisner, 2008). The International Council on Systems Engineering (INCOSE), which is the most important agency in the industry, defines systems engineering as a perspective by "an interdisciplinary approach and means to enable the realisation of successful systems". "It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem" (INCOSE, 2012). To create awareness for the challenges in implementing, managing, and executing the methodology, this paragraph will elaborate on the fundamentals of the systems engineering methodology, the activities that are to be performed as well as the roles and corresponding responsibilities of these roles. As the approach of the methodology might slightly differ per industry, the latter topics are specifically considered for the civil construction industry.

2.1.1 Systems engineering life cycle processes

Systems engineering makes use of systems thinking principles for the engineering of products or projects. Therefore, the full package of systems engineering life cycle processes are presented in an integral overview, see Figure 2. Applying the full package is not required to apply systems engineering successfully (INCOSE, 2012). The universal system life cycle processes consist of the following four process groups: technical processes, technical management processes, agreement processes and organisational project-enabling processes. Each process group consists of multiple processes which are presented in the same figure. Despite the enumeration there is no ranking in the processes. These processes are executed concurrently, iteratively, and recursively throughout the entire life cycle of a system. For this research, especially the technical processes and technical management processes are relevant as these processes focus on the project specific development phase. See below a short explanation on the system life cycle processes:

- Technical processes: focuses on the technical processes related to the system that is being delivered, concerning specific parts of a project.
- Technical management processes: processes that enhance managing the complexity of the technical processes concerning projects in particular.
- Agreement processes: processes that capture the relations between supplier and acquirer
- Organisational project-enabling processes: processes that enable the organisation to develop and manage complex systems.

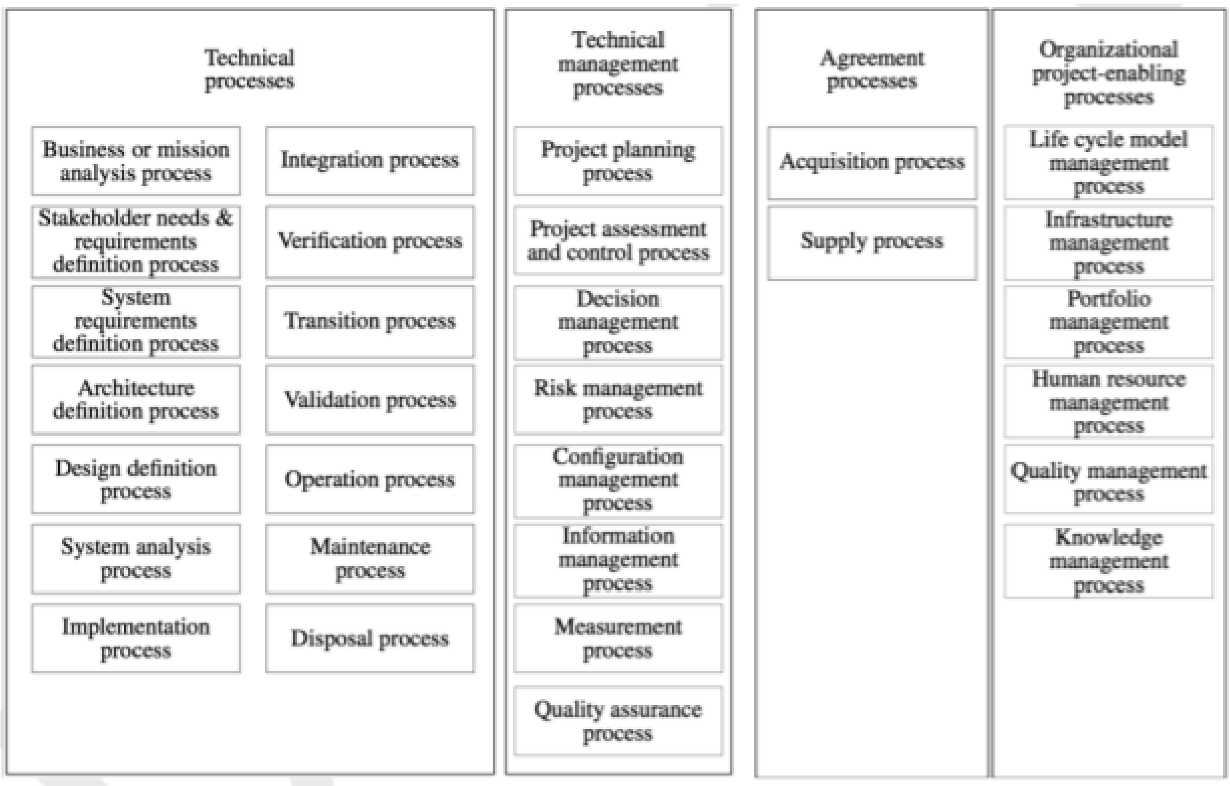


Figure 2 System life cycle processes (ISO/IEC/IEEE 15288, 2015)

2.1.2 Systems engineering in civil construction industry

As stated in the latter, systems engineering has a long and proper track record in managing complex engineering systems. The industries in which systems engineering has been applied, a higher level of trust between client and contractor is experienced. This resulted in a more cooperative character and long term relationship which again leads to an increased level of standardisation and optimisation over project boundaries (van den Houdt, 2013b). These advantages are the motivation for implementation of systems engineering in the civil construction industry in the Netherlands as well. The systems engineering methodology has attracted attention from the major governmental organisation (Rijkswaterstaat) and engineering associations resulting in an industry standard implementation report, the Leidraadse SE (Leidraadse SE, 2013). The goal of introducing systems engineering is to develop a successful system as an integral solution to a complex problem. In case of the Dutch civil construction industry, the implementation should contribute to the traceability of requirements, effectiveness of the working process and an increasing suitability (van den Houdt, 2013b). Achieving this goal is possible when the following subordinate goals are realised: exploring problem statements, scoping problem statement, and characterizing the problem. Focussing on these goals will result in the following: understanding of clients' needs, balancing of superior performance, application of technology and overall balance in conflicting objectives (van den Houdt, 2013a).

Projects executed according to the systems engineering methodology are subdivided into the following 5 phases: concept, development, execution, maintenance, and demolition see the V-model presented in Figure 3. The process of decomposing is performed to specify the project into a level of detail that is manageable. The process of integration takes place in the execution phase of a project. In practice in large infrastructure projects, the development phase is a part of a larger process that is presented in Appendix B. In Figure 3, the development phase is represented by a few steps of decomposition, in practice these steps are considered to be the VO, DO and UO phases. The development phase is a top down process in which the following four processes are considered: requirements analysis, design synthesis, verification and validation, and system analysis and control (Department of Defense, 2001).

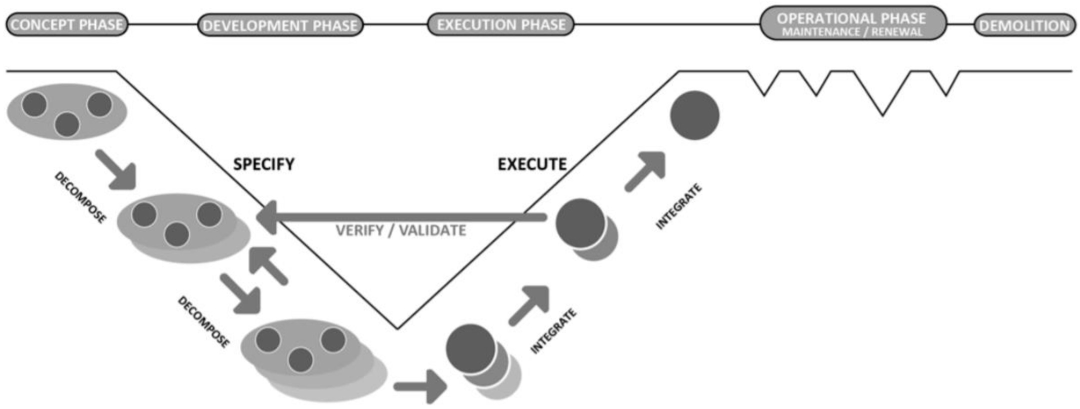


Figure 3 The V-model and life cycle of a civil construction project (van den Houdt, 2013b)

2.1.3 Systems engineering processes and activities

The main systems engineering processes consists of requirements analysis, functional analysis and allocation, design synthesis, verification and validation, and system analysis and control, see Figure 4. In the SE methodology iterations take place at any level of detail between the requirements, functionalities, and objects. Capturing of requirements determine the solution space in which the system should fit (Leidraadse SE, 2013). Furthermore, this paragraph presents other relevant systems engineering supporting processes such as interface management and configuration management (Department of Defense, 2001) (BAM, 2008). The requirements analysis unravels the client needs whereas the design synthesis considers appropriate solutions with the solution space set. Information management of these processes take place in the CMDB; therefore, the individuals are dependent on the system.

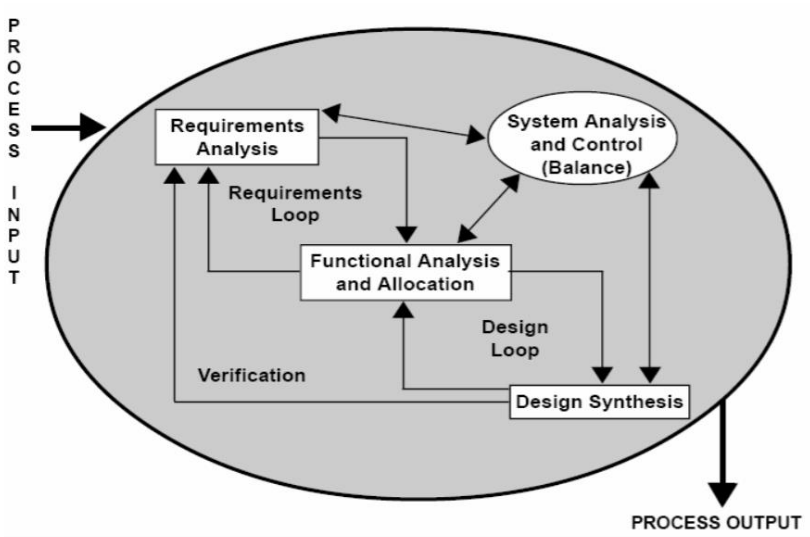


Figure 4 The systems engineering process (Department of Defense, 2001)

2.1.3.1 Requirements analysis

The purpose of the requirements analysis is to transform the client needs into controllable and manageable requirements. The requirements analysis is a vital process in the systems engineering process as it functions as the base of the configuration, which is touched on in paragraph 2.1.4.2. The configuration of the system can be subjected to changes as requirements are added, removed, or changed. Houdt identified the following activities as part of the requirements analysis (van den Houdt, 2013b).

Requirements elicitation

Requirements elicitation is the process of researching and discovering requirements of the intended system at different sources from various customers, users or stakeholders (Rowel & Alfeche, 1997). These requirements could be dynamic as the client needs or the environment might change, therefore, these must be identified, controlled, and managed as well. Although large infrastructure projects are initiated and led by major governmental organisations, local authorities might have location specific needs.

Analysis of the requirements

The requirements specification supplied by the client at the start of the project is often specified on a high level in all different categories. Therefore, the requirements need to be structured. To have an effective and efficient systems engineering process, the requirements specification input need to be analysed. The decomposed requirements always need to be coupled to the original requirements. As each requirement has a specific purpose, the following requirement types considered are: functional, aspect, object, interface and process (BAM, 2008).

Determination of appropriate level of detail

Preliminary to the start of the project, the requirements analysis determines the proper level of detail. Different levels of detail are present in requirements. Levels of detail present: policy, user requirements, performance requirements, construction requirements, material requirements, building material requirements. Both the requirement types and levels are presented in a matrix and are consequently made more detailed by deriving new requirements (BAM, 2008).

Specification of requirements

In certain projects clients might have developed the functional requirements in far detail whereas in other contracts the contractor needs to start from the problem. The design solutions are presented in the Contractor Supply Specification see Figure 5. The solution space is often determined by the following factors: physical limitations, laws and regulations, available time and budget (van den Houdt, 2013a).

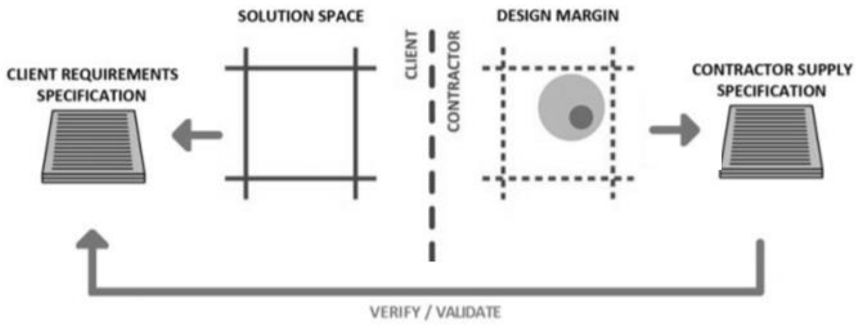


Figure 5 Client requirements specification vs. contractor supply specification (Leidraadse SE, 2009)

Managing complexity of the system

The complexity of the system needs to remain manageable. Decomposing a complex system into manageable parts ensures a better controllability and traceability. Nevertheless, dividing the system into smaller parts results in managing smaller objects and increasing number of relations and interfaces between the decomposed requirements. It is vital to the process, especially in the development phase, that requirements and interfaces are kept up-to-date and are aligned mutually. The number and type of requirements could change throughout the project, see Figure 6. New requirements need to be tracked so that an optimal solution is found according to the clients' specifications.

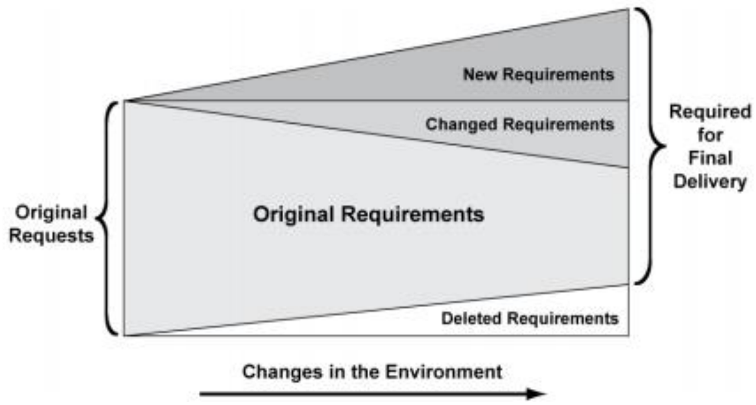


Figure 6 Dynamic environment of requirements (INCOSE, 2012)

2.1.3.2 Functional analysis and allocation

The purpose of the functional analysis and allocation is to convert the requirements analysed in the previous step into functionalities. The specialty engineer requires the functionalities to understand what the system must do, how well and which constraints are present. The functionalities are decomposed into lower-level functionalities and form the base for the determination of physical objects. The activities performed in the functional analysis and allocation are presented below.

Defining system in functional terms

Functionalities are based on the requirements that are determined, especially the higher-level performance requirements. However, these functionalities need to be decomposed into subfunctions. Consequently, these (sub)functions will be the functional and performance design criteria or constraints.

Structuring and allocating of the functionalities to system decomposition

The functionalities form the base of the system decomposition in which the structure of the physical objects is listed, see Figure 7. Obviously, both decompositions need to be balanced meaning that each level has its own allocation link. A physical object can be allocated to multiple functions and a functions can be allocated to multiple physical objects (Leidraadse SE, 2013).

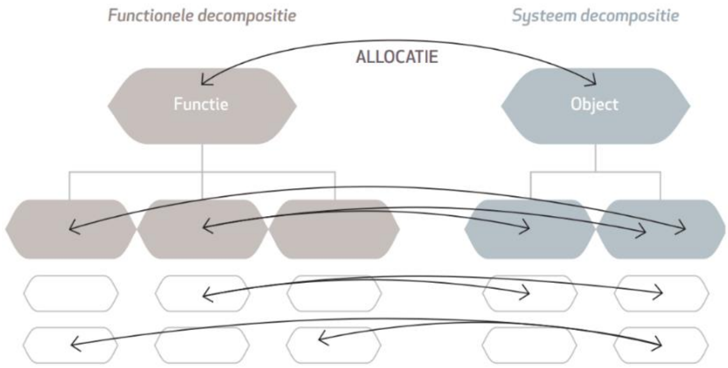


Figure 7 Function-Physical object allocation

2.1.3.3 Designing synthesis

The purpose of the design synthesis is to develop a concrete and feasible solution that meets the clients' requirements. The design synthesis is the last step in the systems engineering process graphic presented in Figure 4 and encompasses the process of defining the intended product in terms of the physical architecture. The physical architecture is developed based on the functional description which is the output of the functional analysis, albeit with an interplay between the two (BAM, 2008). Each time the physical architecture is developed in more detail, the functional analysis could also be developed until a certain level has been reached. The physical architecture functions as the base for design definition documentation, such as, specifications, baselines, and Work Breakdown Structures. In case of the discovery of design issues that require re-examination of the initial decomposition, performance allocation or even higher-level requirements might need to be changed which are called 'design loop' in Figure 4 (Department of Defense, 2001). Houdt stipulates the designing process by the following phases: generation of feasible variants, selecting the optimal variant using trade studies and further development of the chosen variants (van den Houdt, 2013a).

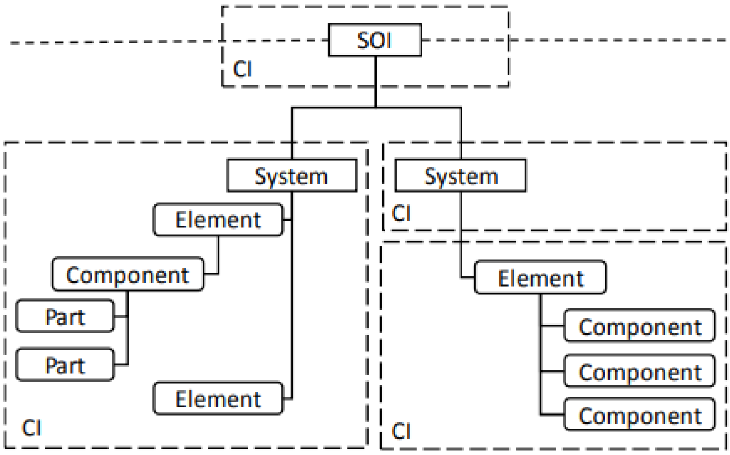


Figure 8 Schematic representation of system decomposition

Method for designing

The design can be made for the whole system as well as for a part of the intended system. The design base information required contains a wide range of information (BAM, 2008):

- Design starting points (project requirements)
- Standards and directives (indirectly responsible for requirements, although not listed in the system)
- Binding and non-binding documents
- (Derivative) Requirements (originate from client needs and derivate requirements originate from other requirements)
- Functionalities (originate from requirements)
- Interfaces
- Environment (to estimate loads)
- Schematisations and calculation methods

The design base should provide the specialty engineer with sufficient information to perform the design of the specific object. In fact, the activity the specialty engineer is performing can be on object level, subsystem level or system level. The corresponding steps to be made could be trade studies, see 2.1.4.3. The compositions in which the objects are to be designed are modular designs. Modular designs are the grouping of components that perform a single independent function or single logical task. In practice modular design relates to modules with different functions for which different teams are responsible, such as, the Logical Function Fulfillers (LFV) in a tunnel like surveillance, light supply, energy supply.

Continue design and secure in design nota

The chosen variant needs to be worked out to the required detailed level in the specific (sub)phase of the project. The goal is to prevent the design or execution from any haziness. The results are captured in a design nota, which is requested by the client, including the required drawings, calculations and explanation and accountability (BAM, 2008).

Check for completeness

After the project is completed, an overview is required of the performed and planned verifications and inspections of the project, see next paragraph. The end result of the design process in which systems engineering is performed results in final documents in which the relations between the Work Breakdown System (WBS), Object Breakdown System (OBS) and requirements trees are explicitly captured (BAM, 2008).

2.1.3.4 Verification & validation

Verification and validation (V&V) are independent procedures used together to check whether the product or system meets the needs and requirements of the client. Verification and validation activities are performed in each phase process mentioned in previous paragraphs. The verification process can be performed in any activity or at any system level. The verification process is performed to show compliance with the system requirements defined by the stakeholders needs. The verification and validation process consists of three phases, which are considered below.

Preliminary to the project

Preliminary to the project, verification and validation plans are to be developed in a V&V management plan. The verification plan is to be developed for each object. The verification plan mainly stipulates the role, the activity, the time of performance, verification method and link to corresponding work package.

Throughout the project

Throughout the project, the design results need to be verified in each (sub)-phase. Bundling of the requirements is recommend for overview. The verifications are captured in a verification report that mainly stipulates the following information per requirement: verification result, document of proof, description of relevant risks and assigned role that has performed the verification (BAM, 2008).

After the project

After the project is finished, a clear and traceable overview is required of the planned and executed verifications as well as checks of inspection for the whole project. Selections of this information is made per object and per phase to support traceability for future control. The final product is called a verification note and should include: traceability of requirement to original client needs, link to inspection report, overview of deviations, link to corresponding work package (BAM, 2008).

2.1.3.5 System analysis and control

System analysis and control consists of a variety of processes. As the name suggests, the process consists of the standalone activities: analysis and control. Analysis includes trade studies, effectiveness analysis and design analysis to evaluate alternative approaches. The alternative studies should satisfy the technical requirements and provide an in depth quantitative base for selecting performance, functional and design requirements (Department of Defense, 2001). The system analysis and control process consist of processes that are stipulated below in paragraph 2.1.4.

On the other hand, control suggests management activities to secure and retain quality. The management activities include risk management, data management and performance based progress management (Department of Defense, 2001). In practice, development activities are often controlled by a Work Breakdown Structure (WBS), which includes an object, activity, and end-product. For organisation purposes the WBS establishes a coordinated, complete, and comprehensive view of program management. For business purposes the WBS establishes a structure for budgets and costs estimates. For technical purposes the WBS provides a structure for e.g. organizing risk, enabling configuration management and developing work packages (Department of Defense, 2001).

2.1.4 Supporting systems engineering processes

There are several supporting systems engineering processes of which some are discussed in this report. At first, interface management is considered to be a relevant process. Furthermore, the principles of the configuration management process are explained.

2.1.4.1 Interface management

Systems are part of other systems and systems can be subdivided in subsystems. The interactions between these systems are interfaces. The definition of an interface is as follows: "An interface is a boundary where, or across which, two or more parts interact" (Wheatcraft, 2010). Interfaces are one of the main causes of why systems engineering goes wrong due to complexity, lack of understanding and communication problems (Davies, 2019). Interface management supports to understand the systems boundaries of the system of interest as it helps to understand the dependencies of the system of interest with other systems and ensures the compatibility between systems (Wheatcraft, 2010). See below in Figure 9 a graphical representation of subsystems with internal interfaces (small grey between with squares) and external interface between the subsystems (grey arrows between grey squares). As in practice not all interfaces are being reported, the circles drawn across the lines represent these.

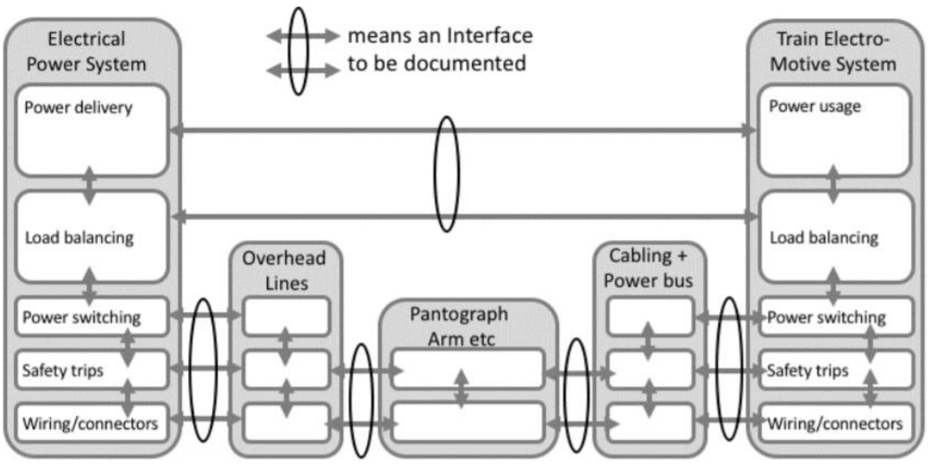


Figure 9 Documentation of relevant interfaces (Davies, 2019)

Interfaces are present at any level in any form such as e.g., electrical, electronic, fluid/gas connector or mechanical. The characteristics of the interfaces such as quality need to be defined including the requirements that come along with the interface characteristics. Standard could also apply to the specific systems of interest and the associated interface. This information is required when someone is interested in a system. The development of interface information is dynamic as it grows with the design process. In order to manage interfaces efficiently and effectively, interface definitions are documented. After identification and definition of the interfaces, the interface requirements are drawn up. The interface requirement is a system requirement that includes an interaction with another system. Interface requirements are double ended, which means that there are two stakeholders involved with different views and goals on the optimum solution (Davies, 2019). These stakeholders should clarify on what is required from each other. Staats describes the process of interface management by the following steps: 1) identification, 2) documentation, 3) communication, 4) control and 5) closing (Staats, 2014).

2.1.4.2 Configuration Management

Configuration management (CM) is defined as "a management discipline applied over the projects lifecycle to provide traceability and to control changes to performance, functional and physical characteristics" (NASA, 2007) (Department of Defense, 2001). A "configuration" consists of the functional, physical and interface characteristic of what is build in the real-world (Department of Defense, 2001). The purpose of configuration management is to establish and maintain system integrity. This means that the components are well defined and documented, systems integrate with neighbouring systems, processes identify how system functions are provided technically and the process provides a baseline with the goal to provide all involved with the proper starting points to prevent from faults occurring (Smith, 2003) (BAM, 2008). The motivation for applying CM principles is because it keeps the documentation consistent with the approved engineering, and to ensure that the product conforms to the functional and physical requirements of the approved design (NASA, 2007).

2.1.4.3 Trade studies

Trade studies are an assessment method with the purpose to make better and more informed decisions. Trade studies identify desirable and practical alternatives among a range of variables such as requirements, technical objectives, design, program schedule, functional and performance requirements or life-cycle costs (Department of Defense, 2001). The level at which trade studies are defined, conducted, and documented vary in level per variable. In general, the level of detail of trade-off studies needs to be in proportion to the costs, schedule, performance and risk impacts (Department of Defense, 2001). Both formal and informal trade studies are performed in systems engineering activities. Formal trade studies are well-documented and become part of the design decisions database. On the other hand, informal trade studies, which are in fact ordinary engineering choices are performed at every level. These decisions are documented in summary only, but they do define the evolvement of the design. Trade studies are performed in any process but mainly in the design synthesis process for reasons such as: assist in selecting designs, examine proposed changes or support decisions. The goal of the trade-off process is to determine and substantiate the choice for a preferred solution. Increasingly complex trade-studies lead to more difficult decision-making; therefore, trade study should be kept understandable and straightforward.

2.1.5 Systems Engineering and Integral Project Management

Projects in the large infrastructure industry are organised according to the model of Integral Project Management (IPM), see Figure 10. This model subdivides a project into the following 5 project components: project management, environment management, technical management, contract management and project control. The systems engineering methodology, which is in fact independent of the IPM model, is implemented in all project components. In order to implement the systems engineering processes effectively and efficiently in these management departments, there needs to be an integral push on the implementation of the methodology. In this research, technical management is studied in detail as this department is responsible for the requirements and constructs the base for the system structure.

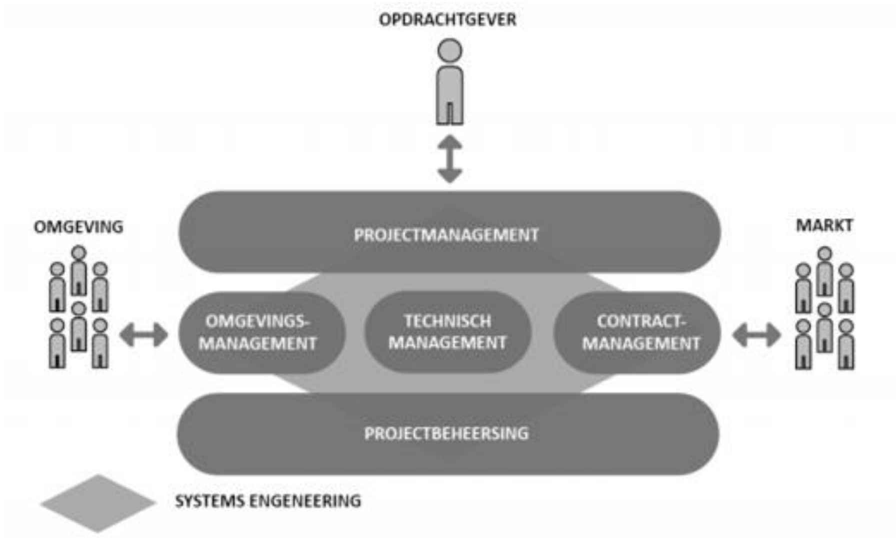


Figure 10 Relation between SE and Integral Project Management in a project (Leidraadse SE, 2009)

2.1.5.1 Technical management

Technical management is the main actor that is responsible for technical contribution in projects (van Heeren, 2010). Technical management transforms the client needs into a program of requirements, design synthesis and contract specification (Gemeente Amsterdam, 2013). In a large infrastructure project, the technical management department consists of the main disciplines: infrastructure, civil structures, and tunnel technical installation (TTI). For each discipline, technical management is subdivided in a lead engineer and a specialty engineer. The lead engineer manages specific engineering discipline teams and focuses on a certain discipline and the associated systems or subsystems. A lead engineer is responsible for the overall design process and the management of the interfaces among internal objects and adjacent disciplines. Therefore, the lead engineer is also interested in information from interfaces of the relevant objects and sub-systems. The lead engineer manages the technical aspects of the design by coordinating and controlling the specialty engineers. A lead engineer is assessed by the end products it delivers by the degree to which the requirements are met related to time, costs, and quality. The specialty engineer is a collective term for the role that performs design activities such as calculating, drawing, and modelling. Whereas the lead engineer manages the processes, the specialty engineer performs the activities that are required to get to certain design solution. The specialty engineer receives a task to design a certain work package that consists of one or more objects. A specialty engineer delivers products related to calculations, trade-offs studies, 3D models and drawings.

2.1.6 Systems engineering information management

Information management is the process of information collection and management from one or more sources as well as the distribution of that information to the end-users (Pickard & Roedler, 2021). The principle of information is that information is a collection of facts organised in such a way that they have additional value beyond the individual value of the facts (Pickard & Roedler, 2021).

Information collection and management is of vital importance to manage effectively and efficiently highly integrated and closely linked systems engineering processes. Due to the integrated and closely linked processes, systems engineering information is characterised to be evolving, growing and dynamic. Changes in highly linked processes and information might propagate to the entire system, which is also known as the butterfly effect. The butterfly effect is used to indicate that systems with great sensitivity could take on exceptional proportions with minor anomalies(Lorenz, 1993).

The work of managers or engineers is largely the work of making decisions and solving problems (Simon, 1992). The managers and engineers together perform the processes; therefore, the single roles perform particular activities and require interoperable information. Each participant in the project requires information to make decisions or solve problems. The information presented or required could be in the shape of physical forms or electronic forms (e.g., paper drawings, documents, e-mails, 3D models). High quality information is required by the end-users to be able to perform their tasks and activities successively. Therefore, the practical collection, management and distribution of information is done in a single source of truth, which is a central data storage. This will be explained in more detail in the following paragraph. Furthermore, the technological advancements are explained in the next chapter in the shape of Model-Based Systems Engineer technology.

2.2 Model-Based Systems Engineering

This chapter considers a broad range of MBSE topics ranging from general MBSE principles to detailed semantic technologies. At first, the principles of MBSE is described by elaborating on transitions steps, information base, and viewpoints. Second, current stage of MBSE advancement is considered. Third, a broad concept of semantic technologies is considered by focussing on ontologies and the concepts of information structuring.

2.2.1 Principles of Model-Based Systems Engineering

Model-Based Systems Engineering (MBSE) use interlinked models to convey the system design throughout the lifecycle, whereas document-based systems engineering uses documents (Chami & Bruel, 2018) (Friedenthal et al., 2012). Models give the ability to fully integrate systems engineering processes that are usually managed in documents (INCOSE, 2007). INCOSE defines Model-Based Systems Engineering as "the formalised application of modelling to support systems requirements, design analysis, analysis, verification and validation activities beginning in the conceptual development phase and continuing throughout development and later life cycle phases" (INCOSE, 2007). According to Henderson, who studied the claimed advantages of MBSE, the frequently mentioned benefits of MBSE are: increased traceability, improved consistency, reduced errors, better communication, reduced time and better management of complexity (Henderson & Salado, 2021). The MBSE development consists of different maturity levels, see Figure 11 the different stages of the MBSE evolution.

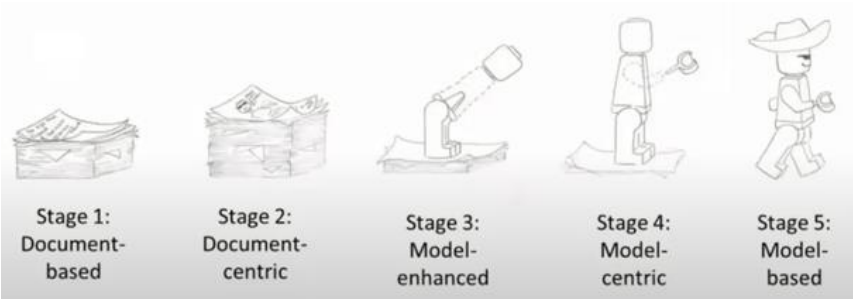


Figure 11 The evolution of MBSE in an organisation

To understand the stages in the evolution towards Model-Based Systems Engineering, the extremities are explained in more detail. In stage 1 systems engineering is performed document-based which could be both electronically as well as paper-based. The information is managed in different documents and the information in the documents is not linked. In stage 5 there is a single source of truth in which data changes are implemented for the whole project. The single source of truth is linked to other software in the project and organisation environment such as design and analysis software. The software is developed in such a detail that it automatically detects shortcomings and faults in the design or other connecting processes. Although the advancement differs per organisation and project, current implementation stage of MBSE is between stage 2 and 3. The industry is transforming from a document-centric environment in the shape of SharePoint towards a model-enhanced environment for systems engineering data. Besides, regarding the design deliverables, the industry appears to partially reside in stage 4 as design products are almost fully performed in 3D models.

2.2.1.1 System model

The concept of a model is something that we all have experienced. A model can convey a message by accentuating a particular function such as a 3D graphical model to visualise a building and experience the space or a maquette to present a touchable new residential area and experience the fitting in the environment. A model focuses on capturing or emphasizing only on particular properties in the modelled object (Long & Scott, 2011). As a result, models will always have shortcomings that need to be considered. That is why George Box already stated: "All models are wrong; the practical question is how wrong they have to be to not be useful", no model perfectly fits the practical reality or could fulfil the needs of each stakeholder (Shoesmith et al., 1987). Information models used to describe the physical structure in the real-world experience the same limitations. Therefore, the following four elements need to be considered when building a model: unambiguous language, structure and relations, enable argumentation and clear presentation (Long & Scott, 2011).

The purpose of MBSE is to integrate models to one system model, see Figure 12. The system model consists of mainly 5 sub models that are cross-connected: structural/component, functional/behavioural, performance, requirements and other aspects such as structural, safety and costs (Hart, 2015). The main focus of this study is on the structural/component model and is later referred to as the structural model.

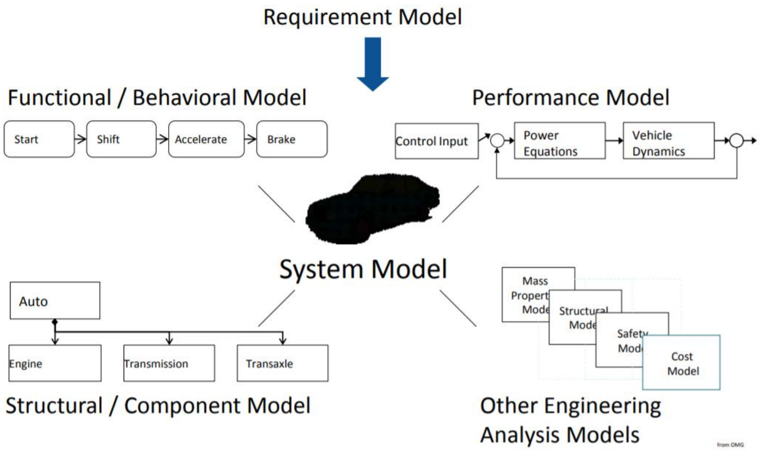


Figure 12 Graphical representation of MBSE system model for a car (Hart, 2015)

The models used to describe systems are called descriptive models, which represent the system at a specific point in time (Oostinga, 2021). The structural model captures the physical real-world objects. In the design synthesis process, the functionalities are translated into a physical structure which is the structural model. Like the other systems engineering information, the structural model will also be managed in a system decomposition, see Figure 8. The decomposition manages all the objects that are present in a project, however, there are some difficulties with decomposing objects such as cables or objects that have a particular length. Cables are often managed as group objects for objects with similar characteristics (Oostinga, 2021). On the other hand, general objects are called point objects. Line objects have the characteristics to cross multiple (sub-) systems or other objects managed in the information system.

2.2.1.2 Information base

The MBSE transformation changes the role of information management as closely linked information gains more value. Whereas document-based practices entail loosely coupled textual information, MBSE provides the possibility to link information and processes. The linked models are considered to become an information base that can be used for future references and purposes such as analytics, predictions and other innovations (Gopalakrishnan, 2015). The fundamental information changes in MBSE provides opportunities such as: focussed information views, enhanced ability to measure change impact, improve measurement of the integrity, completeness, quality and accuracy (Hart, 2015). Furthermore, the MBSE information can be enhanced by defining and adding entities, establishing relations, re-use of information, share information across domains and enhance information visualisation (Hart, 2015). The added information such as relations enables the participants to perform advance knowledge queries in particular situations (Hart, 2015). At last, the changing information management enables the opportunity for process automation (Hart, 2015).

2.2.1.3 Information views

Each role in a project has a particular task and therefore also a particular required information view. As the number of participants in a project can mount up to tens or even hundreds of people of which each role has a particular interest in time, per domain or per problem statement, solely presenting information per object or other element will not suffice. These needs could differ although the roles are interested in the same object. The quote below shows a regular situation of a specialty engineer.

A structural engineer could be interested in mass and size of an electrical box whereas an electrical engineer only requires information regarding the functionalities (Madni & Sievers, 2018)

A solution could be to tailor information to the user's needs, in other words information views. Views, which could be regarded as a particular filter, are a representation of a part of a system from a particular perspective such as safety, performance, or availability. However, a view can be a representation in any way, which means that a view doesn't have to be visual or graphical or doesn't have to focus on a standardised topic (Archimate, 2019) (Hart, 2015). The views are constructed from a subset of the model that addresses their concerns. A viewpoint specifies and manages the rules for constructing a view by setting the stakeholders' concerns and purposes (Archimate, 2019). The stakeholders considered in this item are the roles and their field of interest originating from the discipline. The concerns focus on the topic of interest and especially the composition of the objects and the corresponding information. At last, the purpose considers the reason for the view which can be subdivided into designing, deciding, and informing. In practice, the view is a query that obtains information from the underlying database on any entity or attribute according to the viewpoint constraints.

2.2.2 Configuration Management Database Application

Current systems engineering information management practices are performed in the configuration management database (CMDB). The CMDB used in large infrastructure projects is initiated as a solution to unstructured and fragmented information. The purpose of the CMDB is to store, control and manage up-to-date configuration information in a single source of truth for all users (Relatics, 2016). The software system plays a central role in the configuration management of a project throughout all project phases. Configuration management is "a process of maintaining system integrity while handling changes to both the data-set and real world engineering system it describes" (Lindkvist et al., 2013). In the as-is situation, the CMDB application strives to be in the model-enhanced stage 3, see Figure 11. The software system called Relatics has a monopoly position in the Dutch infrastructure construction industry. Relatics is a web-based semantic relational database which stands for: 1) web-based – the information storage on the internet, 2) semantic – the specified relation that is applied to the objects and 3) database – the accumulation of data (Huijnen, 2014). Relatics features a 'Drag-n-drop' system which gives the possibility to design a systems engineering model without any programming activities. The systems engineering model is a relational model in which entities are managed such as objects, stakeholders, functions, requirements, and activities.

2.2.2.1 Relation model

The information in the relational database is stored in different entities such as stakeholders, requirements, objects, or activities, see blue diagrams in Figure 13. The relations between the entities, see pink lines between blue diagrams in Figure 13, transform data into information. In case data is inserted in the relational model, data is added to the particular entity. The information presentation is done via modules, which is a particular web pages that focusses on a particular topic. For example, a module is presented on requirements management, object management or interface management. Each module is known for a standard composition in which information from different entities could be presented in the particular module. An example of the object module and the particular user interface is presented in Appendix E.

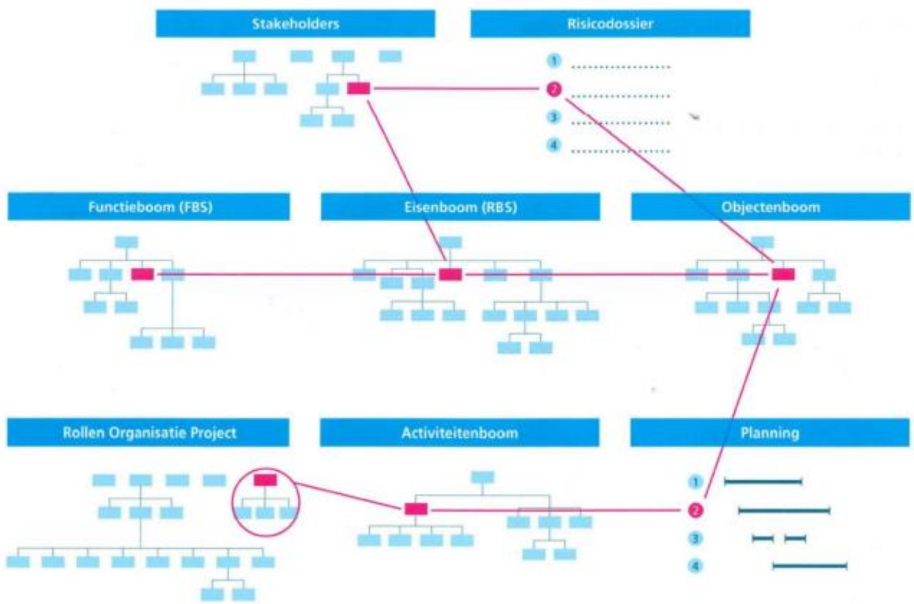


Figure 13 Conceptual relation model construction project in CMDB (Huijnen, 2014)

The data of the relational database is stored in the separate entities. The presentation and management are done in particular modules in which information from multiple entities are merged. This information can be visualised as a table, see Figure 14, and consists of different items such as:

- Attributes: stored in the table column and is related to the particular entity
- Tuples: stored as the table row and represents the information of a specific entity. The tuple also makes information by merging information of different entities.

- **Relation (schema)**: the relation (schema) is the combination of all attributes of a specific entity or information merged from different entities.

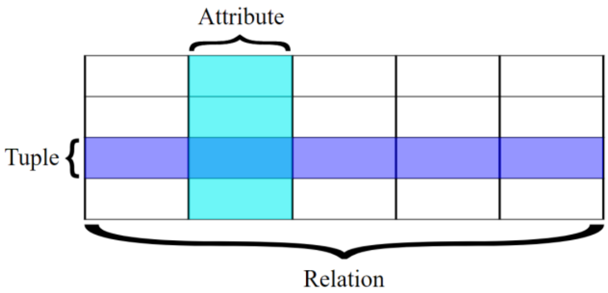


Figure 14 Schematic presentation of terminology relational database

2.2.3 Semantic technologies

The concept of semantics include the meaning of information and is a broadly used term. Semantic technology is to be considered as a new level of depth in information that provides more intelligent information. Therefore, meaning and relationships must be predefined and hard-wired into data formats and program codes at the same time. The information becomes 'meaning centered' and include concepts such as semantic representation, entities and their interrelationships, and information and meaning extraction. The visualisation of nodes and edges are represented in Figure 15.

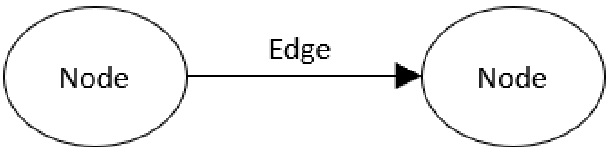


Figure 15 Nodes and edge

2.2.3.1 Ontologies

In large infrastructure projects there are sizable number of stakeholders involved throughout a project lifecycle having different conceptualisations of 'things' (Madni & Sievers, 2018). Ontologies are an explicit, formal specification of a shared conceptualisation (Gruber, 1993). Ontologies can describe relationships between things, concepts and categories of things which might results in advantages such as reasoning (Madni & Sievers, 2018). Ontologies show to be helpful in the communication about systems engineering between involved parties in the engineering pages (van Ruijven, 2019). Ontologies link domain concepts with relationships to support deeper understanding (Salem & Alfonse, 2008). Ontologies focus on formal, explicit and shared characteristics 1) formal: machine readable, 2) explicit: explicit description of a domain and 3) shared: agreed vocabularies by a domain (Martin et al., 2021). To attain focus, ontologies capture the set of concepts and categories in a subject areas or domains by a controlled vocabularies and controlled hierarchical structures. At first, a controlled vocabulary is a list of terms that have been enumerated explicitly and mutual relations between objects could be defined such as synonyms. Second, a hierarchical structure in which objects are classified and grouped. Examples of hierarchical structures are a taxonomy or a specialization, which are further explained in the next paragraph. Ontologies could vary in expressivity and weight as a higher degree of formalization gives more understand as well as requires more logic.

2.2.3.2 Hierarchical structure

In construction projects there are an abundance of almost equal objects that need to be modelled. Therefore, the science of categorisation and classification is introduced. A taxonomy represents a hierarchical structure in which groups or types are organised. Each level is called a class and therefore, the parent or child classes are super- and subclasses. The information with a common denominator is stored in each class. The elements are structured by an 'is a' relation. A taxonomy attains more ontological value when properties and constraints are assigned to the classes and subclasses, this advanced taxonomy is called the specialisation (van Ruijven, 2019).

2.2.4 Abstraction levels

In order to effectively and efficiently capture the project information in civil engineering projects, Oostinga proposed a model that consists of abstraction levels: specialisation, abstract and concrete, see Figure 16 (Oostinga, 2021). At first, the specialisation which is considered to be a generic reference model and in practice called the object type library (OTL) stores the general conceptualisation of objects. Second, the abstract decomposition stores the system decomposition of a recurring system decomposition in a particular project. At last, the concrete decomposition stores the project-specific systems engineering model by adding specific names or codes to the physical objects in the system. There is a hierarchy and predetermined direction of information flow between the sub models as the objects in a child sub model inherits the information of the object in the parent sub model. The elements that are stored in the abstract decomposition are called object types and objects stored in the concrete decomposition are concrete objects. Other 'things' such as project management information could be stored as well in the model such as functions, activities, risks and persons (Oostinga, 2021).

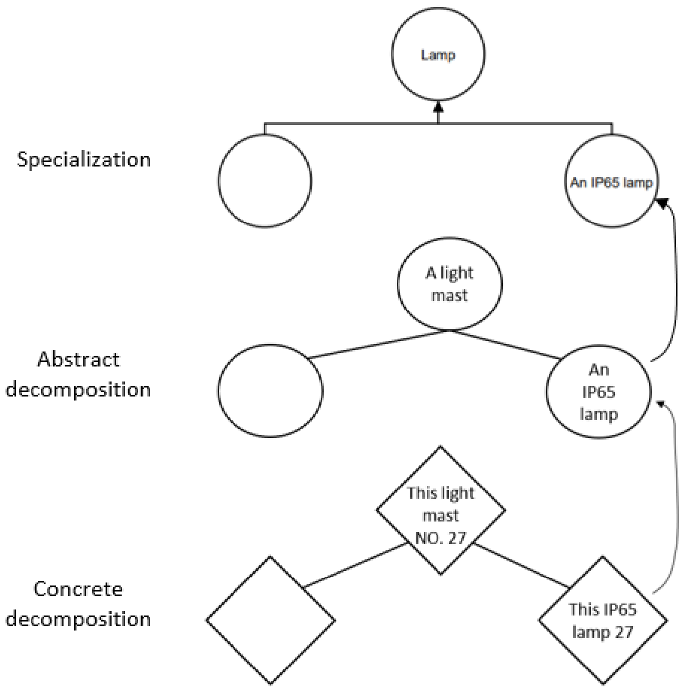


Figure 16 Roadmap for capturing elements (Oostinga, 2021)

2.2.4.1 Specialisation

Standardisation enables effective and efficient cross-discipline, cross-project and cross-organisation communication (Sebokwiki, 2022). Therefore, the OTL is initiated in which standardised project-transcending or even organisation-transcending information is captured for enhancing the interoperability. The objects that are stored in a specialization tree structure. In practice this is called an OTL (van Ruijven, 2019).

2.2.4.2 Abstract decomposition

Abstract elements are imaginary and do not really exist (Oostinga, 2021). The abstract decomposition manages abstract 'object types' in a decomposition. The abstract decomposition is a system breakdown structure used to cut up a project from coarse to smaller systems that are better manageable. The hierarchical relations between abstract elements are characterised by a 'Has part' relation (Oostinga, 2021). In practice, the abstract decomposition is used to manage projects with matching system structures but could also be implemented for specific projects in which repeating structures occur. The abstract decomposition functions as interlayer between the industry standardised object definition and the physical real-world objects. Project information such as requirements, functionalities, objectives, activities, or end products could be allocated to the abstract elements. Furthermore, abstract elements obtain their properties by an inheritance relation with the specialisation tree.

2.2.4.3 Concrete decomposition

The concrete decomposition manages concrete physical objects that are visible around us, real and only one exists. The concrete decomposition is an instantiation of the object type in the abstract decomposition and inherits the information from the abstract object. To enable the instantiation, object specific information is added to such as a code, name, and number. As an inheritance relation does exists between the abstract and concrete decomposition, the project specific information such as object specific properties, relations, or project-specific information also applies to the concrete objects. As a result, each object in the system contains all the relevant information including context information for that object. The relevant context information consists of relation which consequently also give the possibility (not mandatory) to present user specific information in views (Hart, 2015).

2.3 Summary

The context study focuses on the conceptual understanding of the systems engineering processes in large infrastructure projects as well as the information management that is associated with the processes. Furthermore, the technology frontier MBSE is explored by identifying the opportunities and advantages of the single source of truth regarding information modelling. Two questions are being answered in this chapter.

SQ 1 *How are systems engineering processes managed in a configuration management database?*

The systems engineering processes consists of requirements analysis, functional analysis and allocation, design synthesis, verification and validation, and system analysis and control. These processes are managed in iterative loops. Furthermore, there are systems engineering supporting processes, which apply to all the aforementioned processes, such as trade studies, interface management and configuration management. These processes are entangled, and the input and output information are used by a high variety of users, especially the technical management in the development phase. The technical department contains the main disciplines civil works, infrastructure, and electrical engineering. The roles involved in these management of the processes are the lead engineer who performs management activities and the specialty engineer who performs design activities. The high number of project participants, the interconnectivity and dynamicity of information requires a single source of truth. Therefore, the systems engineering information is managed in a web based CMDB which a semantic relational database in which the processes are linked. The information managed in the system is inserted and controlled by the project participants. The CMDB manages the process outputs (requirements decomposition or object decomposition) by creating entities for the particular processes and link this process to each other. For example, the requirements are linked to functionalities and functionalities are linked to the physical architecture. On the other hand, the interface management module is linked to the physical architecture as objects have interfaces with each other. Consequently, this information is presented in specific modules which are named after the name of the process.

SQ 2 *Which aspects of Model-Based Systems Engineering could contribute to fitness for use of the CMDB adopted in the development phase of large infrastructure projects?*

In the concept of Model-Based Systems Engineering (MBSE), systems engineering processes are managed with tightly coupled models instead of the previously applicable document-based method. As a result, the dynamics of information management severely changes. In these tightly coupled models, physical objects exist once in the system and therefore data values are to be inserted once as well. These tightly coupled models are merged in the system model which consists of several models: structural, functional, performance and other engineering analysis models. This research focuses on the structure model. The concept of the structure model consists of three sub-models: the generic object management, abstract model, and concrete model. Each model has its own function. The generic object management manages an agreed conceptualisation of objects as it captures all the object definitions and corresponding standard properties and relations. The abstract model manages general decompositions that for trans-project use or multiple use in a single project.

Consequently, the instantiation of the abstract model is the concrete model. The objects in the concrete model are allocated a specific number, name or code and have the specific properties and relations assigned. As a result, the objects in the concrete model are the physical objects that exist in the physical world. Project specific information such as requirements, activities, roles, or interfaces can be allocated to both the abstract and concrete model, depending on the abstractness of the objects. The structured and detailed management of objects enables the opportunity to tailor information presentation to the needs of the specific users. As participants, who could mount up to tens or hundreds, require different information compositions (e.g., properties, relations), MBSE could meet the needs by tailoring the presentations.

3 Literature study

The purpose of the literature study is to improve understanding of the theory on user specific information needs, the fitness for use and the corresponding experience assessment framework. Therefore, the literature study is subdivided into three main topics: the general concept of information needs, the fitness for use and the conceptual DQ/IQ assessment framework. At first, information needs are described in general by identifying the characteristics of information needs. Second, the fitness for use is considered by the general concept and the phenomena of non-fitness for use. At last, a framework is introduced that is used to assess the DQ/IQ of the information systems used in the construction industry. The following two sub questions are being answered in this chapter.

SQ 3	*Which variables characterise role specific information needs of engineering specialists and engineering managers?*
SQ 4	*How to analyse the fitness for use of a configuration management database used in the development phase of large infrastructure projects?*

3.1 Information needs

In the development phase of large construction projects there are plenty of roles involved in controlling and managing systems engineering processes, each with their role-specific information needs. At first, the general concept of information needs is considered. Second, the corresponding information seeking is considered to understand the steps in the seeking process in an information need event. Third, the information needs are identified by distinguishing the characteristics of information needs. As the word suggests, the concept of information needs is strongly related to the concept of needs, which originates from theory on human "need". Human needs are listed in Maslow's hierarchy of needs (Block, 2011). Meanwhile, the definition of information needs is slightly different. A need is generally characterised as an "inner motivational state" that triggers thought and action (Grunig, 1989). Kirkelas describes that the information seeking is initiated by a "need-creating event/environment (Krikelas, 1983).

3.1.1 Information seeking model

The phenomena of information needs are part of the larger information seeking concept which is defined as "the purposive acquisition of information from selected information carrier (Johnson, 1997). Therefore, the information seeking model of Leckie has been introduced, in which the information needs originate from tasks and are conducted in information sources. see Figure 17 (Leckie et al., 1996). Even though more recent and more advanced models are developed on the information seeking process, the model of Leckie is chosen for simplicity and the focus on tasks related information seeking of professional. Besides, Leckie considers the engineer (specialty engineer) and managerial role (lead engineer) in particular whereas other models focus on different role types in different industries. The characteristics of the roles are elaborated below:

- Specialty engineer: Engineers are largely specialists in subspecialties. In the context of large infrastructure project these are mainly civil, mechanical, and electronic. The emphasis of engineering work lies on solving technical problems. The end product of the engineer is to be considered as a product instead of knowledge (Leckie et al., 1996). As a result, engineer consume information instead of producing information and considered documentation as a by-product (Leckie et al., 1996).
- Lead engineer: The managerial engineering role that is often taken in later stages of their career, performs a different set of activities resulting in different information needs. These different set of activities relate to internally and externally coordinating work in the discipline, quality and planning (Leckie et al., 1996). The information needs range from information internal as well as external in the discipline, progress information and end product results (Leckie et al., 1996).

The information seeking model of professionals developed by Leckie, see Figure 17, considers the following items: work roles, tasks, characteristics of information needs, sources of information, awareness of information and outcomes. The work roles presented in the information model are explained in the latter enumeration. In the context of professionals, the tasks originate from the systems engineering approach which is explained in the systems engineering chapter. In addition, the information needs are elaborated on in more detail in the next paragraph. To provide in the information need, information sources are required which could vary from colleagues to shared information systems.

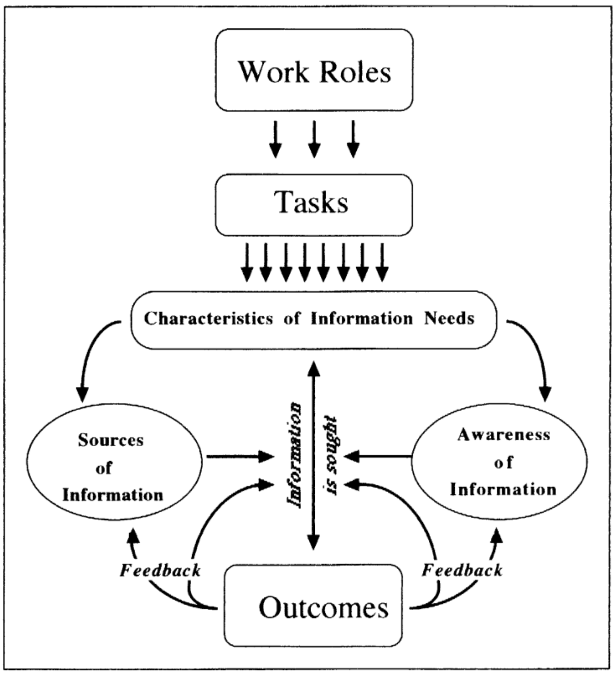


Figure 17 A model of the information seeking process of professionals (Leckie et al., 1996)

Preliminary studies show that information sources of engineers are mainly oral communication, personal files, personal knowledge, and personal experience. Written sources consists of textbooks, technical reports, catalogues and trade journals instead of official literature (Leckie et al., 1996). Nevertheless, Hurd states that engineers despite their technological background fail to benefit of electronic information retrieval and access (Hurd et al., 1992). Another study identified two principal factors that inhibit use of those resources: information systems are considered awkward and difficult to use, and they do not directly meet the problem-oriented information needs of engineers (Weinschel et al., 1986).

3.1.2 Characteristics of information needs

The information seeking model presented in former paragraph shows that the characteristics of information are strongly related to the tasks that are to be performed. The information needs could change through time as the tasks change or the view of the engineer changes (Leckie et al., 1996). To be able to analyse the information needs, the information needs characteristics are introduced. Leckie shows that several variables influence or shape the information needs of professionals: individual demographics, context, frequency, predictability, importance and complexity, see Figure 18 (Leckie et al., 1996). The variables are elaborated on in more detail below.

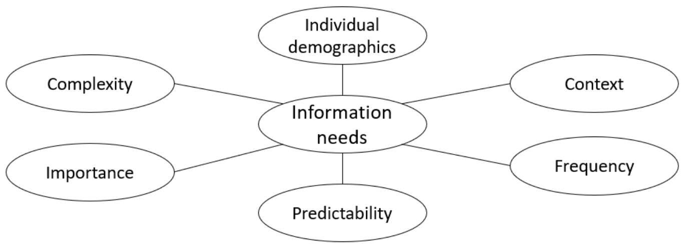


Figure 18 Schematic overview of variables that influence or shape information needs

Individual demographics

The individual demographics consider the nature of specific profession, and factors such as career stage, age of the individual, area of specialisation and geographic location (Leckie et al., 1996). The profile of the individual could for example require a particular language in the shape of textual or visualised information or a particular level of context to a particular topic. The extremes of the variables are skill in which low and high are obvious.

Context

The context variable considers the situational specific need. The situational context of the processes is dynamic through the project. The factors that determine the situation are the process, tasks and responsibilities, phases, and discipline. The tasks and responsibilities of the roles vary through time and are related to the project phase. The objects of interest strongly relate to the role and the discipline the role works for.

Frequency

The variable frequency considers the returning rate of similar information needs. A high returning rate might argue for a well-functioning system in any shape that satisfies the needs. The extremes of the variables are recurring (high frequency) and new (low frequency).

Predictability

The predictability variable considers the degree to which the information needs can be anticipated on. The predictability of the information implies the degree to which the information need could be satisfied. The extremes of the variable predictability are anticipated and unexpected.

Importance

The importance variable considers the degree of urgency of the information needs. The urgency implies the maximum time window given by the applicant that is given to satisfy the needs. The extremes of the variable importance are obviously stated in low and high urgency.

Complexity

The complexity variable considers the degree to which the information need can be resolved. The complexity implies the ability to which the information need could be satisfied with limited quantity of resources such as time and labour. The extremes of the variable are expressed in easily resolved and difficult to resolve.

3.2 Fitness for use

The information needs are obtained from information sources as stated in the information seeking model of Leckie, see Figure 17. These information sources are evaluated by the fitness for use, which is a widely adopted concept in information quality literature. The fitness for use is defined as "emphasises the importance of taking the consumer viewpoint of quality because ultimately it is the consumer who will judge whether or not the product is fit for use" (Wang & Strong, 1996). The fitness for use concept considers the viewpoint of quality by the conception of the user. However, the experience of the user also needs to be understood by the researcher. Therefore, in this paragraph some important phenomena towards obtaining information are considered by focussing on decision making and workarounds. The paragraph finalises with the DQ/IQ assessment framework that is used to assess the fitness for use.

3.2.1 Decision-making

Engineering activities are well-known for the variety of complex decision-making process in a design process. The fundamental purpose of an information system is to communicate processed data into a relevant form for "users" who need the information for decision making or taking actions (Petter et al., 2012). The CMDB is regarded as an information system that manages day to day design operations. In order for an engineer a variety of information is required such as physical architecture specifications, technical manuals, engineering drawings or systems engineering information (Department of Defense, 2001).

Construction projects are well-known for their islands approach culture between discipline, department and organisation (van Ruijven, 2019). The phenomena of the island approach are related to the persistent and differential gap as well as the knowledge gap. Persistent and differential gap: individuals encounter with a discrepancy of lack of sense in their environment. Knowledge gaps: human groups persistently differ from another human group in what they know. In the worst case this issue is establishing information poverty which is the cause of knowledge gaps as it is considered to be a self-selected condition freely entered into and accepted by the actor (Case & Given, 2016). The miscommunication might lead to wrongly informed people which consequently might lead to erroneous decisions.

Decision making is also influenced by the quantity of information presented. Both Information underload and information overload could reduce decision accuracy. Rogers defines the information overload by "state of an individual or system in which excessive communication inputs cannot be processed, leading to breakdown" (Rogers, 1986). As a result, a user could implement workarounds or could even fully omit the use of the system (Case & Given, 2016) (Alter, 2014). Another possible response is known as information avoidance or selective attention in which all information that is not required is filtered out. (Miller, 1960). Miller states that if people are not able to adjust to too much information, the result is stress or anxiety which consequently might lead to lower performance of the individual. In a research conducted by Farhoomand and Drury involving 124 managers of governmental agencies and organisations described information overload by excessive or irrelevant volume or by the inability to manage or understand information (Farhoomand & Drury, 2002). Roetzel has graphically presented the increasing decision accuracy with increasing information overload till a certain point after which information overload is considered, see Figure 19 (Roetzel, 2019). Interestingly, a counterintuitive phenomenon was noted as O'Reilly reported that too much information degrades the job performance whereas the user satisfaction increased. In contrary, too little information reported lower satisfaction than workers with too much information (O'Reilly, 1980).

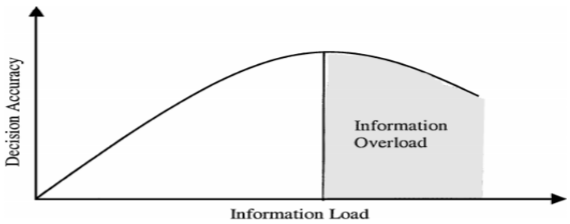


Figure 19 Visualisation of information load and decision accuracy (Roetzel, 2019)

3.2.2 Workarounds

The promising goals of the implementation of software are not always achieved. As a result, users might implement countermeasures such as workarounds. Workarounds are a well-known and frequent occurring phenomena in processes that include software tools. A workaround is defined by a goal-driven change to one or more aspects of an existing work system in order to be able to achieve a desired level of efficiency, effectiveness or other goal. (Alter, 2014). Alter researched the workarounds in far detail by analysing phenomena, types and direct effects (Alter, 2014). A selection of the relevant items for this research are described below.

Phenomena of workarounds

Workarounds could have different causes and could therefore also occur in different situations and shapes. As workarounds have direct effect on the operability and evolvement over time of work systems, a broad range of topics are to be considered. At first, workarounds are often considered as improvisation and bricolage which is constructing something with what is at hand (Levi-Strauss, 1967). Second, workarounds are often considered to be exception handling and/or sanctioned or unsanctioned deviations from routines, processes, and methods. Third, articulation work is often present when workarounds are initiated of obstacles, exceptions and cumbersome processes (Strauss, 1985). At last, technology misfits are considered in information systems as the participants in these systems often see a need for workarounds to achieve goals related to efficiency, output, and responsiveness to customer needs.

Types of workarounds

Several articles in literature have made classification schemes for workarounds, often for specific contexts. In this research, distinctions are made based on the relation to different types of operational goals for the workaround. At first, workarounds arise to overcome the inadequate IT functionality of work systems. Many systems lack functions or capabilities that are needed to perform specific work steps or record specific data. Especially in case of the CMDB in which sequential processes are managed on which multiple actors are dependent. As a result, participants search for other software systems that can fulfil their needs. Second, workarounds can be initiated in the shape of software workarounds, shadow systems, modifications of existing software, or other resources that were previously unavailable (Alter, 2014). For example, a paper-based system can be initiated to augment the electronic system (Fitzpatrick & Ellingsen, 2013). At last, although the expectation and promise of computerised systems is to increase productivity and establish a "single source of truth", such systems might decrease the information accuracy and lead to information asymmetry. As a result, individuals might feel the urge to performed manual counts to verify the accuracy of data from computerised systems leading to inefficiencies and ineffectiveness (Petrides et al., 2004).

Direct effects of workarounds

The effects due to the implementation of the workarounds are positive in the short term because of the continuation of work. However, there are also downsides to the implementation of a workaround, both in the short term and the long term. At first, the workarounds could continue the work despite obstacles, mishaps, or anomalies. Employees would lie to a software systems in order to be able to let them do what they defined as their real job (Russell, 2007). Second, the implementation of a workaround might have impact on subsequent activities of different actors. At last, the workarounds might lead to noncompliance with management intentions as official systems and methods are bypassed.

3.2.3 Data Quality/Information Quality

Information quality is considered to be the degree to which information meets the needs of its users (Gasser & Twidale, 2005). As users of the system use the information for different purposes and consequently have different information needs, the quality of the information can be considered differently for each user. For example, the purpose of the engineer and the manager vary widely while both make use of the same system. Wang and Strong defined high quality data as data that is fit for use by data consumers – which is considered to be a widely adopted criteria (Wang & Strong, 1996). Therefore, the term 'fitness for use' is used in the context of this research.

The fundamental purpose of the CMDB is to manage information and provide employees the information they need for their daily activities (Petter et al., 2012). Information quality is a definition that frequently occurs in literature, so does it in the IS success model of McLean and Delone in which the information quality has a relation with the user satisfaction (Delone & McLean, 1992). Consequently Petter showed that the information quality has a strong relationship with the user satisfaction (Petter et al., 2008). To make the assessment tools more industry specific, the data quality and information quality framework of Westin has been introduced to qualitatively measure the information quality of which the dimensions are presented below in Table 1.

Table 1 Dimensions for DQ/IQ assessment framework (Westin & Sein, 2013)

Dimension	Description	Reference
Accessibility	available	Ge et al. (2011)
Security	secure, protected, authorized access	Ge et al. (2011)
Relevancy	relevant	Ge et al. (2011)
Completeness	include all necessary (required) values	Ge et al. (2011)
Consistency	consistent meaning	Ge et al. (2011)
Timeliness	current, delivered on time, timely	Ge et al. (2011)
Logical coherence	Two or more values do not conflict with each other	Singh et al. (2009)

Accessibility

Accessibility entails the degree to which information is available, obtainable, or quickly retrievable. Key attributes of access are knowledge of the existence of information, its availability, and the tools necessary to acquire it (Fuerth, 1997). Accessibility focuses on whether the system is accessible, via for example the internet. Obtainability focuses on the effort that is required to obtain the information measured by for example time or clicks.

Security

Security is subdivided into internal security and external security as there are internal and external threats to the information system. Internal security considers the information security within the system securing the information against intentional or unintentional bad human acts. External security considers the security against external threats. The security of information systems relies on logical barriers such as data encryption, passwords, and process transaction authentication (Singh et al., 2009) (Westby & Allen, 2007).

Relevancy

Relevancy is the extent to which the information provided is useful, relevant, applicable and helpful to the task of the user (Ge et al., 2011) (Singh et al., 2009). Usefulness focuses on the fitness for use of the information presented. For example, information is useful when the full context of that particular information element is presented. On the other hand, relevancy focuses on the situational context of the end-user such as the task, process, or phase. So, a lot of information presented on the object page might not be relevant for a particular user in a specific point in time.

Completeness

Completeness is the extent to which information is sufficient, complete, comprehensive, detailed and includes all the necessary values (Ge et al., 2011; Singh et al., 2009). The level of detail subtheme considers the required level of detail by the user such as an object that is managed generically but is required on concrete level. The comprehensiveness considers the project information context such as the physical relation with another object.

Consistency

Consistency is defined by the degree to which the information has a consistent structure and is presented in the same format and vocabulary (Gasser & Twidale, 2005; Ge et al., 2011). The subtheme structure considers the consistency of the information structuring in a project. The subtheme format considers the consistency of the user interface in a project or in between projects.

Timeliness

Timeliness is the degree to which information is up to date, current, delivered on time and timely (Singh et al., 2009). Up to date considers the degree to which the information is in sync with the practical situation. Timely considers the degree to which the information in the system is presented in a specific point in time for when it is required.

Logical coherence

Logical coherence is derived from logical that refers to reasoning and coherence which indicates values that do not conflict with each other (Singh et al., 2009). Logical incoherent information considers the harmony within a process with other stakeholders. Logical coherent information focuses on the relation with external processes and information systems.

3.3 Summary

The theoretical study of this research focuses on the literature on information needs, fitness for use and assessing the DQ/IQ of information systems. At first, the conceptual understanding of analysing information needs of roles involved in the development phase of large infrastructure projects are considered. Second, the fitness for use is generally considered including workarounds. At last, a DQ/IQ framework is introduced that is used to assess the information in the CMDB. To be able to answer the main research question, several sub questions have been made of which two are answered below based on the theoretical study.

SQ 3 *Which variables characterise role specific information needs of engineering specialists and engineering managers?*

The literature study shows that the information seeking model introduced the information needs characteristics, which is depended on the roles and tasks of the roles. The tasks and responsibilities differ per role as well as through time which consequently might lead to different information needs in different situations. Consequently, Leckie shows that the information needs of specialty engineers and management roles can be characterised by individual demographics (age, role), context (situation specific need), frequency (recurring or new), predictability (anticipated or unexpected), importance (degrees of importance) and complexity (easily resolved or difficult).

SQ 4 How to analyse the fitness for use of a configuration management database used in the development phase of large infrastructure projects?

The fitness for use considers the consumers viewpoint on the data that is to be used. In fact, the fitness for use consists of the information needs and the experiences in the information system. The user requires the system for obtaining information for mainly decision-making activities. In these activities the role can experience information underload or information overload. The consequences of both information underload and information overload are time losses and possible workarounds. Workarounds are the phenomena of not using the information system for its intended purpose. A paper-based system can be initiated to augment the electronic system (Fitzpatrick & Ellingsen, 2013). The next step of information overload is system avoidance. Consequently, information asymmetry and reduced information accuracy might be observed which lead to the fact that the system might lose its intended purpose of the single source of truth.

The literature study shows a variety of assessment framework of the experiences of individuals with the CMDB. The reason for using the system vary widely per user role. However, the purpose of the system is to serve each user effectively and efficiently. Wang and Strong defined high-quality data as data that is fit for use by data consumers – which is considered to be a widely adopted criteria. Therefore, the term 'fitness for use' is used in the context of this research. The fitness for use per specific tasks of different users is assessed by the DQ/IQ framework in which the following dimensions are considered: accessibility, security, relevancy, completeness, consistency, timeliness and logical coherence (Westin & Sein, 2013). By introducing this framework, the experiences and problems observed by the users can be structured.

4 Practical study

The purpose of the practical study is to identify the perceived fitness for use of different roles in the CMDB. The roles participate in different processes and have different tasks and responsibilities as well as information needs. The qualitative research is performed by interviewing roles involved in the development phase of large infrastructure projects. The research question that is to be answered in this chapter is shown below.

SQ 5 *What is the perceived fitness for use in the configuration management database used in the development phase of large infrastructure projects?*

4.1 Qualitative research

The qualitative research is a practice-oriented study in which experiences on the use of a CMDB in the development phase of large infrastructure projects are considered. The qualitative study is performed by interviews with specialty engineers and lead engineers of various disciplines. The chapter is subdivided into the methodology, data collection, data analysis and interview results.

4.1.1 Interview methodology

The goal of the empirical study is to identify and understand the perceived fitness for use of different roles with the use of the CMDB in different systems engineering processes in the development phase of large infrastructure projects. A qualitative research is conducted in the shape of interviews as practical information is required.

4.1.1.1 Interview process

The objective of the interviews is to identify the tasks and responsibilities, information needs and fitness for use of the CMDB. The information seeking model of Leckie functions as guidance to understand where information needs come from, see paragraph 3.1.1. The model consists of subsequent steps consisting of roles, tasks, information needs and experiences. This information is obtained by conducting the following steps: preparation, collection, analysis and results. The overview of the processes and the corresponding steps are explained in detail below in Figure 20 in which each step is given a particular colour. At first, the participants are strictly selected based on their role, discipline as well as individual demographics. Second, the interview data has been collected, merged and presented in quotes in the Appendix F & G. Consequently, the interview data is analysed based on a thematic analysis method which result in a set of problem observations. These problem observations are analysed by the 5 Whys root cause analysis which resulted in a set of core problems. This analysis is presented in the analysis paragraph. At last, the interview results contains results of the analysis and the perceived fitness for use in relation to the information needs is particular tasks.

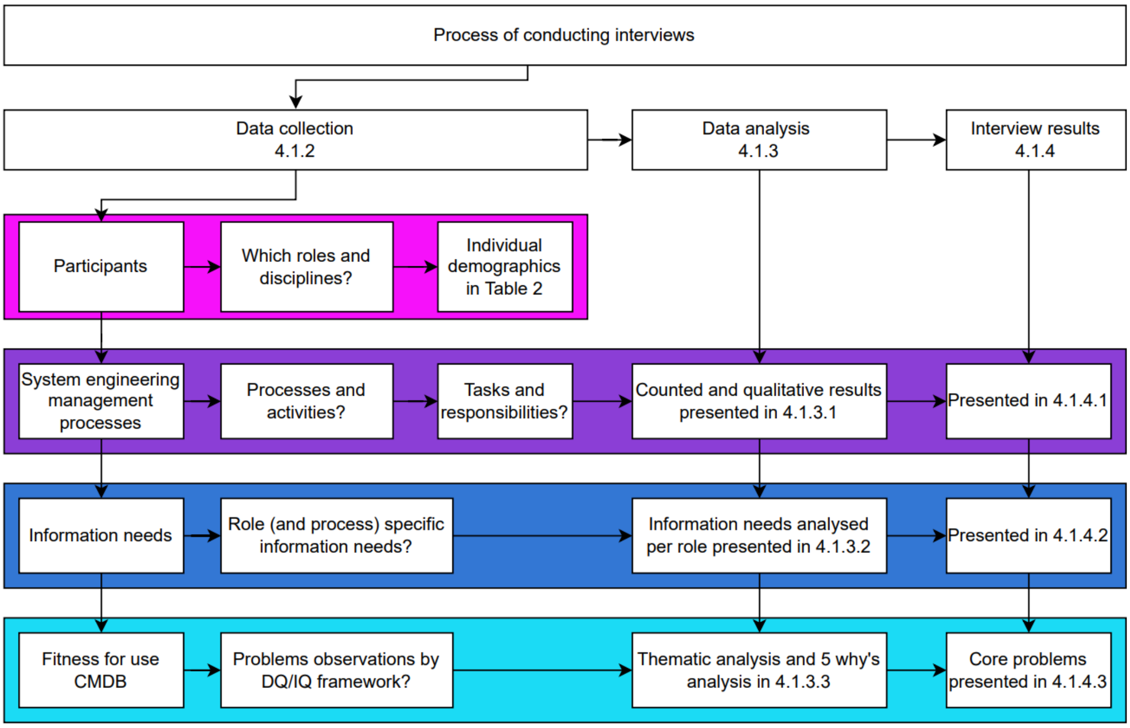


Figure 20 Process scheme of conducting interviews

4.1.1.2 Participants

There are a variety of departments, disciplines and roles involved in the development phase of large infrastructure projects. Therefore, initially, the interviews were planned to conduct on the environmental and technical department as both departments appeared to have a significant share in the development phase and disparate perspectives. However, the results of these departments were too far apart, and more focus was required. As a result, the roles and department were narrowed to solely the technical department. The technical department has a central role in the systems engineering development process, which is presented in paragraph 2.1.5, and the hierarchical roles appeared to have different perspectives. The participants belong to the staff from the major technical disciplines in large infrastructure projects including infrastructure, civil, and electrical (TTI). As these disciplines operate in different teams and might have different experiences, these are all considered to increase the reliability of the findings. Leckie argues that these roles are having complementary responsibilities and therefore different tasks (Leckie et al., 1996). Therefore, a distinction is made between the specialty engineer and lead engineer. Focussing on roles with distinct views is considered to improve reliability of the findings. Furthermore, the broad population regarding the variety of disciplines and roles increase the population validity as the major perspectives are included more than twice. The lead engineer is considered three times each and each discipline is considered twice. Furthermore, to improve the external validity, the interviewees are selected on their experience with systems engineering, years of experience with the CMDB or technology skills in general. For example, the individual characteristics could vary in years of experience as the participants with a low number of experiences were selected based on their technology skills and on recommendations of peers. A detailed overview of the interviewees' demographics is presented in Table 2. Some of the interviewees have experiences in multiple roles, especially the lead engineers have preliminary working experience as specialty engineer. The interviewee numbers referred to in the results and analysis section originate from Table 2 below.

Table 2 Overview individual demographics of interviewees

Interviewee	#1	#2	#3	#4	#5	#6
Role	Engineer	Engineer	Engineer	Manager	Manager	Manager
Specialty	Designer/ modeler	Designer/ Modeler	Modeler	Lead engineer	Lead engineer	Lead engineer
Working experience	15	3	2	18	18	14
Discipline	Infra	Civil	TTI	Infra	Civil	TTI
Relatics experience	15	3	2	12	10	8
Sex	Male	Male	Male	Male	Male	Male
Education level	Bachelor	Bachelor	Master	Bachelor	Master	Bachelor

4.1.2 Data collection

As stated in the latter, the objective of the interviews is to identify and understand the tasks and responsibilities, information needs and fitness for use of the CMDB. The data collection is performed by a short questionnaire at the start of each interview. This questionnaire focuses on the tasks and responsibilities and gives context to the processes in which the interviewee is involved. Obtaining the tasks and responsibilities is fundamental to the successive information needs and fitness for use. Semi-structured qualitative interviews with both closed and open-ended questions are conducted to be able to dive deeper as the different parameters to be measured require different approaches (DiCicco-Bloom & Crabtree, 2006) (Adams, 2015). The interviews are conducted in Dutch as both the interviewees and interviewer's mother tongues are Dutch. Furthermore, the interviews are expected to last 60-75 minutes. All individuals were interviewed in a consistent setting via a video call and have been recorded, ensuring the ecological validity. The interviews have been guided by an interview protocol, which has been supplied preliminary to the interview and can be found in Appendix C. The interview protocol and therefore the results of the interview, are presented in three parts: tasks and responsibilities per process, information selection (information needs) and fitness for use. The interview protocol is a work in progress document and will be assessed after each interview. The interviews are held iteratively as new findings could emerge after interviews as well as during the interview, therefore, follow up questions are listed. Besides, after finishing the interviews, a finding according to the information needs in a particular process has been cross-checked with an interviewee of both role types, this is further specified in this analysis paragraph.

4.1.3 Data analysis

The results of the interviews are subdivided into tasks and responsibilities, information needs and perceived fitness for use. These are considered separately for clarity. The tasks and responsibilities part give context to the distribution of tasks and are analysed straightforward. The information needs are analysed by the information needs characteristics and the fitness for use results are structured by thematic DQ/IQ framework. The interview data that is used for the analysis presented as quotes or referred to in Appendix F - I.

4.1.3.1 Tasks and responsibilities

Each role has its own function in the development phase of construction projects. The tasks and responsibilities are the base for the information needs in a professional setting (Leckie et al., 1996).

Therefore, Table 3 presents a summary of the involvement of the roles in each process and the tasks and responsibilities in these processes. The data originates from the questionnaire conducted preliminary to the interview. The original list of processes is used as guidance during the interview, a full overview is presented in Appendix D. The list is based on the systems engineering processes mentioned in chapter 2.1. For all processes, the CMDB is used or should be used. The tasks and responsibilities are fixed and can be easily explained by the interviewees. The system analysis and system control processes have been recognised in a later stage as these were discussed during the interviews as trade studies, changes, or alternative solutions. System analysis and control are split in two separate items as the specialty engineer is only involved in system analysis and both processes have a significant different meaning.

Table 3 Tasks and responsibilities per role per process

Processes	#	Specialty engineer	#	Lead engineer
Requirements analysis	-	NA	3	Fully responsible for (re)structuring of requirements information
Functional analysis and allocation	-	NA	3**	Fully responsible for (re)structuring of functionalities and allocating to objects
Design synthesis	3	Largely responsible for processes in which solution space information is obtained and design product is to be developed	3	Managing and assisting specialty engineer
Verification & validation	3*	Provides lead engineer design product information	3	Fully responsible for assessing design products and performing V&V process
System analysis	3	Partly responsible for researching and assessing inquiries related to e.g., a change or impact study	3	Partly responsible for managing, researching, and assessing inquiries related to e.g., a change or impact study
System control	-	NA	3	Fully responsible for managing the progress of the work packages
Interface management	2*	Requires information for solution space on objects and might identify interfaces the design process	3	Fully responsible for identifying, management and resolving interfaces

Number of counts
* Only involved in a single activity of the process
** Not always performing functional analysis and allocation in practice

4.1.3.2 Information needs

In the information seeking model of Leckie the information needs are successive to the tasks (Leckie et al., 1996). The information needs are analysed by the information needs characteristics: individual demographics, context, frequency, predictability, importance and complexity (Leckie et al., 1996). The information needs originate from the tasks that are performed in the systems engineering processes, therefore the needs are stated per role and per process. As the tasks and roles differ, the interview data are analysed and presented per role, see Table 4 and Table 5. The analysis results are substantiated by quotes presented in the right column. Furthermore, the noteworthy information needs variables are between brackets. As the functional analysis and system analysis and control processes are perceived as noteworthy, separated processes after the interviews were conducted, the interview tapes are listened back. In 5/6 interviews the concept of the system analysis or system control was discussed. Besides, one interviewee of each role has requested on the relevance of the process which is verified. Furthermore, the functional analysis has been discussed in the interviews with the lead engineers as well, but this process appeared to be less important.

Table 4 Information needs specialty engineer

Processes	Information needs	Quotes
Design synthesis	3 out of 3 specialty engineer state that their information needs are on a daily basis (recurrent, predictable). The information required is related to the particular objects of interest and the environment. To align the solution space with other specialty engineers, discussions take place. The information is required in general object related overviews (As-is situation) as well as in overviews on request (new, complex).	*"Information needs are related to object's solution space (e.g., object specifications, requirements, functionalities, design decisions, dimensions, starting points) which could differ per subphase (VO, DO, UO)." (Quote A1-1 & Quote A1-2)* *"The information needs could also include the presentation of a set of (adjacent) objects for overview or comparison." (Quote A1-3)*
Verification & validation	3 out of 3 specialty engineers state that the self-made design products and the solution space information of the particular object(s) are required to demonstrate to the lead engineer (recurrent, predictable)	*"Information is to be accumulated on the design products on any level in the hierarchy." (Quote A2-2)*
System analysis	2 out of 3 specialty engineers characterise the system analysis by a varied scope of dynamic and sudden inquiries. Inquiries such as change assessments, impact assessments or alternative engineering studies need to be initiated, developed, and assessed (new, unpredictable, urgent). The practical information needs could range from single objects to overviews of similar entity types and compositions of different entity types located on different system levels (complex)	*"The information needs appear in situations such as new information (e.g., requirements) or new insights (alternative designs). The changes could contain any kind of entity in any kind of composition, which will be known when the information is available." (Quote A3-1)*
Interface management	2 out of 3 specialty engineers state that they identify interfaces by accident, however, before reporting an interface, contextual research is required (new, unpredictable, urgent, and complex). After resolving, the information is required as input for the design synthesis.	*"Interface identification is performed by lead engineers but missed items are identified by specialty engineers. To be sure on identifying interfaces, proper information overview is required." (Quote A4-1)*

As the tasks of the lead engineer are in most cases complementary, the associated information needs are as well complementary.

Table 5 Information needs lead engineer

Processes	Information needs	Quotes
Requirements analysis	3 out of 3 lead engineers state that requirements are obtained from the client or external stakeholders. The requirements are assessed and are SMART formulated, for which an alternative route is used such as Excel (complex).	*"The process of requirements analysis requires a system that is capable of restructuring, colouring or filtering of information to understand and process the requirements" (Quote: A1-4)*
Functional analysis and allocation	1 out of 3 lead engineers (electrical engineering) require the requirements analysis for the functional analysis process (new).	*"The implementation of functional trees depend on the wishes of the client as the client often determines the solution space, often not used in infrastructure and civil." (Quote: A2-4)* *"The functional trees are used in the electrical discipline as the solutions are structured in independent decompositions, called the Logical Functional Fulfillers (LFV)." (Quote A2-6)*
Design synthesis	3 out of 3 lead engineers require the progress information of the specialty engineers in the	*"As the lead engineer is familiar with the information structuring in the CMDB, the*

	design process. Furthermore, the specialty engineer is assisted by presenting solution space information (predictable, noncomplex).	*specialty engineer is assisted with obtaining information on the solution space" (Quote: A3-4)*
Verification & validation	3 out of 3 lead engineers require the solution space information of the particular object(s) to assess the products and manage the verification in the CMDB (non-complex).	*"The design product and solution space information are required to assess whether or not the design product complies with solution space" (Quote A4-4)*
System analysis	1 out of 3 lead engineer state that information required in the system analysis could be in any shape or composition. However, as the lead engineer is aware of his own discipline and the related disciplines, the impact is automatically estimated (complex, unpredictable).	*"In the system analysis process information could be required on any type of object or other entity. Depending on the size and impact there are higher managers involved." (Quote A5-4)*
System control	3 out of 3 lead engineers state that they require progress information in an easily checkable format that is easily traceable. Decisions and the corresponding considerations made in the past are required as well (predictable, noncomplex).	*"The work packages representing the progress include all information that is to be managed such as finished activities or verified requirements." (Quote A6-5)*
Interface management	3 out of 3 lead engineers state that interface information is obtained via specialty engineers, other lead engineers or technical insights of the lead engineer. Interfaces can appear in any shape, between any object, and vary in complexity and therefore need to be managed closely (urgent, complex).	*"Information needs for both interface identification and management. The identification requires clear context on the object whereas management requires straightforward information to be aligned between disciplines both internally and externally, which require time and intensive management for optimal solutions." (Quote A7-6)*

4.1.3.3 Fitness for use

The fitness for use interview data presents the experiences with the system of both the specialty engineer and the lead engineer. The experiences are presented independently of the systems engineering process. A deductive thematic analysis is conducted on the interview data by the DQ/IQ framework (Westin & Sein, 2013). Data analysis resulted in a set of problem observations that are categorised per theme, which are presented in appendix H. After the thematic categorisation, the core problems are identified by a root case analysis, see appendix I. The results of both the thematic categorisation and core problems are linked and presented below in Figure 21. Each theme represents a selection of problem observations, however, the total list of problem observations can be found in Appendix I. The coloured links between the themes and the core problems represent the core problems that cause the problem observations.

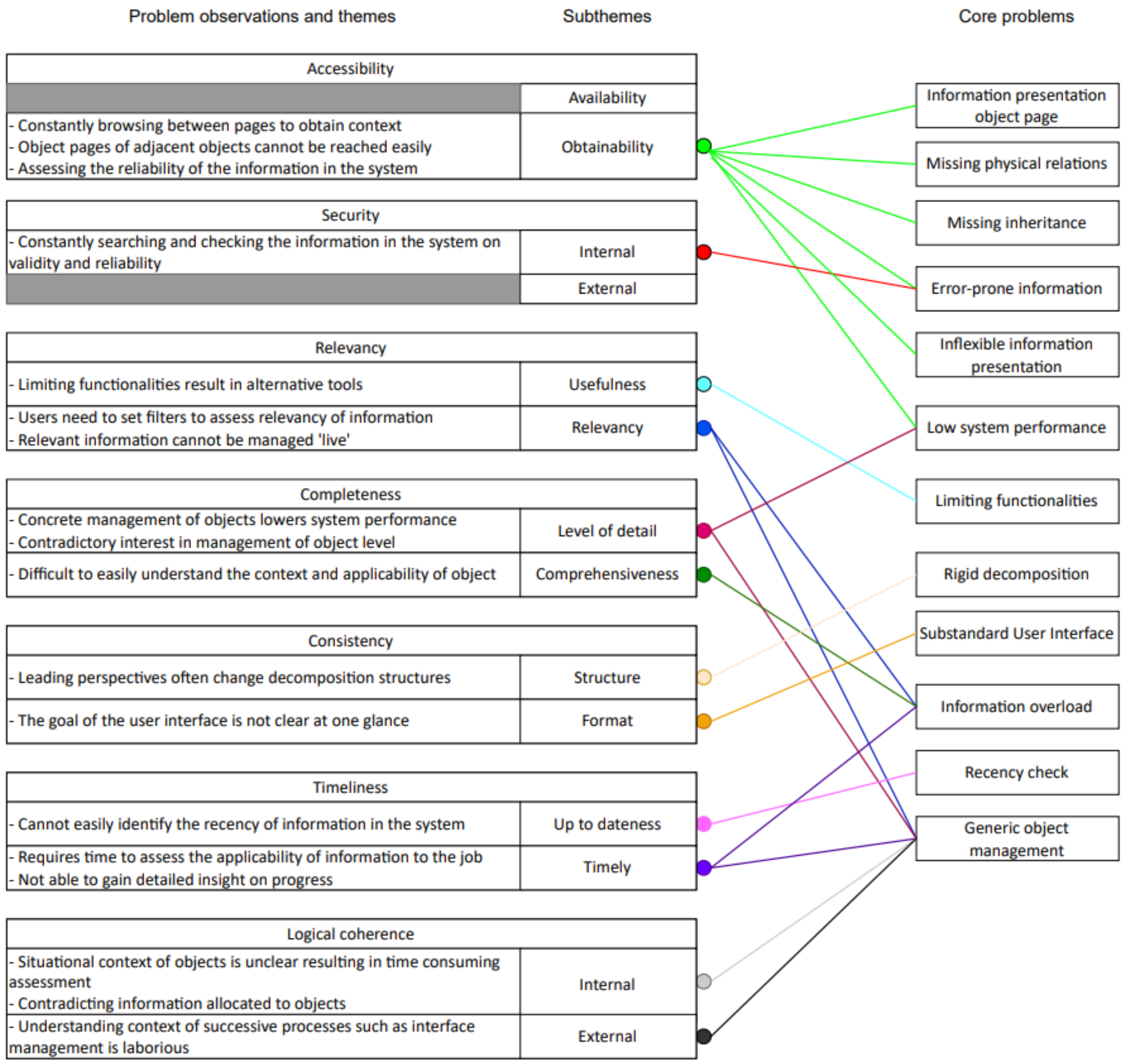


Figure 21 Problem observations - Themes - Core problems

For overview, the problems are categorised into structuring, presentation, and others. The main core problems relate to the structuring and presentation categories. The majority of the core problems are observed at the specialty engineer that obtains object specific information on the particular object pages in the design process. In practice, the specialty engineer is hardly able to succeed in this. Below in Table 7 the problems are explained in more detail including a quote and a coloured circle is assigned representing the associated role, see Table 6.

Table 6 Identifiers of problems represented by coloured circle

	Specialty engineer
	Lead engineer
	Both roles

Table 7 Overview core problems

Presentation – Information presentation object page

Information on the object page is presented fragmented or is not managed at all in the system. For example, requirements information on the object page the user needs to browse between two different pages for which the loading speed is low. On the other hand, relations between objects or design decisions are not managed at all in the system. (Quote: B1.2-1a & B1.2-3a & B1.2-3c)

> *Analysing object requirements on a single object might take up to 30 minutes as I frequently (up to tens times at once) have to browse (30 sec loading time) between different web pages to understand the fragmented requirements presentation such as requirements text. This process is repeated dozens of times for understanding the objects in the vicinity and requirements allocated to parent objects" (Interviewee 3).*

Structuring – No relations between physical objects

There are no physical relations present between physical objects. As a result, the user cannot easily gain context on a particular object, browse to an adjacent object, and cannot search for information based on a particular relation. The ideas need to be imagined by the user and the actions are to be performed manually. (Quotes: B1.2-3c & B1.2-6)

> *"My own developed system structures are not the problem, however, in case I need information from other disciplines such as Civil I need more context information as the object decomposition is not clear." (Quote B1.2-6)*

Structuring – Missing inheritance

There are no inheritance relations present in the model between parent objects and child objects. As a result, the user needs to identify the applicability of information (requirements) allocated to parent objects. (Quote: B1.2-3b)

> *"At the moment I am working on the service corridor and the boundary condition minimum clearance outline (PVR) is not presented on object level while it is extremely relevant. As a result, the information is not directly incorporated, and users are expected to memorise this" (Quote 1.2-3b)*

Structuring – Error-prone information

The information in the system is manually inserted and managed. Besides, the information is loosely coupled. As a result, human errors, subjectivities, and information asymmetry are experienced. Consequently, the reliability and validity of information is disputed. (Quotes: B2.2-1 & B1.2-6)

> *"The process of recording information in the CMDB is subjected to subjectivities and typos resulting in decreasing reliability of the information. For example, the conceptualisation of objects might differ per perspective. The object names, properties or any other data could be captured wrongly due to e.g., minor writing mistakes which might result in a low obtainability for particular users." (Quote: 2.2-1)*

Presentation – Inflexible queries and information presentation

The information presentation in the system cannot be easily adjusted. Therefore, other systems such as Word are used for tweaking activities in the analysis process. In case of deviating information needs such as composing different entities, specialists are required to develop new queries as the system is not fit for purpose for flexible information needs. (Quotes: B3.1-1)

> *In case of major design decisions, a trade study is performed in which the system needs to be assessed. Consequently, a detailed and traceable assessment is being made for which detailed information is required. Therefore, the specialty engineer requires the information in the composition of the situation. However, the CMDB doesn't support this function. (Quote 3.1-1)*

Others – Low system performance

The loading speed of pages is considered to be low. As the information needs of the user result in many browsing activities between different pages to understand the situation, the user loses time on loading pages. (Quotes: B1.2-3a & B1.2-6 & B4.1-4)

> *"When managing information in too much detail the system might work against you as the speed of the system reduces and the findability of information decreases" (Quote: 4.1-4)*

Others – Limiting editing functionalities

The functionalities of the system are lacking in the basics. Therefore, the information is exported and tweaked on the hard drive. As a result, the single source of truth objective is not met. (Quotes: 3.1-4)

> *"In the process of requirements and functional analysis, a major list of requirements is presented to the lead engineer. These requirements need to be analysed, decomposed, and allocated to objects. Therefore, tweaking of this information is required. However, Relatics doesn't offer the functionalities to easily tweak this information such as hiding columns, colour objects or other functionalities that Excel does offer." (Quote 3.1-4)*

Structuring – Rigid information model

The preferences of the decomposition structuring change through time in a project. As the information model cannot easily adjust to these changes, information will get lost. As a result, users need to search for particular information again. (Quote: B5.1-1)

> *"In the development phase of a project there is a lot of discussion on the preferred system decomposition as different disciplines have their preferences and enter the project in a different point in time." (Quote: B5.1-1)*

Others – Substandard user interface

The user interface is considered to be substandard as the format might change for each project whereas the result is considered to be not improved. Therefore, the clarity of interface might affect the first period of working in a new project. Besides, working on multiple projects at once might be disturbing. (Quotes: B5.2-2&3 & B5.2-4)

> *"At the start of a project, the user interface takes some time to get used to. As the lead engineer spends so much time in the system, the system becomes easy to work with." (Quote: 5.2-4)*

Presentation – Information overload

The information presented on e.g., object pages is abundant as variables such as time, activity or interest are not considered. As a result, the user needs to assess the relevancy of information. In fact, the user applies a human filter to the information. Whereas in frequently considered objects the learning curve will be fast in case the specialty engineer searches for information at adjacent objects, the ability of the specialty engineer to assess relevancy will be significantly lower. (Quotes: B3.2-3 & B4.2-3 & B 6.2-1 & B5.2-4)

> *"I often encounter requirements that are not relevant for my task at a specific point in time. For example, a requirement on the colour of the roadside is not of interest to me in the VO phase. In large projects there are thousands of requirements" (Quote: B6.2-1)*

Presentation – Recency check

In a project there is a lot of face-to-face communication that might result in information asymmetry in the system. Currently, users are not able to check the recency of the information and need to use in good faith or inquire the responsible person. (Quotes: B6.1-1)

> *"When searching for information, I often question myself whether or not the information is still valid. The answer is found at the responsible discipline which I contact in that case." (Quote B6.1-1)*

Structuring – Generic object management

Physical objects are managed on generic level in the system. Consequently, information is generically allocated as well (e.g., requirements or physical relations). As a result, identifying the situational context of concrete objects require searching and assessing time. Furthermore, queries cannot be performed on detailed level as well. Besides, successive processes such as interface management also require additional assessing time. The contradicting interests of both roles need to be resolved. (Quotes: B4.1-1 & 4.1.4 & B7.1-1 & B7.1-2 & B7.1-3 & B7.2-1 & B4.1-4 & B6.2-4 & B7.1-4 & B7.1-5 & B7.1-6)

> *"Objects are generically managed in the system decomposition, as a result, the situational context is not considered, whereas information of the specific objects is very relevant." (Quote B4.1-1)*

> *"When managing information in too much detail the system might work against you as the speed of the system reduces." (Quote 4.1-4)*

4.1.4 Interview results

The interview results are presented by the tasks and responsibilities, information needs and fitness for use. The tasks and responsibilities elaborate on the complementary division of roles between the specialty and lead engineer. The information needs generally focus on the information needs per role as well as the differences between the roles. The fitness for use focuses on the core problems that have been identified and the difference in the perceived fitness for use between the specialty and lead engineer. At last, the relation between the information needs and the fitness for use is stipulated.

4.1.4.1 Tasks and responsibilities

The shape of the information needs and the perceived fitness for use are dependent on the tasks and responsibilities. Therefore, the tasks and responsibilities function as base for the information data. The tasks and responsibilities per role are regarded to be similar on abstract level, despite the variety of disciplines in which the roles are involved. The specialty engineer's tasks mainly consist of decisions-making on detailed object level. Although the specialty engineer might assist the lead engineer in other processes, the specialty engineer is mainly involved and largely responsible for the design process. The tasks and responsibilities of the lead engineers of different disciplines match as well. The tasks of the lead engineer focus mainly on management activities such as requirements analysis, controlling progress and assisting in design process, interface management and verification and validation. In this perspective, the lead engineer carries the full responsibility for all the processes.

4.1.4.2 Information needs

According to the model of Leckie the information needs are dependent on the tasks of a role. These tasks are to be performed in a particular process, therefore, the information needs are analysed per process. In this paragraph the results of the information needs are stated by focussing on the general results as well as outliers.

The information needs of the specialty engineer originates from the decision-making process and mainly focus on the object of interest the engineer is working on. The required information is related to the particular object as well as the context such as adjacent objects. Besides, the specialty engineer is also interested in information from parallel managed processes such as interface management. The information is developed and originates from other participants in the project. The specialty engineers' information needs in the different processes appear to be comparable as these are related to the solution space of the object of interest. Therefore, the information needs can be characterised as recurring and predictable. However, the information needs related to the system analysis processes are characterised to be new, unexpected and could be highly urgent and difficult to resolve. In practice, these information needs could focus on particular objects at any level, the context of object, the composition of multiple information entities.

The information needs of the lead engineer vary per process as for the requirements analysis detailed and flexible information composition is required, whereas for the management activities, the lead engineer focuses on managing the aligment between parties in the process. The tasks in these processes do vary strongly and therefore the information needs as well. In the requirements analysis process the lead engineer receives information that is partly unpredictable and the structuring process is complex. On the other hand, in the management tasks in the processes, the lead engineer requires progress and alignment information.

4.1.4.3 Fitness for use

The results of the perceived fitness for use are transformed into core problems which consequently are grouped into presentation, structuring and others. The core problems originate from the problem observations which originate from the interviews. As the problem observations are stated by a particular role, the core problems are as well stated per role. As most of the problem observations recurred in multiple processes, the processes are not included.

It is noted that the specialty engineer is the role that experiences the most drawbacks in the system. Some core problems appear to have multiple problem observations and are mentioned frequently by the interviewees. The specialty engineer is often not able to efficiently and effectively identify the context as relevant systems engineering information cant be obtained. In other words, the individual does not perceive the advantages of using the system. In order to obtain the particular information, workarounds are implemented by the specialty engineers. However, the implementation of workarounds means that the main system is omitted which consequently leads to a snowball effect. The core problems that have been identified for the specialty engineer are the generic management of objects, the limited scope of entities managed in the system.

The lead engineers perceive the fitness for use differently per process. Workarounds are implemented for the requirements analysis and functional analysis, whereas the system is considered to be fit for use in the verification and validation and interface management processes. The lead engineers require flexibility in the information composition and presentation in the requirements analysis and functional analysis. Therefore, the information is exported to Word and Excel so that it can be tweaked. On the other hand, the verification and validation and interface management process requires central control and management from a central system for which the CMDB is considered to be fit for purpose.

The main differences between the perceptions of the fitness for use between both roles originate from the deviating information needs of the roles in the systems engineering processes. The specialty engineer requires detailed engineering information whereas the lead engineer needs to manage the systems engineering processes. Consequently, there are contradicting interests as the specialty engineer requires detailed management and the lead engineer prefers abstract object management. However, in the end, the lead engineer develops the information model and therefore determines the information in the system. The summaried overview of the core problems identified in the interviews are presented per category and succintly explained in Table 8.

Table 8 Core problems

Category	Roles	Core problems	Problem explanation
Presentation	●	Recency check	Users are not able to check the recency of the information
	●	Information overload	Information presentation do not differentiate on variables such as time, activity, or interest
	●	Information presentation object page	Necessary information is not managed or presented fragmented
	●	Inflexible information presentation	Not possible to easily query random information or present information randomly

Structuring		Missing physical relations	No possible to easily browse to adjacent physical objects
		Missing inheritance	Not possible to selectively pass information to child object(s)
		Error-prone information	Information is manually inserted and loosely coupled
		Generic object management	Objects are managed on generic level representing up to dozens of real-world objects in different situations
		Rigid information model	Information cannot be easily adjusted to other perspective(s)
Others		Low system performance	Browsing time of web pages takes too long (up to dozens of seconds)
		Substandard User Interface	Goal of interface is not clear at one glance
		Limiting editing functions	Information cannot be easily tweaked and edited or differently presented

	Specialty engineer		Lead engineer		Both roles

4.2 Summary

The goal of the practical study is to identify and understand the perceived fitness for use of different roles in the CMDB. Therefore, interviews are held to identify the tasks and responsibilities of the roles, the information needs that arise as well as the perceived fitness for use in the CMDB. The sub research question below is being answered.

SQ 5 *What is the perceived fitness for use in the configuration management database used in the development phase of large infrastructure projects?*

The interviews focus on identifying and understanding the tasks and responsibilities, information needs and fitness for use of the different users. The tasks and responsibilities need to be identified as these function as base of the information needs and therefore the fitness for use. The interview results show that the tasks and responsibilities of the roles differ per process. The specialty engineer is predominantly involved and responsible for the design synthesis and system analysis process and to a lesser extent in the verification and validation and interface management. On the other hand, the lead engineer is involved in and fully responsible for all systems engineering processes: requirements analysis, functional analysis, designing, system analysis and control, verification and validation and interface management.

The interviews show that the tasks and responsibilities of both roles deviate. As a result, the information needs and perceived fitness for use also differ. The information needs of the specialty engineer are diverse and mainly originate from the design synthesis and system analysis processes. In the design synthesis the specialty engineer requires information such as the solution space of particular objects, or the adjacent objects. In the system analysis, the specialty engineer needs to evaluate or assess change, impact, or variant studies. Information could be required on any entity in any composition. In these processes, the specialty engineer often experiences time-consuming activities, non trustworthiness and incomplete information or is even unable to identify and obtain relevant information. In order to effectively obtain information, people use workarounds in the shape of other software tools or direct communication with other participants which might lead to incrementally asynchronous information and consequently cause a snowball effect. The information needs of the lead engineer differ per process as the requirements analysis and functional analysis are characterised by restructuring of information. The lead engineer requires functionalities to be able to restructure and colour the information whereas in the management activities the lead engineer needs to be able to manage and align progress of processes.

Analysing the fitness for use of both roles results in the following core problems: recency check, information overload, information presentation object page, inflexible information presentation, missing physical relations, missing inheritance, error-prone information, generic object management, rigid information model, low system performance, substandard user interface and limiting editing functions. To summarise, the perceived fitness for use strongly depends on the information needs of the particular user. The specialty engineer requires detailed object information whereas the lead engineers often focusses on managing the systems engineering process. As a result, the specialty engineer experiences severe drawbacks, and the lead engineers declares to be satisfied.

5 Design of solution

The results of the previous chapters in the report brings us at the design of solution. The context of the systems engineering information system has been identified as well as the involvement of the particular roles and the core problems in the system. The core problems are considered as base of this chapter for further development. This chapter focusses on a particular use case in which several solutions are proposed. The chapter finishes with a use case example that state the practical relevance and a verification and validation paragraph.

SQ 6 How to incorporate identified role specific information needs to improve fitness for use?

5.1 Design focus

The goal of the design focus is to improve the fitness for use of the CMDB by meeting the various information needs of the users. As stated in the latter, the results of the report so far function as the base for the design focus. In the design focus, the problems will be adduced shortly. Furthermore, the design will focus on the target group that is served in the particular use case.

5.1.1 Problem statement

The motive for conducting this research is that users are dissatisfied with the CMDB in the development phase of large infrastructure projects. The results of the implementation evaluation show that especially the specialty engineers experience drawbacks in the fitness for use of the CMDB. The specialty engineer mainly uses the CMDB for obtaining information for decision making activities. However, the particular information needs of the specialty engineer strongly differ in the design synthesis and system analysis process. In the design synthesis the information needs are recurrent, noncomplex, and predictable. However, the specialty engineers' experiences problems with obtaining this information from the CMDB as the presentation is not sufficient. On the other hand, the specialty engineer is also involved in the system analysis in which the information needs are characterised to be new, unpredictable, urgent, and complex. The specialty engineer has difficulties to obtain the information in an effective and efficient way. As a result, the particular users experience time-loss in identifying and obtaining information. Consequently, they omit the CMDB in their processes and alternative routes are implemented. The implementation of workarounds results in risks of incomplete information, non-aligned processes and consequently a snowball effect as the reliability of the dynamic systems engineering information decreases. This is contradicting to the goal of the transition towards MBSE which states that all stakeholders should benefit and be included in the single source of truth in order to make it work. In the end, the CMDB is not able to serve this information need as both the presentation as well as the underlying structuring cannot handle these needs. The main problems identified in the practical research are listed per category and core problem, see Table 9 below.

Table 9 Main core problems specialty engineer

Category	Core problems	Problem explanation
Presentation	Recency check	Users are not able to check the recency of the information
	Information overload	Information presentation do not differentiate on variables such as time, activity, or interest
	Information presentation object page	Necessary information is not managed or presented fragmented
	Inflexible information presentation	Not possible to easily query random information or present information randomly
Structuring	Missing physical relations	No possible to easily browse to adjacent physical objects
	Missing inheritance	Not possible to selectively pass information to child object(s)
	Error-prone information	Information is manually inserted and loosely coupled
	Generic object management	Objects are managed on generic level representing up to dozens of real-world objects in different situations
	Rigid information model	Information cannot be easily adjusted to other perspective(s)

5.1.2 Target group

The results of the interviews show that the specialty engineer role is the group that experiences crucial drawbacks with the fitness for use of CMDB, especially in the design synthesis and system analysis processes. Due to the abstract approach the variety of disciplines in the specialty engineers' group are considered to be a uniform group.

5.1.3 Use case

The use case considered in this research mainly focusses on the specialty engineer in the systems engineering processes, see Figure 22. The use case presents the different modules in the CMDB that are relevant for the specialty engineer. In the design synthesis process, the specialty engineer mainly resides in the object modules to obtain object information. For the verification and validation process, the specialty engineer obtains information such as requirements on particular objects and uses the verification and validation module. For both the design synthesis and verification and validation process, the specialty engineer makes use of the requirements modules, especially when detailed information on requirements is needed. Furthermore, the interface management module is used when for identifying and obtaining information on interfaces. At last, in the design synthesis the specialty engineer mainly uses the object module and requirements module.

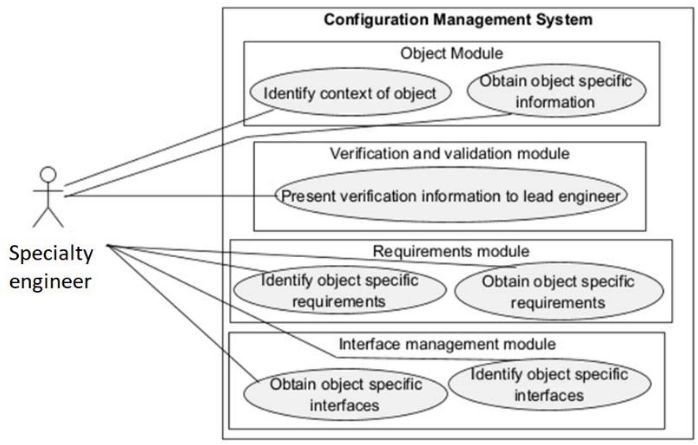


Figure 22 ERD use case diagram of specialty engineer in CMDB

5.2 Artifact design

In the artifact design chapter, a conceptual approach is proposed that contribute to solving the problems presented in Table 9. At first an overview of the problems and solutions are proposed. Secondly, the solutions are elaborated on in further detail by elaborating on the development approach as well. Furthermore, each solution relates to the problems and elaborates on how the information needs are served and how the fitness for use will be improved.

5.2.1 Overview problems – solutions

The problems identified and the corresponding solutions are presented in Table 10. The conceptual solutions could solve multiple problems and some problems are solved by multiple solutions; therefore, multiple pink boxes are checked in Table 10. The solutions are developed based on the iterative design cycle process that stipulates on the problem, goal, requirements, and solutions, see Appendix J.

Table 10 Problems – Solutions matrix

		Solutions				
		Physical relations	Abstraction levels	Conceptual data model	One stop object page	Custom query
Problems	Recency check				■	
	Information overload				■	
	Information presentation object page				■	
	Inflexible information presentation		■	■		■
	Missing physical relations	■		■		
	Missing inheritance			■		
	Error-prone information		■	■		
	Generic object management		■	■		
	Rigid information model		■			

5.2.2 Approach to conceptual solutions

In this paragraph, each particular solution is further specified in this paragraph by stipulating on the design cycle process activities as well as the relatedness to other solutions. Furthermore, the solutions are visualised by graphics. In order to make the solutions tangible and understandable, the solution visualisations contain concrete information.

5.2.2.1 Physical relations between objects

Physical objects have all kind of relations with other physical objects. In current practice, information models often not manage these relations. Therefore, this solution focusses on the establishment of mutual relations between physical objects. Figure 23 visualises relations of a particular CCTV camera with a power supplier like a transformer and a mainstay such as a wall. Besides relations between physical objects, relations could also be established between any type of entity such as functionalities. Establishing physical object relations in a model improves the fitnes for use in several ways. At first, relations between the objects improve obtainability as links can be presented on the object page, see solution in paragraph 5.2.2.4. Second, relations between data elements improve context of the objects and other information. At last, establishing relations between data elements strenghten the information model and empowers the users to obtain information in different compositions, see solution presented in 5.2.2.5.

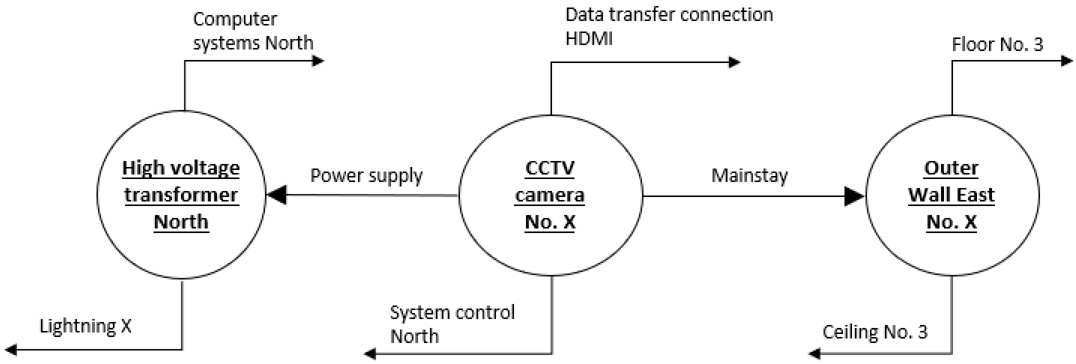


Figure 23 Conceptual overview of relations established to objects in system breakdown structure

5.2.2.2 Abstraction levels

The abstraction level solutions comprise three solutions at once as each sub models have a particular function. The approach to the abstraction level solutions consists of three layers that manage information from generic to concrete information. This solution is proposed to solve the error prone information and generic object management problem.

Generic object information

The upper abstraction level manages the generic object information. The generic object information formalises the conceptualisation of the project information. The model is formalised by adding systems such as controlled vocabulary and a specialisation tree. In practice, the sub-model is often referred to as a OTL or reference library. The controlled vocabulary reduces the error proneness of the information. The specialisation manages the conceptualisation of particular objects, see Figure 24. The generic object information model reduces the ambiguity of the conceptualisation of objects between users with different perspectives.

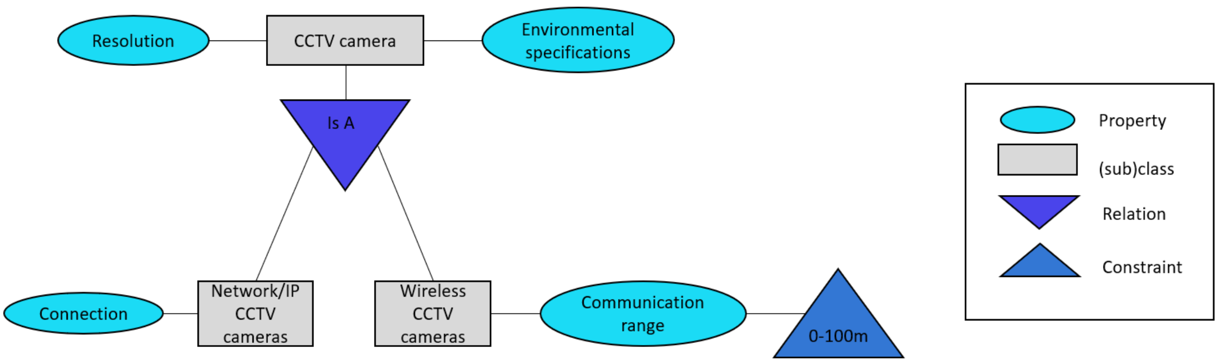


Figure 24 Specialisation CCTV camera

Abstract level

The abstract level fulfils the function as middle layer between the generic objects and the concrete objects. The decompositions could be required for multiple projects but could also be used multiple times for a recurring decomposition in a single project. The abstract level comprises 'has part' relations which are added to the objects originating from the specialisation sub model. As a result, a system structure arises. Abstract object management empower end users to efficiently allocate project information and unambiguously structure and allocate information. At last, the relations between physical objects are also valid for abstract objects and therefore, the users can also browse between abstract object pages. The abstract level meets both the information needs of the lead engineer and the specialty engineer as the project information can be allocated to generic objects.

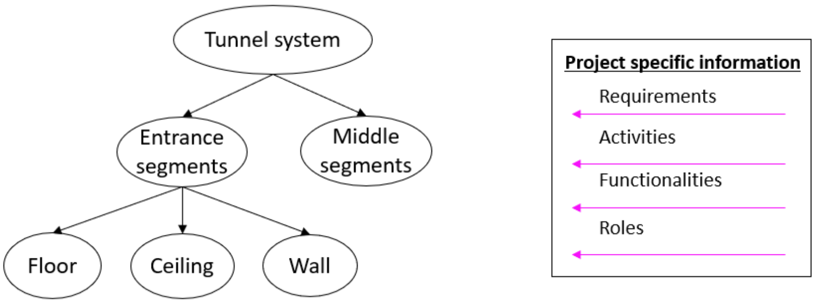


Figure 25 Abstract decomposition and project specific information

Concrete level

The concrete level manages concrete project information by adding information to the objects or relationships like codes, names, or numbers. Besides, the information is inherited from the abstract level by a classification relation. As a result, the project information allocated to abstract objects passed on to concrete objects. Therefore, information that is relevant to each object such as relationships or adjacent objects can be presented on particular object page. The concrete level enables the possibility to manage information on a detailed level or implement custom views. Therefore, the concrete level meets the detailed information needs of the specialty engineer. See below in Figure 26 the concrete 'has part' relation between an entrance segment and some components.

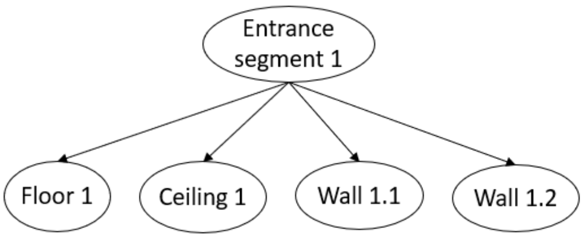


Figure 26 Concrete decomposition

5.2.2.3 Conceptual data model

The conceptual data model solution is an approach to structuring data model and the required functionalities, see Figure 27 and Table 11. The goal of the conceptual data model is to visualise the data management on different abstraction levels. The management on different levels enables the one stop page and custom queries solutions. A conceptual model is presented in an Entity Relationship Diagram notation, shows the entities, attributes, and relation types. The specialisation (pink) is presented on top, the abstract level (blue) is presented in the middle and the concrete level (turquoise) is presented below. The entities and relations presented in each sub-model give an indication on which information is managed in the model and how the information is managed in the model.

Table 11 Functionalities of conceptual data model

Functionalities	Explanation
Inheritance relation between sub models	Inheritance relations are present between the sub models. The inheritance function is one-sided and flow from top (specialisation tree) to bottom (concrete level).
Inheritance relation in specialisation tree	The specialisation tree requires a hierarchy and an inheritance relation between the objects. Properties are to be passed on to child objects.
Relations between entities	The mutual relations between physical objects are managed in the relation entities. This entity is linked to the object's entity in each sub model.
Hierarchy in entities	Recursive relations are applied to the specialisation, abstract level, and concrete level to manage hierarchies between objects.
Allocated information selectively passed on to child objects	Project-specific information allocated to physical objects in the abstract and concrete sub model might be relevant for child objects. The database model should give the opportunity to selectively flow down project-specific information to child objects.

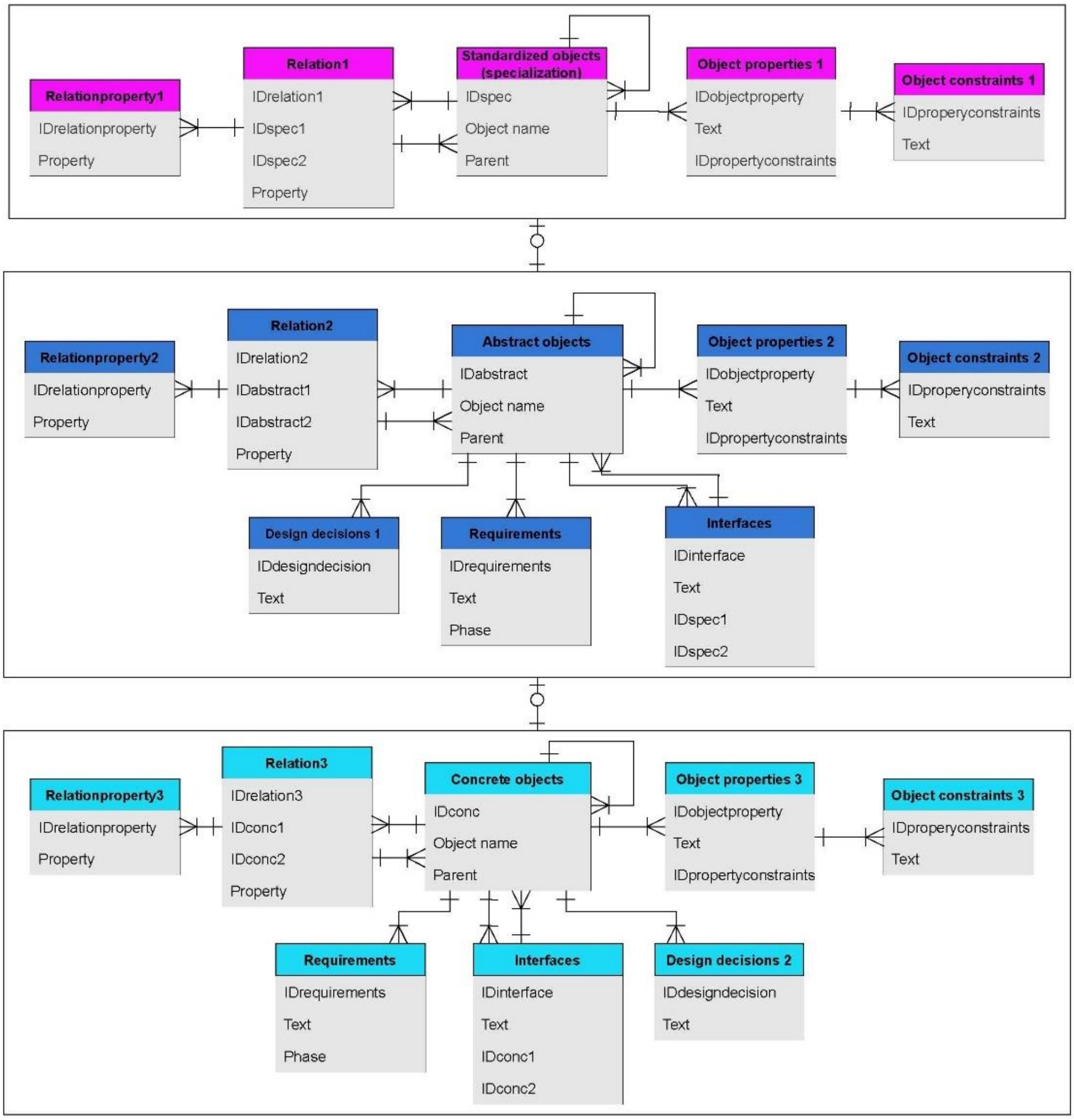


Figure 27 Conceptual data model (ERD)

5.2.2.4 One stop object page

The one stop page meets the predictable, recurrent information needs of the specialty engineer in the systems engineering processes. The specialty engineer mainly resides in the object module of the CMDB to obtain information allocated to objects. Therefore, the one stop page is initiated that includes the information that is associated to the particular object. Besides, the object page should also present the possibility to easily browse to related information, see Figure 28. The object page is relevant to represent both abstract and concrete objects. The page is enables by pre-established queries. The presentation solution consists of five solutions that mainly focus on the information entities and attributes ranging from recency check to design decisions to information tailoring, see Appendix K. The solutions focus on the improvement of relevancy by reduction information overload, logical coherence on an object page by only presenting relevant information, completeness by adding information such as design decisions that is required by engineers and obtainability by presenting links to other relevant physical objects. The information presentation could be further tailored by filtering or prioritizing according to which information is used for a particular role. However, this user specific view characteristics needs to be further studied in practice.

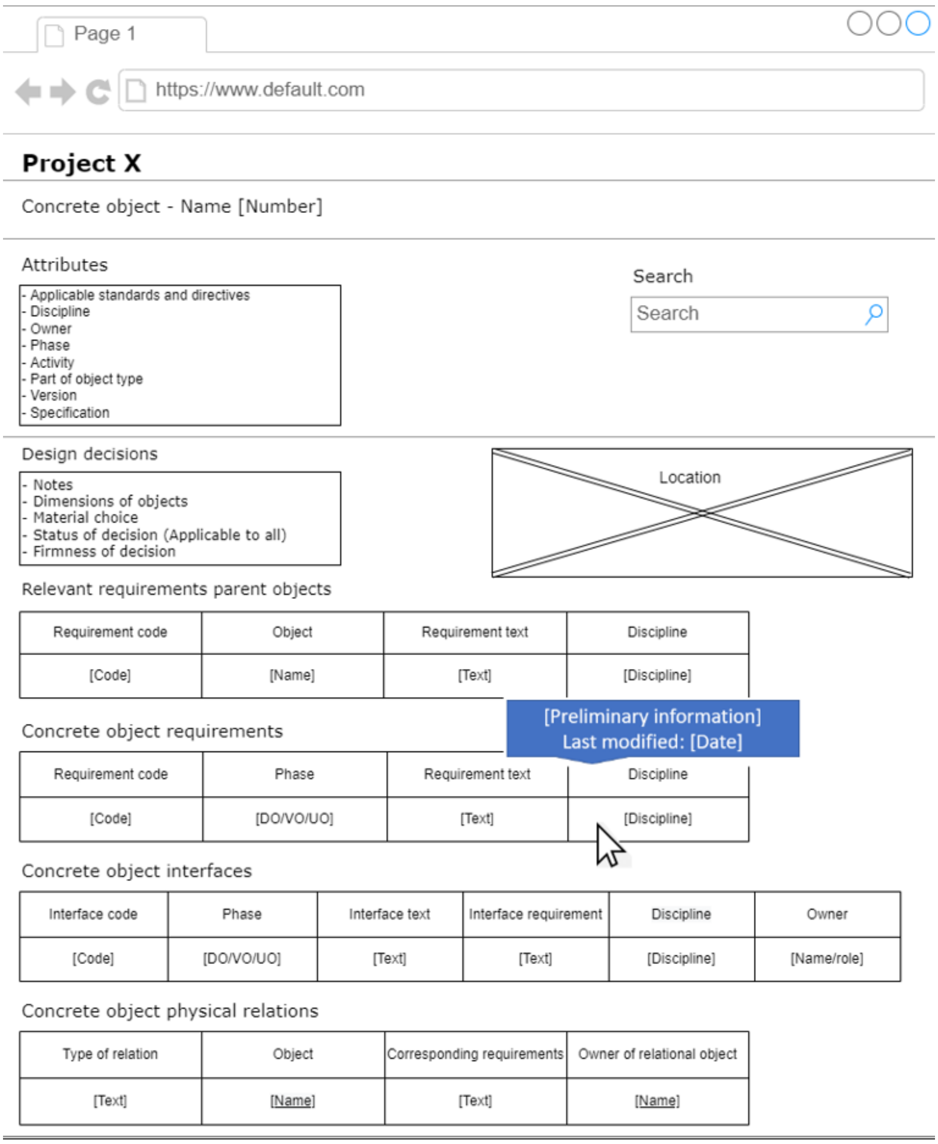


Figure 28 Example object page presentation

5.2.2.5 Custom queries

The conceptual custom queries solution serves the unpredictable, urgent, new, and complex information needs of the specialty engineer which are mainly observed in the system analysis process. The approach to the conceptual user specific view solution empowers the user to freely search for information in the system. In the as-is situation, information is presented in a static manner and complex information needs require detailed software skills. Besides, the added physical relations between objects enables empower the information model and therefore the information retrieval. The custom query consists of a viewpoint and a view as the viewpoint state the conditions and the view represent the obtained information, see in Figure 29. The custom query aims to improve: 1) obtainability as data can be obtained in any shape of any entity in any quantity, 2) relevance as the composition of data also might change the conceived information, and 3) completeness as more information needs can be satisfied. The custom query empowers the user to build user specific views as information can be obtained in any quantity, of any entity in any shape. The build queries could be saved for future use in case similar information models are used.

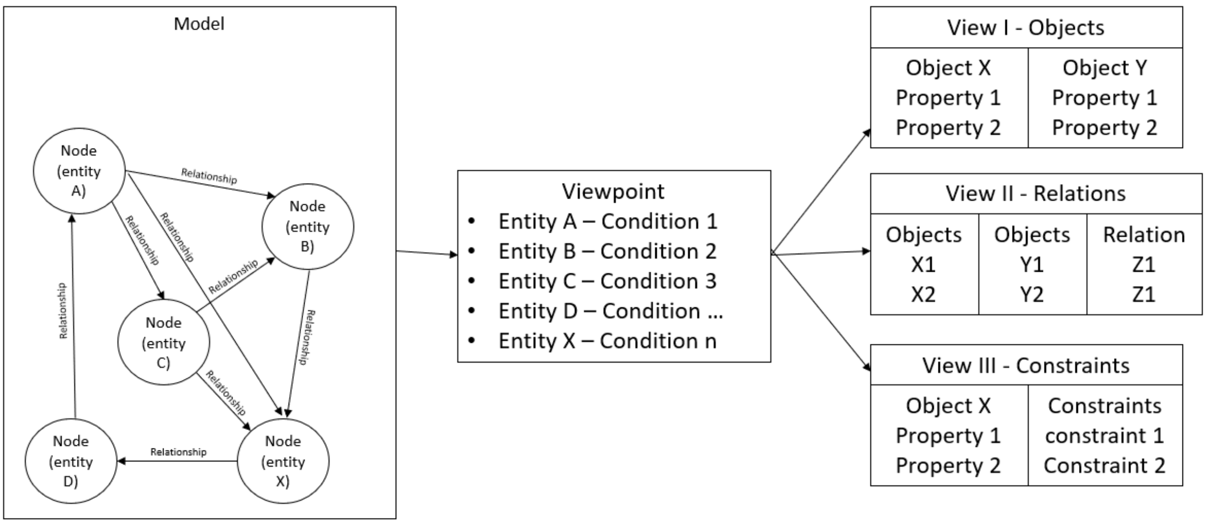


Figure 29 Schematisation of model and related viewpoint and views

5.3 Example of use case

In order to improve understanding of the solutions proposed in former paragraph, a use case is considered in the shape of a simplified infrastructure project in the development phase. The use case stipulates on a varied set of perspectives. At first, the use case characteristics are explained by a general description of the project, objects, and participants. Second, the step-by-step information model development is stipulated. Thirdly, the static information presentation is explained by presenting the object page. Fourth, the dynamic information presentation is explained by elaborating on user specific views. At last, the use case example is evaluated.

5.3.1 Use case project description

The simplified tunnel project considered consists of structural items, infrastructure items and electrical objects, see a top view of the project below Figure 31. The tunnel consists of two tubes for both driving directions, only the two middle segments have a ceiling.

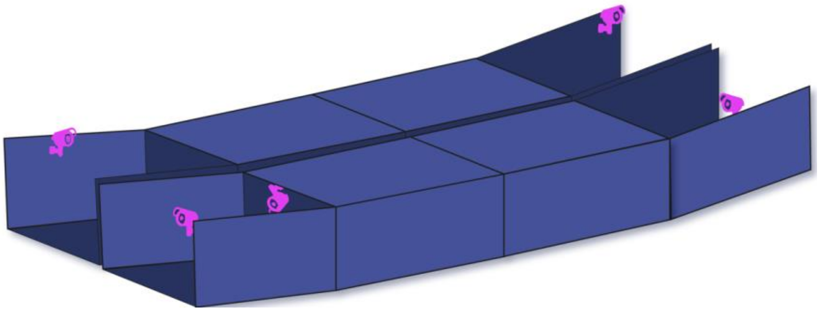


Figure 30 3D sketch of Tunnel project

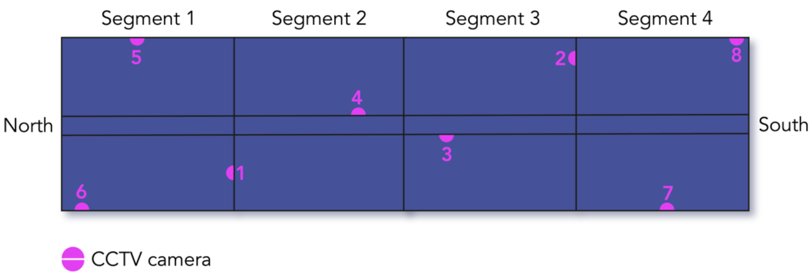


Figure 31 Schematic top view of Tunnel project

The physical objects managed in the CMDB are presented in Table 12. Each object has certain quantity, property, and relation data. Furthermore, different roles are involved in the development phase, see Table 13. The system engineer role does not belong to a particular discipline but assists the lead engineer in information management activities.

Table 12 Tunnel objects in use case project

No.	Object name	Quantity	Property 1	Property 2	Relation 1	Relation 2
1	Outer wall	8	Strength	Concrete cover	Connects to	Mainstay for
2	Inner wall	8	Strength	Concrete cover	Connects to	Mainstay for
3	Floor	4	Strength	Concrete cover	Connects to	Mainstay for
4	Ceiling	2	Strength	Concrete cover	Connects to	Mainstay for
5	High voltage transformer	2	Capacity	Voltage	Attached to	Provides power to

6	CCTV indoor type A	2	Mass	Turnability	Power supply	Suspended to
7	CCTV indoor type B	2	Mass	Turnability	Power supply	Suspended to
8	CCTV outdoor type A	2	Mass	Turnability	Power supply	Suspended to
9	CCTV outdoor type B	2	Mass	Turnability	Power supply	Suspended to

Table 13 Roles in use case project

Roles	Discipline
Lead engineer	Concrete/Infrastructure/Electrical
Specialty engineer	Concrete/Infrastructure/Electrical
System engineer	Not applicable

5.3.2 Information model development

The process of populating an information model is characterised to be incremental. Project specific information models require project specific information. In order to formalise the process of developing useable information, three abstract levels are introduced: the generic object management, abstract level, and concrete level. The generic object information manages the controlled vocabulary and specialisation, the abstract level functions as an overall project model and the concrete level manages the project specific relations. Particular information is added in each level, see Figure 32. Table 14 presents the roles that are involved in the processes that are presented in Figure 32. As the dynamic project information needs to be easily adjustable, the abstract levels are linked.

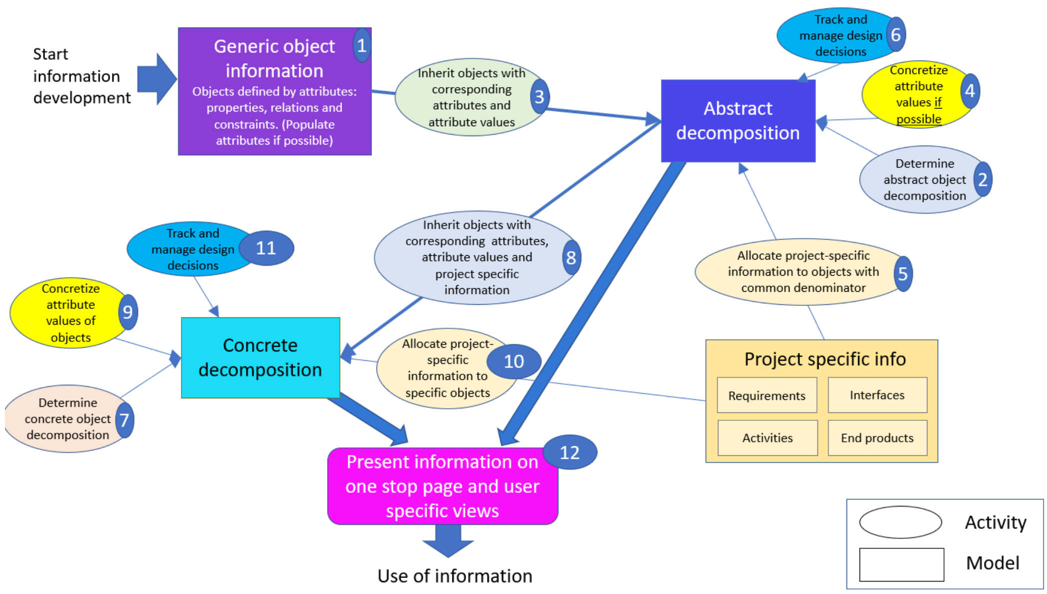


Figure 32 General scheme of development process model

Table 14 Step-by-step activities in information development process

No.	Activity	Role(s)
1	Generic object management in place	System engineer
2	Determine objects in abstract decomposition (object type)	System engineer
3	Inherit objects with corresponding attributes and attribute values from generic object management	System engineer/lead engineer
4	Concretise attribute values in the abstract decomposition if possible	Lead engineer/system engineer

5	Allocate project-specific information to object types	Lead engineer/system engineer
6	Track and manage design decisions	Lead engineer/system engineer
7	Determine objects in concrete decomposition	Specialty engineer/lead engineer
8	Inherit object with corresponding attributes, attribute values and project specific information from abstract decomposition	Specialty engineer/ lead engineer/ system engineer
9	Concretise attribute values of objects	Specialty engineer
10	Allocate project specific information to physical objects	Lead engineer
11	Track and manage design decisions	Specialty engineer
12	Present information on object(type) pages by user specific views	System engineer

5.3.3 One stop page

The goal of the design solution is to meet the specialty engineers' information needs by improving the fitness for use. The information needs are considered to be vary in complexity, frequency, predictability, and importance. The one stop pages serves the noncomplex, frequent, predictable, and recurrent information needs. As the information needs of the specialty engineer in the design synthesis are related to one or more particular objects, relevant information is presented in a central place, the object page. Object pages are implemented for both abstract and concrete objects each representing particular abstract information or concrete object information. Besides, the abstract and concrete levels consist of decompositions. These decompositions are stated on the system overview page. The information that is presented on both the systems overview page as the object page(s) can be tailored by time, role, or discipline. These tailoring options enable the user specific views and will improve the useability of the particular solutions.

System overview page: object (type) lists

The information model manages both abstract (object types) and concrete (individuals) objects, which are presented in overviews in Figure 33. In this figure, the straight pink arrows present the instantiation relation (abstract to concrete object), whereas the bended arrows represent the mutual relations. The coloured bended arrows represent the mutual relations 'power supply' (turquoise) and the 'connected to' (royal blue). The user is able to click on both objects to go to the object (type) page, which is presented in the next example.

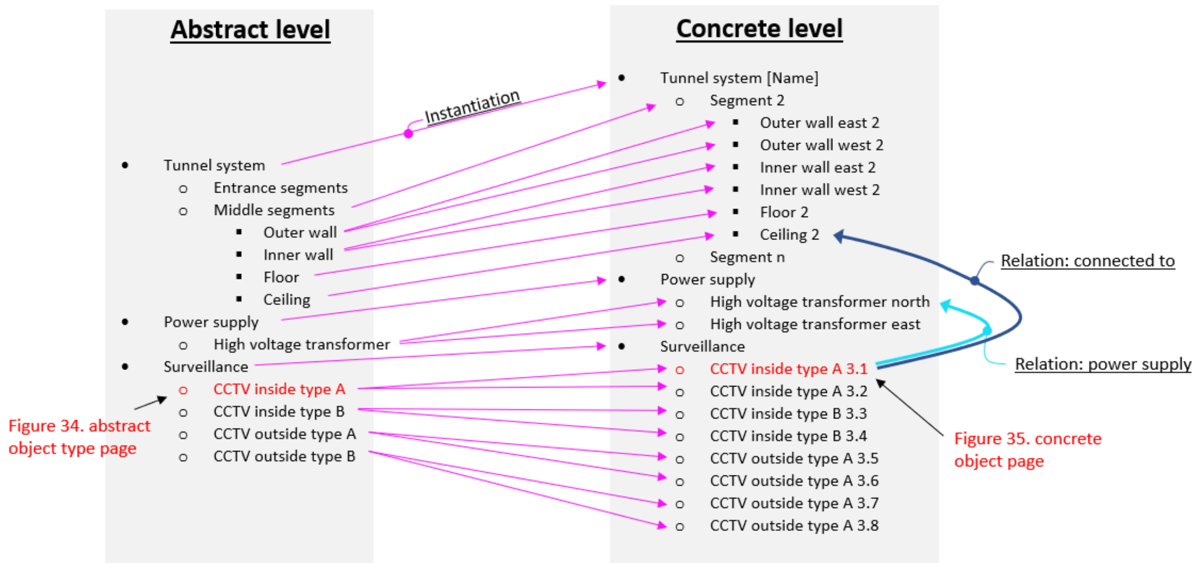


Figure 33 Lists of abstract and concrete decomposition

Object presentation: abstract object (object type)

The object page functions as the one stop page at which the majority of object information can be obtained. Object pages are present for both abstract and concrete objects. The abstract object page focusses on the information that has a common denominator between the objects, see Figure 34.

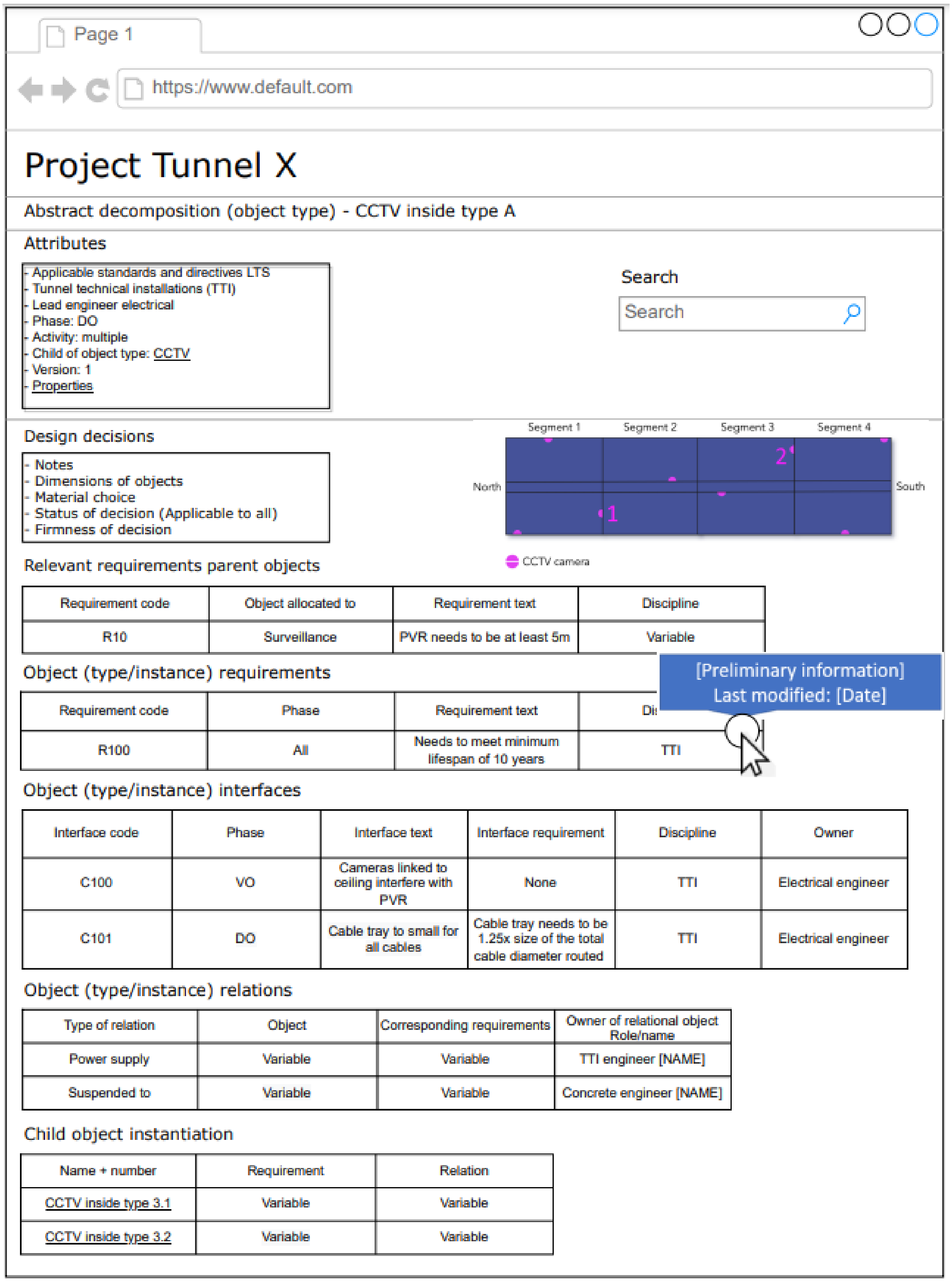


Figure 34 Presentation abstract object type page

Object presentation: concrete object

The object page of the concrete object functions as the one stop page at which the concrete object information can be obtained, see Figure 35 below. The concrete object page differs from the abstract object page as it contains concrete object information such as properties, relations with other concrete objects and project-specific information. Hyperlinks are presented to the concrete object pages of these objects. User specific views could be implemented in the shape of filters or prioritizing regarding variables such as phase, role, activity, or discipline.

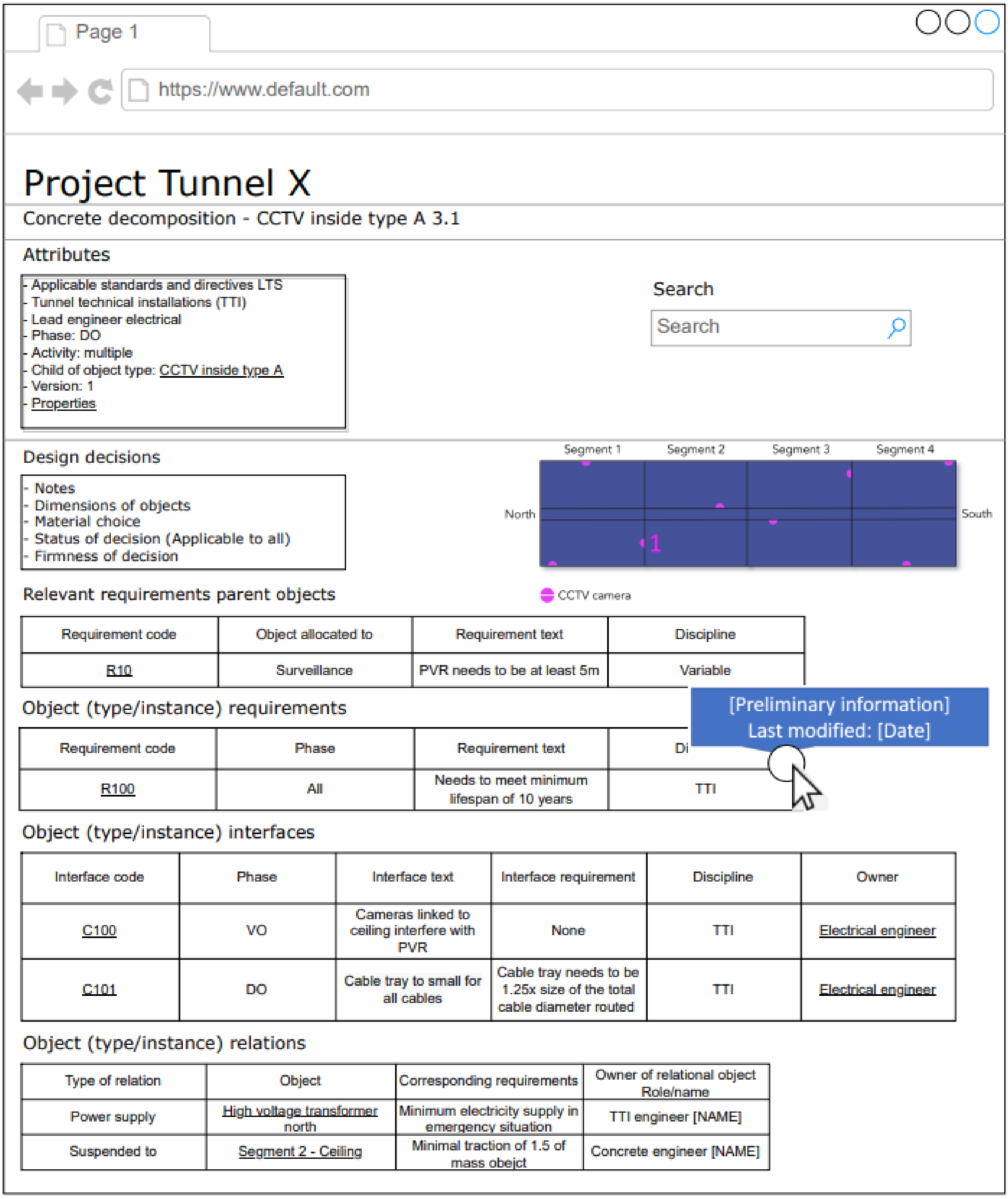


Figure 35 Presentation concrete object page

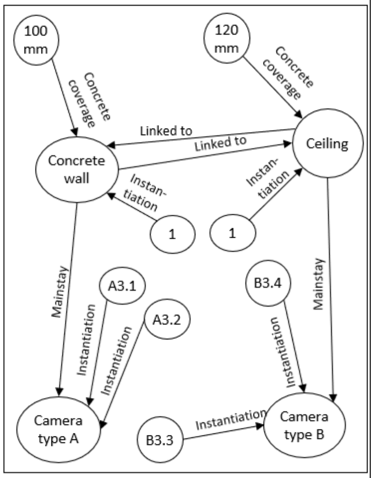
5.3.4 Custom queries

The custom query solution meets the specialty engineer's information needs that are complex, new, unpredictable, and urgent. Custom queries empower easy and quick user specific views as information can be obtained on any entity in any shape or composition (entities such as: objects, requirements, or functionalities). The solution contributes to a variety of improvements of the work practices of the specialty engineer. Implementing unambiguous information and reuse of information structures gives the possibility to effectively reuse queries and further optimise the queries. The conditions of the information needs are stated in the viewpoint, the information that is retrieved is from the information model and the information needs results are presented in the view, see Figure 36. The information model represents how the information is stored. The viewpoints present the conditions of the query and the view present the presentation of the information.

<u>Practical question</u>: *What is the concrete coverage of the concrete objects (ceiling and wall) to which cameras (type 1&2) are connected?*

<u>Main question</u>: What is the concrete coverage of the objects to which the cameras (type 1&2) are connected?

<u>Information model</u>



<u>Viewpoints</u>

<u>Conditions</u>

- Present all cameras (type A&B) that are relevant for the trajectory
- Present concrete objects that have connection "mainstay" with these cameras
- Present all links
- Highlight (purple) the values above 100 (>100)

<u>View</u>

Concrete Coverage (mm)

	Concrete wall 1	Ceiling 1
Camera A		
A 3.1		100
A 3.2		100
Camera B		
B 3.3	120	
B 3.4	120	

Figure 36 Information model, viewpoint, and view

5.3.5 Evaluation of use case example

The objective of the research is to meet the specialty engineers' information needs by improving the fitness for use of the CMDB. In current practice, the users spend plenty of time searching for information and assessing the validity of information. The conceptual solutions proposed in this research aim to meet the information needs by adjusting the presentation to the particular information needs. The use case example mainly focusses on the presentation solutions, as this the presentation is what the particular user will experience. However, the structuring solutions are just as important as these empower the presentation solutions. The presentation solutions consist of the one stop page and the custom queries presentation. The one stop page information presentation satisfies the recurrent, predictable, and urgent information needs of the specialty engineer by presenting the object information centrally. The goal of the one stop page is to enable the user to find the majority of the relevant information on a single page or within a single click. The other presentation solution is the custom query via which any information can be retrieved from the database by developing its own query. The solution meets the urgent, complex, unpredictable, and new information needs of the specialty engineer. Unambiguous information capturing provides the opportunity to reuse the query statements in future projects. The solutions presented significantly improve the fitness for use of the information system regarding a variety of dimensions. At first, the obtainability is improved as the required level of detail is easily accessible and overview is provided. Second, the security of information is improved as the information is tightly coupled. Third, the relevance of the information is improved as the information can be presented in any composition. Fourth, the logical coherence is strongly improved as the information is managed on both abstract and concrete level. At last, the timeliness is also improved as information can be obtained instantly and information can be tailored according to variables such as phase, role, or discipline. Nevertheless, the building and implementation of the system will be time-consuming, especially the first time. However, the benefits of proper implementation are expected to outweigh the disadvantage, particularly in the long run.

5.4 Artifact verification and validation

The artifact verification and validation consider the assessment of "building the product right" and "building the right product". The verification is performed by assessing the requirements that are assigned to the artifact. The validation assesses the used needs and is performed in the shape of an expert panel in which the product is reviewed according to the user needs.

5.4.1 Verification

As stated in the latter, the verification assesses if "the product is built right". This assessment is done by reviewing the requirements that are set before the product is build, requirements are reviewed by inspecting the design of solution. As the end solution is a visualisation of the intended situation, the inspection is done by a visual check.

5.4.2 Validation session set-up

Validation focuses on whether or not the artifact meets the needs of the end-user. The information needs of the specialty engineer are taken as a starting point for designing the artifact. Therefore, similar roles are requested for the validation process in the shape of an expert panel. The panel has been introduced in order to elicit expert knowledge and their opinions about issues. Also new ideas are considered. A few questions have been drawn up to structure the meeting and to reach consensus:

- Are the improvements clear/understandable?
- Does the artifact satisfy the information needs?
- Does the information presentation really contribute to the fitness for use of the end-users?
- Are there any strengths and weaknesses of the information representation?

In order to improve the validity of the answers of the expert panel, a variety of different users are requested. These vary in experience and role. The interpretations and perceptions of the ideal information presentation could differ as well. The expert panel participants received the required information 7 days preliminary to the expert panel which took about 1 hour. In order to be able to process the gained information, the expert panel has been subdivided into 2 separate meetings. During the expert panel, the researcher acted as moderator.

Table 15 Role and experience of the expert panel

Role	Years of experience	Specialty
Specialty engineer	10	Infrastructure
Specialty engineer	2	TTI
Lead engineer with specialty engineering experiences	10	Infrastructure
System engineer	6	Software structuring/ systems engineering

5.4.3 Findings and improvement recommendations

The results of the expert panel, of which the detailed analysis can be found in Appendix O, are categorised by the goals. The results of the expert panel are subdivided into 'added to the solution' and 'future research'. The added to the solution items are implemented in the solution. Some of the future research results are implemented in the future research chapter.

5.4.4 Validation

The experts assess the end solutions presented as a valid base for fulfilling their information needs. The one stop page on the object page is considered to be an interesting perspective by the people involved. All the entities that are required by the end-user are considered. However, the specialty engineers also state that the information presented could still lead to an information overload as many entities and attributes are presented that incrementally grows in the project. Furthermore, features should be added to the design decisions as this information is extremely dynamic, so direct links are implemented to 3D model systems such as Revit in order to let the CMDB function as single source of truth. Moreover, the specialty engineers are debating the necessity of the level of detail at which the system should be managed. The detailed object management might be time consuming and complex. Nevertheless, the experts are considering the solutions presented as a fundament for what is required by the specialty engineers in their designing activities.

5.5 Summary

The design of solution chapter elaborates on the conceptual solutions that are based on the problems resulting from the interviews. The design of solutions consists of five solutions and are developed by the process: problem, goal, requirement, solution. The practical relevance is illustrated in the use case example. At last, the solutions are validated by an expert panel. The main question that is being answered is presented below.

SQ 6 How to incorporate identified role specific information needs to improve fitness for use?

The design of solution chapter presents the process of converting the core problems identified in the practical study into well substantiated solutions. The solutions, which need to be regarded as an approach to a conceptual solution, focus on the use case in which the specialty engineer retrieves information from the CMDB. The goal is to meet the information needs of the specialty engineer. The development processes consist of processes such as problems, goals, requirements, and solutions.

The problems identified in the implementation evaluation are translated into conceptual solutions and are grouped into physical relations, abstraction levels, conceptual data model, one stop page and custom queries. At first, relations between physical objects: enable the user to browse between object pages and perform complex queries. Second, abstract levels enable the user to easily obtain unambiguous object information on a single concrete object page. Third, the conceptual data model presents a conceptual solution for storage of the information that is presented in the other solutions. Fourth, the one stop page is the static information presentation that serve the predictable, noncomplex, and recurrent needs on a single page. At last, the user specific view solution provides the specialty engineer with the required flexibility on the information composition of any entity at any time in the project. The solution meets the information need characteristics such as unpredictability, urgency, new and complexity.

In order to make the benefits of the solutions more tangible and to clarify the relations between the solutions, a use case example is developed in the shape of a simplified tunnel project. The use case presents the newly introduced approach towards information management and information presentation. The information management presents the development and population of the information model as well as the associated activities to particular sub models. The presentation solutions shows the populated one stop page and an example of a custom query. Both solutions meet diverse information needs in particular processes. At last, a verification and validation session are presented which is performed with the help of an expert panel. The results of the panel show that the solutions are build right. Nevertheless, a single expert was discussing the benefit of the detail object management. Altogether, the fitness for use of the system is improved as the identified information needs of the specialty engineers are served by both a static presentation solution and a flexible entity presentation solution enabling the possibility to meet the extremes of the information needs characteristics: predictability, frequency, importance, and complexity.

6 Discussion

The discussion chapter presents the implications, limitations, and recommendations of this research. The implications evaluate both the theoretical and practical implications. The theoretical implications focus on the comparison with findings of existing literature whereas the practical implications focus on the consequences for practice. The limitations consider the reliability and validity of the research. At last, the recommendations focus on the practical recommendations and future research. However, at first, the research results are shortly considered.

6.1 Implications

Theoretical implications

- This research provides new insights in the information needs of both the specialty engineer and lead engineer in the systems engineering processes. The information needs of the specialty engineer are not met in particular. Besides that, the specialty engineer experienced the most drawbacks in the system with the fitness for use. This research has revealed the information analysis by the individual characteristics, context, predictability, importance, frequency, and complexity.
- The research results show that the degree of formalisation of information models improves the understanding for all users. The MBSE literature abstractly describes what is required and what the information management contains. However, little attention is drawn to the detailed structural objects management. This research gives meaning to the information management and the added value of detailed information management. The added value of the complex technical solutions is conceptually evaluated in this research.

Practical implications

- The industry is diligently searching for solutions on the practical systems engineering information management problems experienced in the development of large infrastructure projects. The conceptual solution approach proposed in this research empower the companies to reduce the implementation of workarounds as information needs are met in various processes of the roles. Both the research approach, and design of solution might be used as fundamental approach for future information management strategies.
- Putting the conceptual solutions into practice will fundamentally change the organisational information management strategies. Nevertheless, the development and implementation of the technical solutions are expected to be costly, time-consuming, and technical challenging. Skills and experience are required of both operations (engineering practices) as well as the software developers. It is expected to be more advantageous to join forces as an industry and standardise information on industry level. Nevertheless, each organisation could distinguish itself on the further development of knowledge creation.
- In order to create useable information in a software system, participants need to be engaged. In case of the CMDB, the interviewees experience a substandard fitness for use which results in

a snowball effect. In other words, the engagement is low and reduces through time. However, in the scenario of a fit for use CMDB in which people are engaged and rely on the system as the information source, a flywheel might be created strengthen the information base. In case the fitness for use is improved till a certain level, the people might perceive the benefits of the CMDB and use the system for convenience.

6.2 Limitations

- Qualitative research is prone to subjectivity because of the interpretations and the perceptions of both the researcher and the interviewees involved. The semi-structured interviews might result in poor responses of the interviewees as these might have limited understanding on the headed direction of the interview. Therefore, the semi-structured interviews require time-consuming iterative processes to understand the interview data and refine the direction for successive interviews. Although full reliability can never be guaranteed, quickly and constantly reassessing interview data has vanished the gap between the interviewer and interviewee.
- The population for the interviews is relatively small and no distinctions are made between the specialty of the specialty engineers and lead engineers. Furthermore, the 85% of the interviewees came from the same company. Moreover, whereas the specialty engineers' demographics (gender, experience, and career path) are pluriform, the lead engineer's population appears to be uniform which might affect the results of the interviews as the particular group mainly represents a single perspective.
- The expert panel is not the strongest form of validation as it is based on first impressions of the experts and the experts did not test the solution in practice. Nevertheless, the validity of the expert panel is increased as the population of the expert panel is diversified. The specialty engineers are able to assess the presentation solution according to their information needs. The solutions associated to the structuring of the objects is validated by a systems engineer specialised in information management.

6.3 Recommendations

6.3.1 Practical recommendations

- More practical research is required on the further development of both the one stop page and custom queries solutions. These solutions are recommended to further develop by establishing design, build, and test phases. The expert panel showed that the experts were satisfied with the implementation of the system, however, the solution needs to be further developed and tested in more detail. The one stop page solution needs to focus on the completeness of the information presentation and the visualisation of the information. The custom query solutions needs to focus on the ability to retrieve the complex queries and the visualisation and presentation of the information obtained.
- This research studies the systems engineer information management in the development phase of a construction project. However, more software systems are used in the development phase such as analysis (calculations), visualization (3D models) or reporting (plan reports) software. In fact, there are even more software systems used throughout the whole life cycle of a construction project. The proposed conceptual solutions in this research give the possibility to effectively link

these systems. However, the detailed development of integrating these systems need to be studied in further detail.

- The development of custom queries in particular use cases might be a complex task. Therefore, storing and sharing custom queries between the project organisation, with an organisation or with the industry might improve the user specific views application. This could be possible in case information structuring is done by the same principles. In a later stage, the integrated data gives the possibility to make use of artificial intelligence concepts. The detailed management of a particular structure could enable software to answer questions on a project environment like Google answer regular questions. In a later stage, projects could even be merged, and the system could answer questions that are project transcending.

6.3.2 Future research

- For further research quantitative research is to be conducted on the detailed information needs of the particular users on the one stop page. In current research, the information needs have been researched qualitatively which might be prone to subjectivity. Additional quantitative research will assure and refine the results of information needs of different users. In addition, the information needs on the object pages of adjacent objects could also be identified. Furthermore, the information needs results give the possibility to further specify user specific views by introducing e.g., filters or prioritise particular information required by a particular user.
- The study should be repeated by using a larger population. This is required to increase the validity of the results. In current research the results are based on six interviews that cover three disciplines and two roles. In practice, there are plenty of other disciplines, roles as well as other departments involved in a construction project. In order to develop a systems engineering information system that is fit for use for all participants in a construction project, the population needs to be extrapolated.

7 Conclusion

In this report the fitness for use enhancement of a systems engineering tool is studied by identifying the information needs. This report consists of a context study, literature study, practical study, and design of solution. In these parts, a variety of results are presented by the research questions. Therefore, the sub research questions and answers will be shortly recapped. Afterwards, the main research question is answered. The chapter is finalised with the contributions which is subdivided into practical and theoretical contributions.

7.1 Conclusion

<u>Sub research questions</u>

1- *How are systems engineering processes managed in a configuration management database?*

The systems engineering processes consists of requirements analysis, functional analysis and allocation, design synthesis, verification and validation, and system analysis and control as well as supporting processes trade studies, interface management and configuration management. These processes are managed in a web based relational database that should function as a single source of truth. The information in the systems is inserted and managed by disciplines such as civil works, infrastructure, and electrical engineering. The roles considered are the lead engineer and the specialty engineer. The information is managed in the system by interlinking the entities. Consequently, the information is obtained from the modules that represents an information entity.

2- *Which aspects of Model-Based Systems Engineering could contribute to fitness for use of the CMDB adopted in the development phase of large infrastructure projects?*

The concept Model-Based Systems Engineering (MBSE) integrates highly interconnected processes by interlinking models. In these tightly coupled models, physical objects exist once in the system and therefore data values are to be inserted once as well. This research focuses on the structure model that is used to manage systems engineering information. The structure model consists of three sub models: generic object management, abstract model, and concrete model. The generic model formalizes an agreed conceptualisation of objects as it captures all the object definitions and corresponding standard properties and relations. The abstract model manages general decompositions applicable for trans-project use or multiple use in a single project. The concrete model manages the physical real-world objects or the abstract models by adding name, number, or code. Project specific information such as requirements, activities, roles, or interfaces can be allocated to both the abstract and concrete model. As a result, the detailed management offers the possibility to tailor information presentations in the shape of user-specific views.

3- *Which variables characterise role specific information needs of engineering specialists and engineering managers?*

The lead engineer and the specialty engineer perform engineering activities and can therefore be classified as engineering specialists. Although the concrete tasks and responsibilities differ per role and per process, the steps are analysed by the information seeking model. This model identifies the following steps: work roles, task, information needs characteristics and source of information. Consequently, Leckie shows that the information needs of the specialty engineer and the lead engineer can be characterised by individual demographics, context (description), frequency, predictability, importance, and complexity.

4- *How to analyse the fitness for use of a configuration management database used in the development phase of large infrastructure projects?*

The fitness for use considers the consumers' viewpoint on the information that is provided by an information system such as the CMDB. In this case the specialty engineers end the lead engineers are the consumers and require information for decision making activities in various processes. The information that is available in the CMDB should match with the information needs of the user in a specific situation. The degree to which the provision of information meets the (varying) information needs is called the fitness for use. The fitness for use is assessed by the DQ/IQ framework in which the following dimensions are considered: accessibility, security, relevancy, completeness, consistency, timelines, and logical coherence.

5- *What is the perceived fitness for use in the configuration management database used in the development phase of large infrastructure projects?*

In order to assess the fitness for use, the steps in the information seeking model are considered consisting of the tasks and responsibilities, information needs and fitness for use. The roles considered in this research have different tasks and responsibilities and therefore different information needs. The main tasks of the specialty engineer originate from the design synthesis and system analysis processes whereas the lead engineer is mainly involved in requirements and functional analysis as well as verification and validation, system control and interface management. The lead engineer, which mainly uses the CMDB in the management of systems engineering processes, declares to perceive the fitness for use of the CMDB as reasonably well. On the other hand, the specialty engineers experience the fitness for use of the CMDB as unsatisfactory in the design and system analysis processes due to a variety of problems regarding the presentation and structuring. As a result, the information needs of the specialty engineer are not met and the implementation of workarounds might lead to a snowball effect.

6- *How to incorporate identified role specific information needs to improve fitness for use?*

Information needs are incorporated by focussing on the twofold information needs originating from the design synthesis and system analysis. The design synthesis is characterised by a predictable, recurrent, and non-complex needs whereas the information needs in the system analysis process are characterised to be unpredictable, urgent, new, and complex. As a result, the solutions are differently shaped. In total there are 5 solutions: physical relations, abstract levels, conceptual data model, one stop page and custom queries. The physical relations, abstract levels and conceptual level enables the development of the one stop page and custom queries. Besides, the one stop page and custom queries are the presentation of the information that the users experience.

Main research question

How to improve the fitness for use of configuration management databases used in the development phase of large infrastructure projects?

The purpose of the current study is to improve the fitness for use of the CMDB by determining and meeting the information needs of users in the systems engineering processes. Therefore, several successive studies have been conducted such as a context study in which the systems engineering processes and associated information modelling approaches are considered, a literature study in which information needs and a fitness for use assessment method are introduced. Consequently, an empirical study is conducted on the information needs and the perceived fitness for use by interviews. The interview results, design of solution and final conclusions are enumerated below:

- Significant differences have been identified between fitness for use assessment of the users in the CMDB. The lead engineer experiences the system as reasonably well with some shortcomings, whereas the specialty engineer experiences major drawbacks in the fitness for use and is forced to implement workarounds. As a result, the majority of the fitness for use problems identified originate from the specialty engineer and the problem-solving design of solution chapter also focusses on the problems identified by the specialty engineer.
- The information needs, which form the base of the fitness for use assessment of the CMDB, depend on the tasks and responsibilities of the particular user. Therefore, the information needs of the users are determined. The interview results show that the information needs of the specialty engineer are two-fold and originate from the different processes. The information needs in the design synthesis process are characterised to be predictable, recurrent, and non-complex needs whereas the information needs in the system analysis process are characterised to be unpredictable, urgent, new, and complex. The fundamental different information needs results in a different fitness for use assessment of the system.
- The fitness for use is experienced to be substandard for both the processes design synthesis and system analysis. The information provision of the CMDB does not consider the diverse information needs in the different processes. Besides, the specialty engineer experiences fundamental problems regarding the presentation and structuring of information. These problems are concretised as the specialty engineer experiences low obtainability, inconsistency, incompleteness, and incoherent information. Therefore, the specialty engineer is not able to obtain information effectively and efficiently from the system. Consequently, the specialty engineer experiences time loss and implements workarounds such as information management on local storage or communication electronically or in-person. The implementation of workarounds might result in incremental asymmetry which might cause a snowball effect.
- The solutions proposed aim to meet the specialty engineers' information needs by focussing on the problems gained from the interview. The application of physical relations, abstract levels and conceptual data model empower the system to improve trustworthiness, flexibility, obtainability, coherence, and completeness. Furthermore, the one stop page and custom queries provide the user with the ability to easily find related information on particular objects as well as search for previously untrodden data compositions. Therefore, the solutions improve the CMDB's fitness for use as these empower the user to meet their diverse, sophisticated, and dynamic information needs.

7.2 Contributions

7.2.1 Practical contributions

The results of this research contribute to bridge the gap between the construction industry and the technology industry as well as between the organisation perspective and the individual perspective on the systems engineering process. The technology industry describes the MBSE developments and advantages on an abstract level without elaborating on domain specific situations. In this research the advantages of the particular concepts are explained by researching the needs and proposing particular solutions. Furthermore, this research focusses on the different perspectives that are present in a project. The software is developed according to the organisational perspective whereas the individuals do not perceive the benefits. In this research this phenomenon is explored in detail by focussing on the different perspectives and solutions which are proposed that solve the contradiction in perspectives. In addition, the technology advantages have also been merged with the individual perspective which resulted in the ability to meet the diverse, dynamic, and sophisticated information needs of the individual.

7.2.2 Theoretical contributions

Systems engineering information management is a rarely studied topic in literature, especially when it comes down to information needs and fitness for use of particular users. In current practice, the individuals are having a non positive attitude towards the application of SE as they as they do not perceive the benefits of using the CMDB. This research focusses on identifying the processes in which the individuals are involved as well as the experiences the individuals have in the particular tools. The multidisciplinary research topic requires detailed domain knowledge on the systems engineering processes, information modelling technology and the general concept of information needs and fitness for use. As a result, this research introduced an approach to identify the information needs of the particular roles in the processes and the fitness for use of roles in systems engineering software. The results of this research present the concretised information needs of the particular user in the related processes and identified the relevance of the MBSE in particular solutions proposed to improve the fitness for use.

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Appendix

Appendix A – Explorative interview users Relatics

Topic: User interaction with Relatics
Interviewer: Kije Zijlstra

Interviewee:
Job title:
Date:

<u>Introduction on the thesis subject and interview</u>

This interview is part of my graduation thesis from the master Construction Management & Engineering at the TU Delft. Currently I am in the explorative phase of my thesis in which I study the user satisfaction with Relatics in a construction project. The reason for writing this thesis is the low user satisfaction of end-users of Relatics. Consequently, end-users start to use former tools such as Excel. In Excel the end-users have the possibility to easily process and manipulate the data according to their own wishes. As a result, the information is stored on their own computer resulting in ineffective processes. The interview is semi-structured and therefore focuses on themes.

<u>Questions</u>

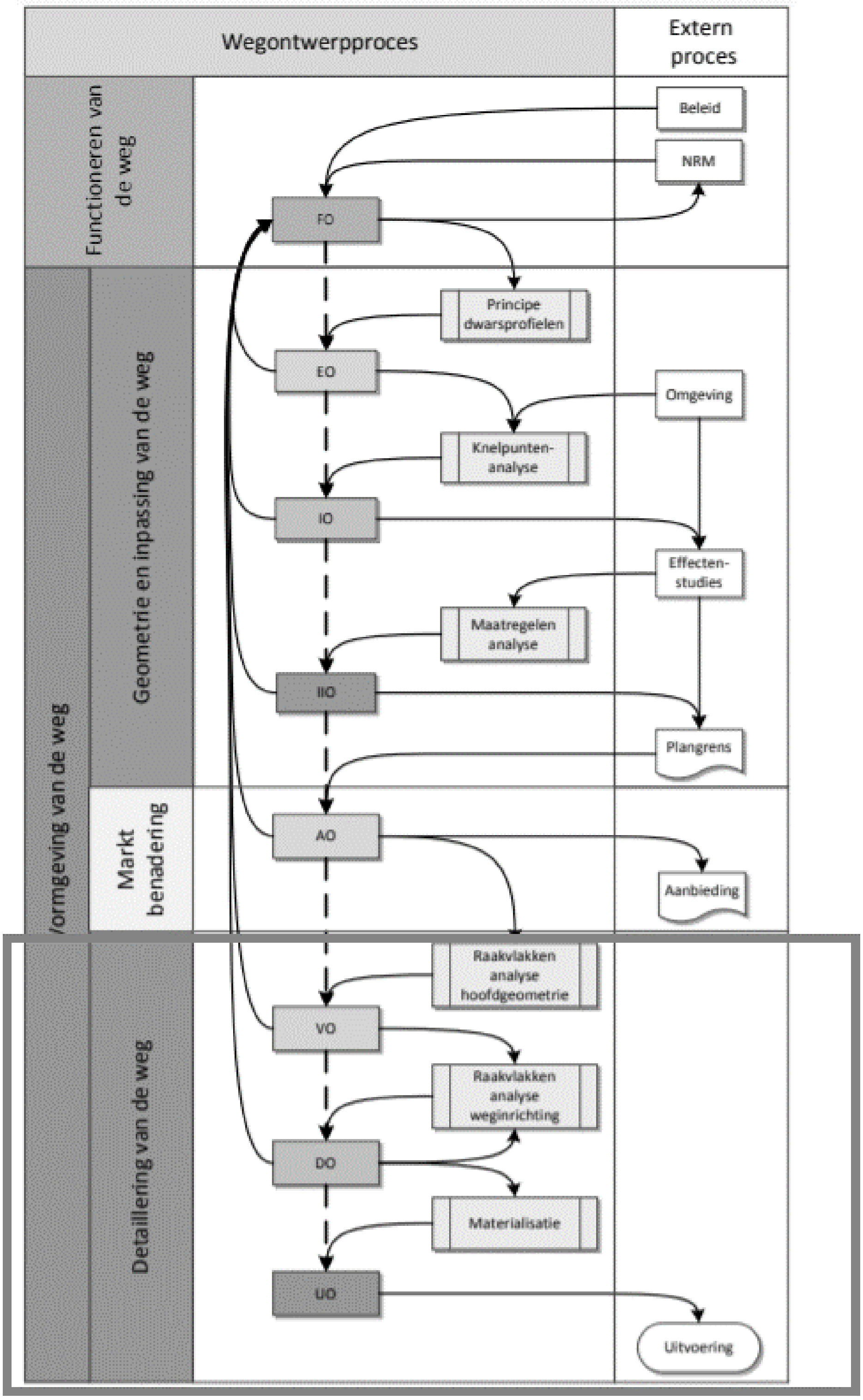
Each project and related Relatics environment are configured differently. Which project(s) would you like to discuss?

- *When is Relatics used in the project in your role?*
- *Why is Relatics used in the project in your role?*
- *How is Relatics used in the project in your specific role? (Information need and return)*
- *What is your personal experience with Relatics? What are your user needs and requirements?*
- *The goal of Relatics is to have a single source of truth, are there activities that take place outside of the system? In case of yes, which activities? (Such as using Excel as a workaround)*
- *What do you think of potential improvements of the system?*

Problem categories	Cause	Observations of problem	Consequence	Road designer	SE coordinator	Structural designer	Functional configurator	Information manager	#Count
Data structuring	Although Relatics might supply the required functionalities, it is labor intensive as the layers need to be adjusted majorly	System is not dynamic through different phases or different disciplines in a project. Only one type of structuring of information is used (object tree) while there are different perspectives who require the information in a different manner	Information in the system is hard to understand/read by different end-users. Information needs to be rearranged by the information managers after handovers between discplines and phases				1	1	2
Data structuring	SE methodology is not used or no knowledge on these information. Currently the object tree is developed by a design lead but this role doesnt understand the context of other end-users	Approach on structuring information according to the systems engineering methodology differs between between projects	Inconsistent information management leads to confusion for end-users	1	1				2
Design	Access control scripts are user specific and therefore labour intensive	No distinction made in rights assigned to users with permission to the system	Irrelevant people could change the system	1				1	2
Data presentation	There are no distinctions made in the information presentation to different end users with different roles and from different disciplines	All information is shown to all end-users without exceptions made for certain end-users	Information overload leads to workability issues of non-expert users	1				1	2
Design	Manuals are not fit-for-purpose and help function doesnt exists	Insufficient onboardingsprocess of newly introduced end-users (manuals, help)	End-users do not properly use the system	1			1	1	3
Data presentation	User specific requirements are unknown and its unknown which technology can be used	Information system doesn't take into account the user-specific requirements	Search time for information increases and check of information is hard	1				1	2
Technology	Technology of the system cant handle the size of queries requested	Performance of the system is low	Processing in the system takes too much time	1	1		1	1	4
Design	Relatics functionality doesnt support workflows and interventions are labour intensive	Already verified requirements can be changed afterwards while the status of the check mark doesnt change	Verification process is distrusted	1				1	2
Data presentation	Underlying technology requires labour intensive scripting to improve navigation	System is time consuming because many clicks and search time is needed	Time spill and dissatisfied end-users	1					1
Data presentation	Relatics is not suitable to insert geometry as difficult connect with external applications (not for all object geometry)	Dynamic information elements of specific objects are missing such as geometry or exact location	Information needs to be taken from somewhere else	1	1			1	3
Strategy	Most mega projects are executed by joint ventures and for each project there are different project teams who have various experiences with a prefered system, therefore, the software requirements specification differs	Template of Relatics is build from scratch preliminary to each project whereas in each project a different approach is considered	End-users need to understand the (changed) working processes for each project leading to a learning curve time and confusion	1				1	2
Process	No active procedure on management of requirements	Decision making processes from daily meetings are not structurally updated in the system (downstream)	Information assymmetry between documents and system		1				1
Technology	Relatics is not fit for purpose to store the required information and fulfill the required functionality	The link with other software systems such as naviworks do not work properly	Limited synchronous information in the systems	1				1	2
Data structuring	Process of determining which objects should be in the system is not mature	Physical objects are missing in the database	Distrust in the system		1				1
Data structuring	The underlying data structures are not fit for purpose	Unclear allocation responsibilities to roles	Different roles are unware of their responsibilities and the corresponding required activities in the system	1					1
Data structuring	The designers of the information structure do not have sufficient knowledge on the methodology	Information in the system is not structured by the SE methodology	Lack of vision leads to ambiguous storage of information		1				1
Data structuring	The requirements of endproducts are not allocated to the specific activities and end products of users	Information is missing on what the endproduct requirements are	Unclear what the final goal is		1			1	2
Data structuring	The designers of the information structure do not have sufficient knowledge on the methodology	Insufficient number of requirements allocated to objects	Requirements are missed which leads to insufficient activities		1				1
Data presentation	The designers of the information structure do not have sufficient knowledge on the methodology	No risk mentioned per object	End-users are not aware of the risks and therefore risks could be overlooked		1				1
Process	Requirements supplied by the client are often not SMART defined and change process lacks in efficiency and effectiveness	Requirements and objects are not SMART defined	Ambiguous requirements		1				1
Data presentation	The underlying system is not fit for purpose to store the required information or their is no functionality added to the system that presents improves traceability	Decisions and changes on information in the system is not presented to the end user	Unclear what and which decisions are made, what has been considered and why decisions are made		1				1
Strategy	Projects are often executed in joint ventures and becuase of changing composition of project teams no investments on innovation is made available	No strategy on interproject level	Problems related to changing working processes resulting in ineffecting information sharing are faced each time				1	1	2
Strategy	Document based working method creates disturbance in a circulair information cycle	Information cycle on sector level is not circulair	The information received by the client is difficult to use as input for new processes				1	1	2
Strategy	Digital literacy of end users is low in the construction industry (end-users and administrators)	Innovation in the Relatics application environment develops on low pace	Relatics works with legacy technology					1	1
Process	Document based and model based working methods are not aligned	When transferring the requirements from PDF to Relatics, there are limitations in Relatics such as max 500 characteristics while the PDF exceeds these 500 characters in some cases	Information is left out or stored in a different way					1	1
Strategy	No time evaluate and to improve the process	No evaluation process applied despite quality systems stating these process during the project and afterwards	No adequate measures are taken from both negative and positive findings leading to a flat learning curve					1	1

Technology	6
Strategy	8
Process	3
Data structuring	10
Data presentation	10
Design	7

Appendix B – Development process of large infrastructure projects



Appendix C – Interview protocol practical study

Practical study - Explorative interview CMDB Relatics

First of all, thank you for joining the interview. Its is highly appreciated that you want to take the time to provide your personal experiences with the CMDB Relatics.

<u>Introduction research topic</u>

This interview is part of my graduation thesis (Kije Zijlstra) from the master Construction Management & Engineering at the TU Delft. Currently I am in the practical study phase of my thesis which is about the user interaction with Relatics in the development phase of an infrastructure project. Therefore, I am interested in the tasks and responsibilities of the roles involved in this phase. The purpose for writing this thesis is to improve the fitness for use of end-users in Relatics. Currently, because of the low fitness for use for some end-users, workarounds are implemented. However, there are several critical consequences to the use of workarounds such as security issues, limited transparency, inconsistent data, and negative impact on the project organisation processes.

<u>Interview method</u>

The goal of this interview is to identify the tasks and responsibilities of the specific role and to identify the experiences of the individual in the CMDB. Consequently, the tasks and responsibilities result in information needs and wishes that are managed in the system. Preliminary to the research the interview protocol is provided in which a tasks and responsibilities are listed. The interviewee is requested to send this filled in list preliminary to the interview so that the results can be analysed. The interview conducted is considered to be a semi-structured interview in which the following topics are covered: systems engineering processes, information behaviour, perceived data quality and information quality, and potential solutions.

<u>Compliance:</u>

The interview is documented anonymously, and the results of the whole will be available online when the research is finished.

<u>Person of interest</u>

Date:
Interviewee:
Job title:
Role:
Employer:
Age:
Gender:
Education level:
Level of Dutch:
Years experience with Relatics:

Tasks and responsibilities of the role		
Management processes and activities	Involved in? (YES/NO)	Performed in CMDB?
Systems Engineering		
Requirements analysis		
• Elicitation of requirements		
• Determination of appropriate level of detail		
• Specification of the requirements		
• Analysis of the requirements		
• Structuring and allocating of the requirements		
• Managing complexity of the system		
Designing		
• Drafting design base		
• Trade-off analysis		
• Continue design and write design nota		
• Check for completeness		
Verification & validation		
• Verification plan (preliminary to design)		
• Verification process (while designing)		
• Verification overview (afterwards)		
Others:		

Theme 1
Systems engineering processes and activities
(15 min)

Hypothesis: Each role has different responsibilities and therefore performs different activities in the CMDB

Questions and themes	**Goal of questions**
1.1) How would you describe the tasks and responsibilities of the activities you are involved in?	There is a specific set of activities performed in the CMDB, each role has specific set of tasks and responsibilities in the activities. The goal is to improve understanding of the specific tasks to be performed by the role.
1.2) From the activities that are managed in the CMDB, what specific information is required by the role to perform the activity?	This question is a follow up question on the latter question. The information needs and intensity could differ per task, per role and per activity.
1.3) Are there any activities you perform in the CMDB that are not mentioned in the overview?	The systems are developed to manage the big picture, however, some small activities that are managed ineffectively could have major impact on the workability in the system.

Theme 2
Information selection
(15 min)

Hypothesis: The information behaviour differs per role and individual, therefore the perception of the information behaviour is considered differently

Questions and themes	**Goal of questions**
2.1) How would you describe the information need, seeking and use in specific activities?	The typology of information, which might influence the perception of the individual, is distinguished in the following categories: (vague – very detailed request). Characteristics of information needs consider individual demographics, context, frequency, predictability, importance, and complexity.
2.2) How does the information selection process of the individual take place in specific activities?	Are selective parts of the information system used, try to elaborate on the parts that are used.

Theme 3
Assessment of information quality in different situations
(25 min)

Hypothesis: The information quality is strongly dependent on the activity that is to be performed

Questions and themes	**Goal of questions**
3.1) What are the experiences (user-satisfaction) of the system when performing activities?	An open general question that requires a comprehensive answer is raised to get hold for the next questions.
3.2) How would the user describe the perceived DQ/IQ:	The information quality, which has a major influence on the user satisfaction, is to be assessed by (different questions are raised depending on the role and personal experience): o Accessibility (availability, obtainability) o Security (external, internal) o Relevancy (usefulness, relevant) o Completeness (level of detail, comprehensiveness) o Consistency (structure, format) o Timeliness (up-to-date, timely) o Logical coherence (internal, external)
3.3) Pick three main activities. How would you describe these differences in perception of information quality per activity?	Each activity is different and requires different information as well as presentation. By discussing the specific activity, the interviewee might elaborate in more detail on his experiences which might result in the specific information needs and his perception of the system.

Theme 4 –
Potential improvements of information quality
(5 min)

No hypothesis

Questions and themes	**Goal of questions**
4.1) What is the first that comes to mind when you think about the irritations and potential solutions?	The goal is to use the information acquired in preliminary sections to brainstorm with this knowledge on potential solutions.
4.2) Potential solutions?	

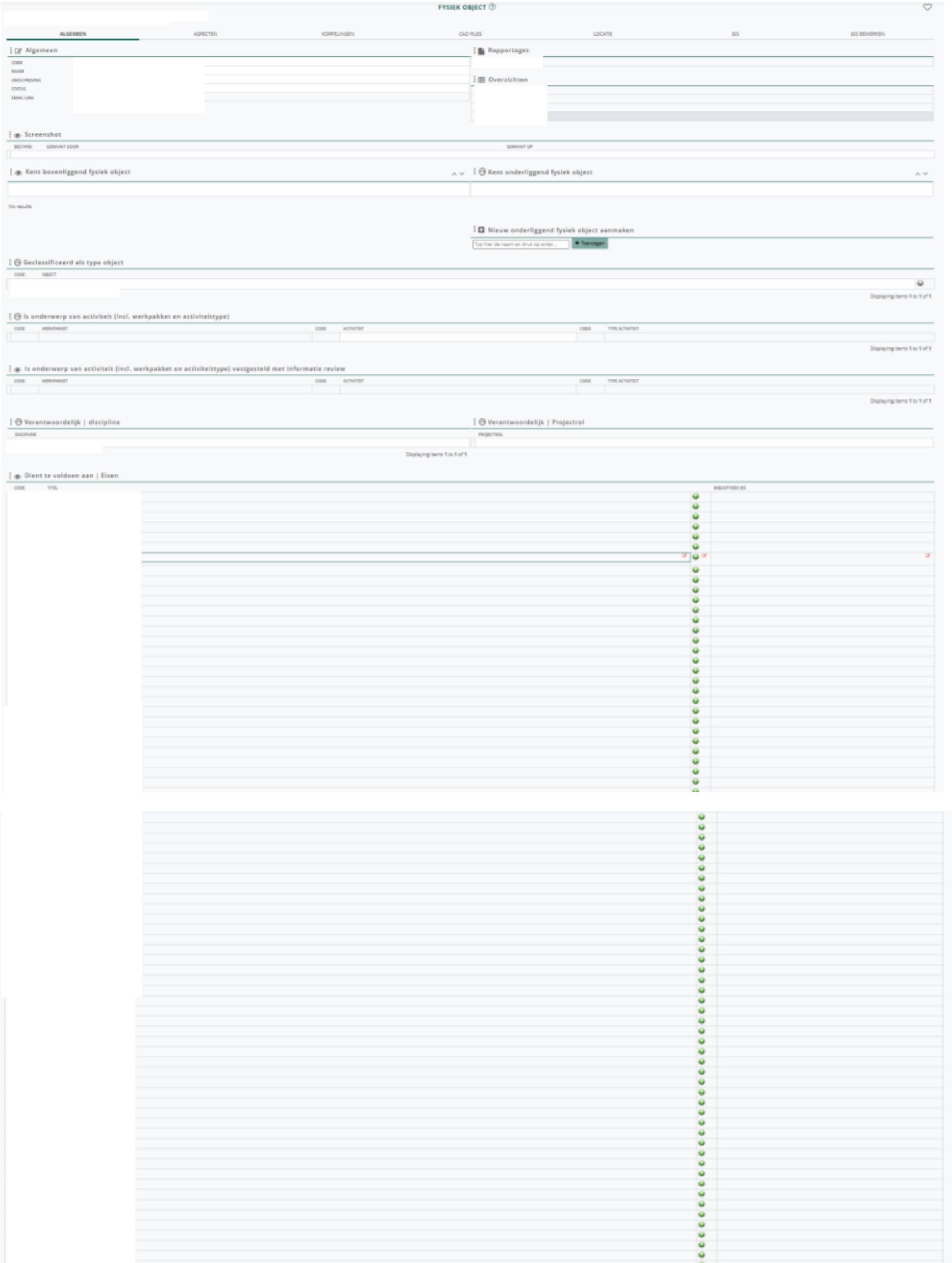
Appendix D – Results involvement roles systems engineering processes

Systems engineering Management processes and activities	Specialty engineer		Lead engineer		Total
	Involved in? (YES/NO)	Performed in CMDB?	Involved in? (YES/NO)	Performed in CMDB?	
Requirements analysis					
• Elicitation of requirements	-	-	3	3	3
• Determination of appropriate level of detail	-	-	3	3	3
• Specification of the requirements	-	-	3	3	3
• Analysis of the requirements	-	-	3	3	3
• Structuring and allocating of the requirements	-	-	3	3	3
• Managing complexity of the system	-	-	3	3	3
Design synthesis					
• Drafting design base	3	3	3	3	6
• Trade-off analysis	3	3	3	3	6
• Continue design and write design nota	3	3	3	3	6
• Check for completeness	3	3	3	3	6
Verification & validation					
• Verification plan (preliminary to design)	1	1	3	3	4
• Verification process (while designing)	3	3	3	3	6
• Verification overview (afterwards)	2	2	3	3	5
Others:					
- Interface management	2*	2*	3	3	5
- Functional analysis	0	0	3	3	3
- Deviations management	-	-	1	1	1
- Request for change	-	-	2	2	2
- Work packages and WBS	0	0	3	3	3
- Trade offs and alternative studies	2	2	3	3	5

* Only involved in a single activity of the process

** Not always performing functional analysis and allocation in practice

Appendix E – Example of object specific page Relatics



Dient te voldoen aan | Eisen vastgesteld met informatie review
Directe impact van wijzigingen
Vraag & Antwoord | Intern
Opmerkingen | Intern

Appendix F – Interview quotes Information needs

Information needs interview quotes	
Processes	**Quotes Specialty engineer**
Design synthesis	*Quote A1-1: "The design process is performed in different phases (VO, DO, UO) in which the information needs in these activities could slightly change. The information required in this process determine the object specific solution space (e.g., object specifications, requirements, dimensions, functionalities, design decisions, starting points). The information is obtained from the specific object pages. (Interviewee 1)*
	Quote A1-2: "What is required are system requirement, PVE, interfaces, input values structural engineer. Currently managed via e-mail. There is also execution who have wishes and demands which as well are managed in notes. Their wishes might affect the solution space so should be considered." (Interviewee 2)
	Quote A1-3: The information required in case of a particular design activity could be related to a particular object but also to a set of objects that are adjacent or in the vicinity of the object of interest. Presenting a set of objects or other entities could provide overview or the ability to compare. (Interviewee 3)
Verification & validation	*Quote A2-2: The information needs in the verification and validation are related to the end products of objects designed by the specialty engineer. The specialty engineer needs to demonstrate to the lead engineer whether or not the design meets the requirements. Afterwards, the lead engineer processes the verification information in the CMDB. (Interviewee 2)*
System analysis	*Quote A3-1: The information in a project is subjected to change for example if the client introduces new requirements or the execution department brings execution requirements at the end of the design process. These changes are to be assessed on the impact. Besides, alternative solutions might be required to study. For these activities, on demand overview of entities could be required (e.g., object, functionalities, requirements) in any composition. (Interviewee 1)* *Quote A3-2:*
Interface management	*Quote A4-1: The identification of interfaces could be done by any type of role; these are often identified by the related engineer. The interface identification is usually done by lead engineers but sometimes the lead engineers miss one. To be sure about interfaces, a proper overview is required of the information in the CMDB. The management and resolving information could be of interest to the particular specialty engineer. (Interviewee 1)*
Processes	**Quotes Lead engineer**
Requirements analysis	*Quote A1-4: The requirements analysis is performed outside the system, afterwards, the requirements allocation is performed in the system. The requirements need to be assessed, SMART formulated and allocated to an object. The CMDB doesn't provide the functionality to perform these activities" (Interviewee 4)*
Functional analysis and allocation	*Quote A2-4: "The implementation of functional trees depend on the wishes of the client as the client often wants to determine the solution space." (Interviewee 4)*
	Quote A2-6: "The functional trees are used in the electrical discipline as the solutions are structured in independent decompositions, called the Logical Functional Fulfillers (LFV)." (Interviewee 6)
Design synthesis	*Quote A3-4: "Lead engineers develop the information in the CMDB from requirements to objects, however, the specialty engineer often requires assistance. As the lead engineer is fully familiar with the information and has interest in designing with all the information required, the lead engineer often assists in obtaining solution space information." (Interviewee 4)*
Verification & validation	*Quote A4-4: "The verification and validation process are ongoing daily processes that is planned in advanced. In order to perform the process, the design information is required as well as the solution space information. The demonstration process which is done by checking marks, is depended on the system decomposition and requirements allocation." (Interviewee 4)*
System analysis	*Quote A5-4: "In the analysis process, which is often performed by the specialty engineer, project information will be required that is managed in the CMDB. The management is done by the lead engineer. Depending on the size of the analysis task there are also higher ranked roles involved next to the lead engineer." (Interviewee 4)*
System control	*Quote A6-5: "The system control is performed by controlling work packages that represent the progress. The work packages include all the information that is to be managed such as design progress or verified requirements." (Interviewee 4)*
Interface management	*Quote A7-6: "Information needs for both interface identification and management. The identification requires clear context on the object whereas management requires straightforward information to be aligned between disciplines both internally and externally, which require time and intensive management for optimal solutions." (Interviewee 6)*

Appendix G – Analysis information needs

Information needs analysis specialty engineer				
Processes	Frequency	Predictability	Importance	Complexity
Design synthesis	Characterised by both new and recurrent inquiries. Majority is on recurrent inquiries	in advance information on solution space is known such as requirements, functions, costs, and planning. Sometimes information required from adjacent objects or functionalities	Designing is a process of sequential steps that depend on each others output. Mistakes might lead to snowball effect	Solution space should be known such as objects, functionalities, or requirements
Verification & validation	Information that is already used	Information required is related to the end products that are to be verified.	Lead engineer could also search for the information	Information required accord to the requirements used for design
System analysis	Always new inquiries	New insights can not be predicted therefore alternative studies as well as the corresponding information required	System analysis requires adequate and urgent conclusions as progress and quality at issue	Each system analysis requires different information and therefore different (unknown) views
Interface management	Both new and recurring information needs as identification requires might new composition whereas management requires recurring information	Common interfaces could be known, outliers not. Besides consensus is often unknown	Overall, not urgent, however, information might get urgent when interfaces are identified by the engineers	Often common interfaces, consensus might not count for all objects on certain topic

Information needs analysis lead engineer				
Processes	Frequency	Predictability	Importance	Complexity
Requirements analysis	Information needs are not recurrent as information is frequently required in different compositions	Origin of majority requirements is known, outliers unknown	In order to obtain context on the requirements the information needs need to be quickly presented to be able to quickly attain overview	Understanding the context might be complex and requires the ability to filter and accentuate information
Functional analysis and allocation	Information needs are not recurrent as information is frequently required in different compositions	Information required originate from requirements analysis	Deriving functionalities is base to proper physical architecture	Context need to be understood on the requirements and the abilities of the functionalities
Design synthesis	Mainly focuses on control of the progress but could be involved in decision-making and therefore requires context on objects	Information need originate from the objects that are to be designed	Information on design activities might be required urgently. Progress information considered not to be urgent	Progress information is obtainable per system or object. Obtaining design information requires
Verification & validation	Information on design products is required that is often related to different objects	Requirements are allocated to object in a specific period	In general not very urgent, however, verification processes are often performed in significant time pressure.	Requires straightforward information; requirement allocated to object
System analysis	Information required is not recurrent as the inquiries differ	Not possible to anticipate on the information inquiries as unknown	Information inquiries need to can be required urgently as could affect major changes	Information inquiries can require different entities, different compositions, and different attributes
System control	Information inquiries do not change as related to the end products	Progress information is scheduled and tracked	Needs to be easily obtainable but no important urgent inquiries	WBS is linked to the progress of design information in system, could become complex when the progress information is getting complex
Interface management	Unclear when and on which objects interfaces appear	Interfaces are not known in advance. Some can be identified from experience; others need to be identified from information	Urgently required to easily obtain context on the interface in some case	Gaining insight into relation objects could be hard

Appendix H –Thematic analysis fitness for use

Specialty engineer				
Themes	Theoretical explanation	Subthemes	Summaries of observations	Quotes interviewees
Accessibility	Accessibility entails the degree to which information is available, obtainable, or quickly retrievable. In this case availability includes the availability of the system in the sense of downturns and resources needed to make use of the system. Obtainability focuses more on the steps to be taken in the system in order to obtain the information.	Availability		
		Obtainability	3 of 3 specialty engineers indicate that contextual object information is hard to obtain from the object page for any process. At first, relevant requirements information such as attributes are not presented on the object page. Second, no hyperlinks presented to neighbouring objects. Third, relevant requirements allocated to parent objects are not clearly presented, either on the child or parent object page. Fourth, typos and subjectivities present in information recordings such as object names or attributes. At last, for the system analysis process in particular, it is not possible to obtain overview on a set of entities in a random composition resulting in time-consuming information capturing activities. To summarise, the incomplete or incorrect information presentation requires high frequency of browsing activities which significantly reduces the individual's work ethic.	Quote B1.2-1a: "At the start of the project, civil engineering discipline is interested in our design decisions regarding the axis of the road. On the other hand, the infrastructure discipline is interested in the decisions regarding the thickness of the civil works as this might e.g., impact the height of the road. In a later stage of the design process, more alignment is required between other disciplines." (Interviewee 1)
				Quote B1.2-1b: "Newly introduced requirements throughout the project are a common phenomenon as e.g., in the UO phase the execution methods are assessed. Consequently, the impact on engineered design is to be assessed and changed as current design is not suitable due to different reasons (e.g., execution time or execution costs). Information collection is laborious, time-consuming and require overview and analytical skills which can not be performed by the CMDB" (Interviewee 1)
				Quote B1.2-3a: "Analysing the requirements that are allocated to a specific object might take up to 30 minutes as I frequently (up to tens times at once) have to browse between different web pages to see requirements information such as requirements text for which the loading time is about 30 seconds. This process is repeated for understanding the objects in the vicinity and requirements allocated to parent objects" (Interviewee 3).
				Quote B1.2-3b: "At the moment I am working on the service corridor and the boundary condition minimum clearance outline (PVR) is not presented on object level while it is extremely relevant. As a result, the information is not directly incorporated, and users are expected to memorise this" (Interviewee 3).
				Quote B1.2-3c: "At the moment we are designing cable trays, so we are dependent on the requirements and technical specifications (design decisions) of the concrete wall to which the cable trays are jointed. We are interested in e.g., concrete strength and coverage, and steel reinforcement. This information is hard to find in the system as there are no such links as 'adjacent objects. As a result, I contact the responsible specialty engineer or lead engineer which results in a few days of delays" (Interviewee 3).
Security	Security focuses on the external and internal security which respectively comes down to security of the system against external threats in the shape of firewalls and internally as in how protected the information is from (un)intentional faults of users in the system.	External		
		Internal	1 out of 3 specialty engineers remarks the sensitivity of the information managed in the CMDB. The information could be subjected to changes, mistakes (typos) or subjectivities in the naming, description of assigning attributes.	Quote B2.2-1: "The process of recording information in the CMDB is subjected to subjectivities and typos resulting in decreasing reliability of the information. For example, the conceptualisation of objects might differ per perspective. The object names, properties or any other data could be captured wrongly due to e.g., minor writing mistakes which might result in a low obtainability for particular users." (Interviewee 1)
Relevancy	The relevancy is the extent to which the information presented in the system is useful, relevant, applicable, and helpful. The subthemes are usefulness and relevant as these respectively consider the fitness for use of the information itself and relevant focuses on the degree to which the information is essential for a specific task.	Usefulness	2 out of 3 state that the data in the systems is not always useful as the data can not be structured in random compositions required for activities such as trade studies or alternative studies.	Quote B3.1-1: "In case of major design decisions a trade study is being performed in which, the system needs to be identified as well as the corresponding information. Consequently, a detailed and traceable decision is being made on the alternatives proposed. Therefore, the specialty engineer requires the information in the composition of the situation. However, the CMDB doesn't support this function. (Interviewee 1)
		Relevant	3 of 3 specialty engineers consider a major part of the information presented in the system as not relevant to the task. The information presented on the object page is considered as non relevant, especially because standard fields are presented that are not used by all users or are white cells. On the other hand, an information underload is experienced as relevant information is missing on object level, think of context or requirements allocated to parent objects.	Quote B3.2-3: "There is a lot of information presented in the system that is irrelevant. At first, all the project objects are presented to me. Second, Requirements that are not of interest for the product I have to deliver in a specific phase are presented. As a result, I don't see the overview and I strongly dislike the system and prefer not to use it. At last, there are plenty of white cells presented on the object page that won't be of interest to me at all, but these white cells cause confusion and I have to scroll each time." (Interviewee 3).
Completeness	Completeness is the extent to which the information is sufficient, complete, comprehensive, detailed and includes all necessary values (Singh et al., 2009). In this research, completeness is subdivided into level of detail and	Level of detail	3 out of 3 specialty engineers experience drawbacks with the level of detail of the physical objects managed in the system for each process. Physical objects are managed on a generic level. As a result, the information allocation is inconsistent, contradicting and communication such as design decisions also limits in effectiveness. Besides, information assessment processes might be time-consuming and risky.	Quote B4.1-1: "Objects are generically managed in the system decomposition, as a result, the situational context is not considered, whereas information of the specific objects is very relevant. The situational context could change due to changing stakeholders, different technical environment, or different functionalities. Different circumstances often lead to different requirements. This phenomenon is relevant for both line and point objects." (Interviewee 1)

	comprehensiveness as level of detail focuses on the level of detail at which the information is presented. The comprehensiveness focuses on the contextual information that is given to the objects managed in the system.	Comprehensiveness	3 out of 3 specialty engineers experience limited contextual information at object level on the object page. At first, there is limited information provided regarding object context such as specifications location or relations at object level, both cross-domain and internal-domain relations. As a result, the specialty engineer needs to search for this object without having the skills to understand the system decomposition and the ability to assess the validity of the information presented.	Quote B4.2-3: "The objects that are listed in the system decomposition are hard to understand by functionality, exact location, objects in vicinity and internal-domain and cross-domain relations with other objects. This is the case for general objects that might be relevant to my discipline as well as objects that are certainly relevant to my discipline" (Interviewee 3).
Consistency	Consistency is defined by the degree to which the information managed in the system has a consistent structure and is presented in the same format. The consistent structure focuses on the system breakdown structure and the format focuses on the presentation of the information.	Structure	3 out of 3 specialty engineers consider the structuring of the information as unclear because of different reasons such as: different strategy on structuring in each project, different structuring strategy throughout the project and no consensus on how to implement systems engineering.	Quote B5.1-1: "In the development phase of a project there is a lot of discussion on the preferred system decomposition as different disciplines have their preferences and enter the project in a different point in time. Furthermore, there is always discussion on the strategy towards decomposing line objects such as road (which is my responsibility). A road intersects with many so to say point object such as viaducts and at these crossings the road is subjected to different requirements which results in complexities regarding object management in Relatics." (Interviewee 1)
		Format	2 out of 3 specialty engineers consider the format of the CMDB as imperfect as the goal of a certain page is unclear at a glance. Overall, there is no proper user interface as it more looks like a nicely made excel format instead of a high-end information management tool.	Quote 5.2-2&3: "The format of the system is disliked because the goal of the system is not clear at one glance, too much information and unnecessary tables" (Interviewee 2 & 3).
Timeliness	Timeliness is the degree to which the information is up to date, current delivered on time and timely (Singh et al., 2009). A distinction is made between up to date and timely in which up-to-datedness considers the validity and credibility of the information and timely considers the information presentation in a specific project phase or for certain process.	Up to date	3 out of 3 specialty engineers experience information asymmetry (non up to date information) as the systems information is lacking behind on the latest status resulting in snowball effects. The date of modification is not presented at the data element. One very advanced specialty engineer in the CMDB has tricks to check whether or not the requirements are up to date. However, this trick to track down the 'date of change' takes time and require skills.	Quote B6.1-1: "When searching for information, I often questioning myself whether or not the information is still valid. The answer is found at the responsible discipline which I contact in that case." (Interviewee 1)
				Quote B6.1-2: "Requirements and the system decomposition are often not up to date. This can be checked by searching in browse history. As a specialty engineer you are aware of discussions on requirements so in this way you can check whether or not the requirement is up to date." (Interviewee 2)
		Timely	3 out of 3 specialty engineers consider the system not to be timely as the information presentation doesn't consider the context such as phase or activity.	Quote B6.2-1: "I often encounter requirements that are not relevant for my task at a specific point in time. For example, a requirement on the colour of the roadside is not of interest to me in the VO phase. In a major project there are thousands of requirements" (Interviewee 1).
Logical coherence	Logical coherence is derived from logical that refers to reasoning and coherence which indicates values that do not conflict with each other (Singh et al., 2009). Logical coherence is subdivided into internal and external coherence. Internal coherence considers the harmony within a process with other stakeholders and the external coherence focuses on the relation with other processes and other information systems.	Internal	3 out of 3 specialty engineers encounter lacking logical coherent physical object entities due to generic object management. Both point and line objects are managed generically without considering the situational context. As a result, generic information is allocated to the particular object. Whereas the user might be able to filter and assess the information required for their object of interest, assessing the validity and applicability of information allocated to neighbouring objects will be hard. Generic object management appears in both point and line objects. Changing situational context of object could originate from different functionalities, technical environments and changing stakeholders.	Quote B7.1-1: "The level of detail of both point- and line objects are often not decomposed to the smallest detail, resulting in inconsistencies, contradictions, and confusion for the specialty engineer. Consequently, I have to perform additional research. In addition, I have to look into the general requirements register or request a lead engineer to answer the questions I have" (Interviewee 1).
				Quote B7.1-2: "The activity of exploring which requirements are relevant for which part of the object (in this case a wall), are not managed object specific. As a result, the information allocated to the specific object is not uniform. Nevertheless, the specialty engineer requires the overview and needs to explore this himself, which is performed in Excel. Object specific management in Relatics might lead to an abundance of verification activities as all general requirements per tunnel part need to be verified." (Interviewee 2)
				Quote B7.1-3: "The requirements allocated to CCTV camera objects are approximately 80. For example, the requirements "provide interface to object" is only relevant in the DO. Besides, there are requirements that are relevant for only one or a few CCTV cameras. For example, one CCTV needs to be jointed to the ceiling as it is not possible to joint it to the wall, which was originally required. Which camera and where the camera is located is unclear. In case of unclarities or discussions, the successive processes might take up to 3 weeks" (Interviewee 3)
		External	3 out of 3 specialty engineers state that the external logical coherence is substandard. Due to generic management of objects, processes such as interface management require assessment time to understand the situation.	Quote B7.2-1: "Interface management in the CMDB is conducted by linking two objects. Because of the generic object management in the CMDB, a road segment is linked to a bunch of 100 wells whereas only one well has a clash with the road segment." (Interviewee 1).

Lead engineer				
Themes	Theoretical explanation	Subthemes	Summaries of observations	Quotes interviewees
Accessibility	Accessibility entails the degree to which information is available, obtainable, or quickly retrievable. In this case availability includes the availability of the system in the sense of downturns and resources needed to make use of the system. Obtainability focuses more on the steps to be taken in the system in order to obtain the information.	Availability		
		Obtainability	All lead engineers state that the obtainability of the preferred data structuring is hard which results in limited information. At first, the loading and processing time is low. Second, obtaining information on objects that are not in my expertise are hard to reach and understand. However, as the lead engineer has built up experience in the design phase and on, the specialty engineer can be assisted easily with obtaining information.	Quote B1.2-6: "My own developed system structures are not problem, however, in case I need information from other disciplines such as Civil I need more context information as the object decomposition is not clear. Furthermore, the presentation of information in the CMDB is not always fit for purpose, therefore, workarounds such as Excel are used because Excel has functionalities such as pivot tables." (Interviewee 6)
Security	Security focuses on the external and internal security which respectively comes down to security of the system against external threats in the shape of firewalls and internally as in how protected the information is from (un)intentional faults of users in the system.	External		
		Internal		
Relevancy	The relevancy is the extent to which the information presented in the system is useful, relevant, applicable, and helpful. The subthemes are usefulness and relevant as these respectively consider the fitness for use of the information itself and relevant focuses on the degree to which the information is essential for a specific task.	Usefulness	3 out of 3 lead engineers assess the usefulness of the system differently per process. In the processes for which different perspectives are required such as requirements analysis, Excel is used as workaround. The CMDB is lacking functionalities such as colouring, restructuring or adding columns. The system is fit for use in processes such as interface management, verification and validation and system control	Quote 3.1-4: "In the process of requirements and functional analysis, a major list of requirements is presented to the lead engineer. These requirements need to be analysed, decomposed, and allocated to objects. Therefore, tweaking of this information is required. However, Relatics doesn't offer the functionalities to easily tweak this information such as hiding columns, colour objects or other functionalities that Excel does offer." (Interviewee 4)
		Relevant		
Completeness	Completeness is the extent to which the information is sufficient, complete, comprehensive, detailed and includes all necessary values (Singh et al., 2009). In this research, completeness is subdivided into level of detail and comprehensiveness as level of detail focuses on the level of detail at which the information is presented. The comprehensiveness focuses on the contextual information that is given to the objects managed in the system.	Level of detail	3 out of 3 lead engineers state that they are partially responsible for the level of detail objects and requirements in the system. Consequently, the level of detail can be easily adjusted to the needs of the lead engineer. The lead engineer tries to balance out the level of detail as 'high level' is not workable whereas managing in too much detail results in abundant successive processes activities and slowing system performance.	Quote 4.1-4: "When managing information in too much detail the system might work against you as the speed of the system reduces and the findability of information decreases. Furthermore, managing objects in too much detail might lead to an abundance of successive processes such as verification and validation. For example, requirements that were already verified in the VO, needed to be verified and controlled again in DO and UO." (Interviewee 4)
		Comprehensiveness		
Consistency	Consistency is defined by the degree to which the information managed in the system has a consistent structure and is presented in the same format. The consistent structure focuses on the system breakdown structure and the format focuses on the presentation of the information.	Structure		
		Format	3 out of 3 lead engineers experience the format of the system as 'not easy' to work with and too big and many changes between the format between projects and different contractors. Changes that are mentioned are important buttons that are located at a different location with a different design. However, as the lead engineer spends a lot of time in the system, once the changes are noted the system is easy to work with again.	Quote 5.2-4: "At the start of a project, the user interface takes some time to get used to. As the lead engineer spends so much time in the system, the system becomes easy to work with." (Interview 4)
Timeliness	Timeliness is the degree to which the information is up to date, current	Up to date		

	delivered on time and timely (Singh et al., 2009). A distinction is made between up to date and timely in which up-to-dateness considers the validity and credibility of the information and timely considers the information presentation in a specific project phase or for certain process.	Timely	3 out of 3 lead engineers experience that the control figures such as the work packages are trustworthy. As the work packages are managed per phase, this will be immediately covered. Although the work packages are linked to abstract objects in a project, the project progress rate give a proper indication.	Quote B6.2-4: "Although the work packages are linked to non detailed system decompositions, the progress values are overall experienced to be trustworthy. Decision-making based on this information is accepted. There are situations in which the values of the work packages are meaningless, but this is only seen in projects were the whole system was set aside" (Interviewee 4).
Logical coherence	Logical coherence is derived from logical that refers to reasoning and coherence which indicates values that do not conflict with each other (Singh et al., 2009). Logical coherence is subdivided into internal and external coherence. Internal coherence considers the harmony within a process with other stakeholders and the external coherence focuses on the relation with other processes and other information systems.	Internal	The answers of each lead engineer differ per disciplines therefore each discipline is considered. The civil structure discipline doesn't encounter problems with the management of a single civil structures. However, when multiple structures are managed at once in a system, problems are observed in the successive processes as the requirements specification has been performed properly. The infrastructure lead engineer observes conflicting requirements to one object or requirements that are not valid for the entire object to which it is allocated. The electrical lead engineer experiences no problems in the system as the experienced employees have no problems with the information overload.	Quote 7.1-4: "The system is not fit for purpose in case of managing line objects as the information allocated to these objects might vary. Examples of point objects: viaduct. Line object: road, barrier, several streetlights. There might be contradicting requirements or not relevant requirements to a certain object. This might be a potential improvement in the system" (Interviewee 4)
				Quote 7.1-5: "I have experienced asymmetry when multiple civil structures are managed at once in the system. In this case there might pop up problems with requirements that are allocated to one civil structure whereas not allocated to another civil structure" (Interviewee 5).
				Quote 7.1-6: "We do not manage the CCTV camera object specific, whereas there are 205 requirements allocated and a search bar is present. With the experience of out colleagues (12 years with the same experience) there are no problems to handle this bunch of information." (Interviewee 6)
		External	1 out of 3 lead engineers state that his discipline (TTI) has experience with database reporting systems so that updates on entities are automated. The main benefit is that the systems don't have to be managed in parallel anymore.	Quote 7.2-6: "There are links with external system such as database reporting systems writing the plan report which are overall experienced to properly work. The specialty engineers consider it as a good tool as the data has to be inserted only once so no parallel management required. (Interviewee 6)

Appendix I – Root cause analysis 5 whys

5 whys root cause analysis - Specialty engineer								
Themes	**Subtheme**	**Quote**	**Problem observation**	**Why 1**	**Why 2**	**Why 3**	**Why 4**	**Problem**
Accessibility	Availability							
	Obtainability	B1.2-1a B1.2-3a B1.2-3c	Constantly browsing between pages to get context on the information	No full presentation of information on the object page (entities and attributes)	Wrong information queried for the object page	Information presentation object page strategy		Information presentation object page
		B1.2-3a	Constantly browsing between pages to get context on the information	Loading time of requirements pages could take up to tens of seconds				System performance
		B1.2-3c	Object pages of adjacent objects cannot be reached easily	No links present on the object page to browse to adjacent object	No relations between objects present in information model			Missing physical relations
		B1.2-3c	Searching information in CMDB and consequently restructure the information in another tool (Excel, on paper)	No possibility to present required information in preferred composition	SMART queries targeting the relations can not be made	Relations are not established between physical object in information model		Missing physical relations
		B1.2-3b	Searching for relevant requirements allocated to parent objects	Requirements relevant for the object allocated to parent requirements not clearly presented on child object page	No inheritance applied to between parent and child objects and no highlights of this entity on object page	Information model doesn't have the functionality to selectively apply inheritance		Missing inheritance
		B2.2-1	Assessing the reliability of the information in the system	Information in the system is no resistant to human errors	Information (e.g., name, coding, attributes) in the system is implemented by hand	There are no standards		Error-prone information
		B3.1-1	Searching information in CMDB and consequently structure in preferred composition in another tool (Excel, on paper)	Limited possibility to present required information in preferred composition	Specialist is required to implement customised queries	Application doesn't offer easy possibility to implement custom queries	Preferred composition is an iterative process and therefore laborious and costly	Inflexible information presentation
Security	External		-	-				
	Internal	B2.2-1	Searching and checking the information in the system on validity and reliability	Loosely coupled information that is subjected to change but can't handle the change	There is no central information model			Error-prone information
		B2.2-1	Searching and checking the information in the system on validity and reliability	Human errors or subjectivities	Individuals perform to many activities by hand that are prone to mistakes	No standards		Error-prone information
Relevancy	Usefulness	B3.1-1	The data in the systems is not always useful as the data can not be structured in different compositions required for activities such as trade studies or alternative studies.	Limited possibility to present required information in preferred composition	Specialist is required to implement customised queries	Application doesn't offer easy possibility to implement custom queries	Preferred composition is an iterative process and therefore laborious and costly	Inflexible information presentation
	Relevant	B3.2-3	User needs to set the filter each time entering the system to assess relevancy of information allocated to concrete object	The system doesn't offer the possibility to save the filter				Information overload
		B1.2-1a	Some relevant information (live information management) about objects is not managed in the system	Generic object management makes managing information such as design decisions or location positions worthless	Some information is on relevant to a particular object or set of objects			Generic object management
Completeness	Level of detail	B4.1-1	Contradicting interests on level of detail in decomposition	Lead engineer determines to manage objects on generic level, otherwise too much successive activities	No integral approach on managing concrete objects			Generic object management
	Comprehen siveness	B4.2-3	Difficult to easily understand and assess applicability and relevancy of information at object of interest and adjacent objects	The experience level of the specialty engineer might differ and therefore is not always able to assess the impact of information related to other fields of engineering				Information overload
Consistency	Structure	B5.1-1	The leading perspectives in a project often change the decomposition approach	Different structuring approach result in different relations in the decomposition which might affect successive processes	The system (information model) can only handle one system approach			Rigid information model

	Format	B5.2-2&3	Users require time to understand the information presentation in new templates	UX not clear at one glance and new items could be experienced to be substandard	No clear innovation on how to effectively present the user interface			Substandard User Interface
Timeliness	Up to date	B6.1-1 B6.1-2	Implements workarounds such as requesting colleagues to obtain the recency of information	Cannot easily identify the recency of information	No skills to find the information in the system			Missing modification date
	Timely	B6.2-1	Require time to assess which information is relevant for the particular job	not considered the phase and process of role	The system doesn't offer the possibility to filter on the particular phase and process			Information overload
Logical coherence	Internal	B7.1-1 B7.1-2 B7.1-3	Situational context of objects is not considered resulting in time consuming assessment of information	The lead engineer determines to manage objects on generic level	Too many activities in successive processes	No integral approach on managing objects on concrete level		Generic object management
	External	B7.2-1	Understanding context in successive processes such as interface management are laborious	Objects are managed too generic	The lead engineer determines to manage objects on generic level as otherwise to much consecutive activities	No integral approach on managing concrete objects		Generic object management

5 whys root cause analysis - Lead engineer						
Themes	**Subtheme**	**Quote**	**Problem observation**	**Why 1**	**Why 2**	**Problem number**
Accessibility	Availability		-			
	Obtainability	B1.2-6	Low loading and processing time	System performance is low	High quantity of relations cannot be managed	System performance
		B1.2-6	Not able to easily browse to adjacent object	No hyperlinks presented at object page	Relations are not established between objects	Missing physical relations
		B1.2-6	Unclear conception of objects	No unambiguous conception of things	No standards	Error prone information
Security	External					
	Internal					
Relevancy	Usefulness	B3.1-4	Limiting functionalities in restructuring compositions and activities such as applying colours	Not considered in business logic		Lacking functionalities
	Relevant		-			
Completeness	Level of detail	B4.1-4	Concrete object management slows down system performance	System needs to perform more calculations	Exponential increasing number of relations	System performance
		B4.1-4	Concrete object management hardens management of successive processes	No controlled approach on decomposing objects till instantiation		Generic object management
	Comprehensiveness		-			
Consistency	Structure		-			
	Format	B5.2-4	The goal of the user interface is not clear in one glance	Important buttons are not pontifically presented	Unknown how to effectively present such as UI	Substandard user interface
		B5.2-4	The goal of the user interface is not clear in one glance	Plenty of information presented that is not relevant to the particular job		Information overload
Timeliness	Up to date		-			
	Timely	B6.2-4	Not able to receive detailed insight on progress	Progress values are based on generic management	System decomposition hosts only generic objects	Generic object management
Logical coherence	Internal	B7.1-4 B7.1-5 B7.1-6	Contradicting information allocated to objects	People need to assess whether information is relevant	Time consuming and prone to errors	Generic object management
	External		-			

Appendix J – Development process Problems – Goals – Requirements – Solutions

Problems – Goals												
		Problems										
				1	2	3	4	5	6	7	8	9
			Category	Presentation	Presentation	Presentation	Presentation	Structuring	Structuring	Structuring	Structuring	Structuring
			Problems noted in report	Recency check	Information overload	Information presentation object page	Inflexible information presentation	Missing physical relations	Missing inheritance	Error-prone information	Generic object management	Rigid information model
			Problem explanation	Users are not able to check the recency of the information	Information presentation do not differentiate on variables such as time, activity, or interest	Necessary information is not managed or presented fragmented	Not possible to easily query random information or present information randomly	No possible to easily browse to adjacent physical objects	Not possible to selectively pass information to child object(s)	Information is manually inserted and loosely coupled	Objects are managed on generic level representing multiple real-world objects in different situations	Information cannot be easily adjusted to other perspective(s)
Goals	**1**	Improve obtainability of relevant and frequently needed information such as entities, attributes, and tuples	Present all relevant information elements on object page									
	2		Presenting relevant entity attributes on object page									
	3		Present relevant requirements allocated to parent objects on child object page									
	4	Simplify the ability to check the recency of information										
	5	Present information that is relevant to the particular user in a particular task, phase, or discipline	Tailor tuples presentation to user specific information needs related to the phase, activity, or discipline									
	6		Tailor presentation of (blank entities) on the object page									
	7	Improve the logical coherence by allocating and presenting uniform information	Develop a decomposition apart from the abstract model that concretely manages objects									
	8		Improve understanding on point and line object management									
	9	Improve object context by presenting physical relations to other objects on the object page										
	10	Reduce the capriciousness of the preferred system decomposition by defining a general object conceptualisation (properties, constraints, relations) that is agreed on by all stakeholders in the design phase										
	11	Enable the user to request a specific composition of information										

Goals – Requirements

Requirements		Goals 1	2	3	4	5	6	7	8	9	10	11
		Improve obtainability of relevant and frequently needed information such as entities, attributes, and tuples			Simplify the ability to check the recency of information	Present information that is relevant to the particular user in a particular task, phase, or discipline		Improve the logical coherence by allocating and presenting uniform information on the object page		Improve object context by presenting physical relations to other objects on the object page	Reduce the capriciousness of the preferred system by defining a general object conceptualisation (properties, constraints, relations) that is agreed on by all stakeholders in the design phase and is linked to from the abstract and concrete levels	Enable the user to request a specific composition of information
		Present all relevant information elements on object page	Presenting relevant entity attributes on object page	Present relevant requirements allocated to parent objects on child object page		Tailor tuples presentation to user specific information needs related to a point of interest such as system or time (object and relations)	Tailor presentation information elements on the interest of the user	Develop a decomposition apart from the abstract model that concretely manages objects	Improve understanding on point and line object management			
1	The object page should present the following information elements: - Object attributes (…), - Design decisions, - Standards & directives, - Relations, - Constraints - Requirements (Parent), - Object- or part sub types - Parent object, - Overview of concrete objects or abstract objects - Object specifications	■										
2	Present relevant information allocated to parent objects on the child object page			■								
3	Present relevant attributes of the information elements on the object page: - Design decisions (Notes, dimensions of object, material, status of decision, Firmness of decision) - Constraints (properties depending on the object) - Requirements (Code, Title, Text, Status) Interface (Phase, relation text, 'relation requirement', discipline, owner) Relation (Type of relation, Object, corresponding requirement, owner of object)		■									
4	Implement three separate models, a concrete decomposition that manages concrete physical objects (instantiations) by a code, number or name and an abstract decomposition that manages the general decomposition, and an OTL that manages the general specifications of the objects							■			■	
5	Object (both point and line) decompositions should be decomposed to a level of detail that the information allocated is uniform and requirements due to factors (functionalities,								■			

		environment, or stakeholders) are valid for the specific object											
	6	Hyperlinks are to be presented to all information that is relevant but not frequently needed for the specialty engineer											
	7	Information elements should be filtered to the interests of the specialty engineer as - Blank cells should not be visible											
	8	Tuples information presentation should be filtered any information elements based on: - System of interest, - Phase of interest, - Discipline of interest											
	9	Present the date of modification within a few seconds when hoovering over an information element											
	10	Establish inheritance relations between the models of OTL, abstract and the concrete layer											
	11	Establish physical relations between physical object that are closely related to each other											
	12	Provide a webpage on which users can request the information of interest in the composition that is required by combining entities into different compositions											

Requirements - Solutions

			Solutions				
		Explanation	Physical relations	Abstraction levels	Conceptual model	One stop shop	Custom query
Requirement	1	The object page should present the following information elements: - Object attributes (...), - Design decisions, - Standards & directives, - Relations, - Constraints - Requirements (Parent), - Object- or part sub types - Parent object, - Overview of concrete objects or abstract objects - Object specifications				■	
	2	Present relevant information allocated to parent objects on the child object page			■	■	
	3	Present relevant attributes of the information elements on the object page: - Design decisions (Notes, dimensions of object, material, status of decision, Firmness of decision) - Constraints (properties depending on the object) - Requirements (Code, Title, Text, Status) - Interface (Phase, relation text, 'relation requirement', discipline, owner) - Relation (Type of relation, Object, corresponding requirement, owner of object)			■	■	
	4	Implement three separate models, a concrete decomposition that manages concrete physical objects (instantiations) by a code, number or name and an abstract decomposition that manages the general decomposition, and an OTL that manages the general specifications of the objects		■	■		
	5	Object (both point and line) decompositions should be decomposed to a level of detail that the information allocated is uniform and requirements due to factors (functionalities, environment, or stakeholders) are valid for the specific object		■			
	6	Hyperlinks are to be presented to all information that is relevant but not frequently needed for the specialty engineer				■	
	7	Information elements should be filtered to the interests of the specialty engineer as - Blank cells should not be visible				■	
	8	Tuples information presentation should be filtered any information elements based on: - System of interest, - Phase of interest, - Discipline of interest				■	
	9	Present the date of modification within a few seconds when hoovering over an information element				■	
	10	Establish inheritance relations between the models of OTL, abstract and the concrete layer			■		
	11	Establish physical relations between physical object that are closely related to each other	■				■
	12	Provide a webpage on which users can request the information of interest in the composition that is required					■

Problems – solutions (Requirements)

				Problems								
			Number	1	2	3	4	5	6	7	8	9
			Category	Presentation	Presentation	Presentation	Presentation	Structuring	Structuring	Structuring	Structuring	Structuring
			Sub category	Recency check	Information overload	Information presentation object page	Inflexible information presentation	Missing physical relations	Missing inheritance	Error-prone information	Generic object management	Rigid decomposition structure
			Problem explanation	Users are not able to check the recency of the information	Information presentation do no differentiate on variables such as time, activity or interest	Necessary information is not managed or presented fragmented	Not possible to easily query random information or present information randomly	No possible to easily browse to adjacent physical objects	Not possible to selectively pass information to child object(s)	Information is manually inserted and loosely coupled	Objects are managed on generic level representing multiple real-world objects in different situations	Information cannot be easily adjusted to other perspective(s)
Solutions	1	Physical relations	Introduce a general information model that is agreed upon between all stakeholders (OTL)					11				
	2	Abstraction levels	Abstract and concrete decompositions				4			4	4, 5	4
	3	Conceptual model	Decompose the system decomposition to self-contained objects (both point and line)				1,4	11	2	4, 10	4, 5	
	4	One stop shop	Establish (horizontal) relations between objects	9	7, 8	1, 2, 3, 6						
	5	Custom query	Filter information elements that are not of interest or blank				11, 12					

Appendix K – Detailed solutions one stop page

The one stop page consists of several small solutions that are presented below. The solutions are shortly described and the explained by presenting the problem, goals, requirements, and contribution. In some case visualisations are added.

- Entities filter

In the system 'blank' tables are presented while no information is presented. Besides, there are also tables presented that are not of interest to the specialty engineer.

Problem	Entities presented on the object page that are not of interest to the specialty engineer at all or could even be blank
Goal	Tailor presentation entities on the interest of the user
Requirements	Entities should be filtered to the interests of the specialty engineer as blank cells should not be presented
Contribution	Reduce information overload

- Tuple filter

Next to filtering information elements, the data in the entities could also lead to information overload. Therefore, filters should be applied to any kind of information. The main filters that are stipulated in this research are: system of interest, discipline of interest or phase of interest. See below more detailed explanation on the filters.

Problem	No distinction made in the tuples (table rows) presented
Goal	Tailor tuples presentation to user specific information needs related to a point of interest such as time, object, or relations
Requirements	Tuples information presentation should be filtered on: - Phase of interest, - Domain – objects, - Domain – relations/properties
Contribution	Reduce information overload

- Phase of interest

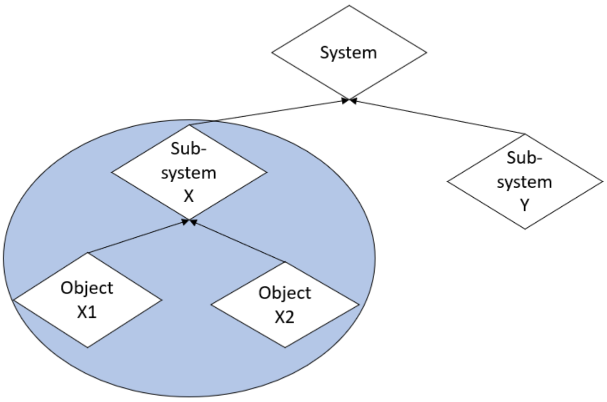
Information presented on the object page is required by the specialty engineer at a specific point in time. In order to prevent from information overload, filtering of information is proposed as a solution. For example, requirements need to be verified in a specific phase and are therefore phase specific, see Table 16. There might be more information presented on the object page that is of interest in a specific point in time due to the phase or end product, which requires further research.

Table 16 Overview of relevance of requirement per phase

Requirement number	Requirement text	VO	DO	UO
1	[Text]	✓	✓	
…	…	…	…	…
n	[Text]	✓	✓	✓

- Domain - objects

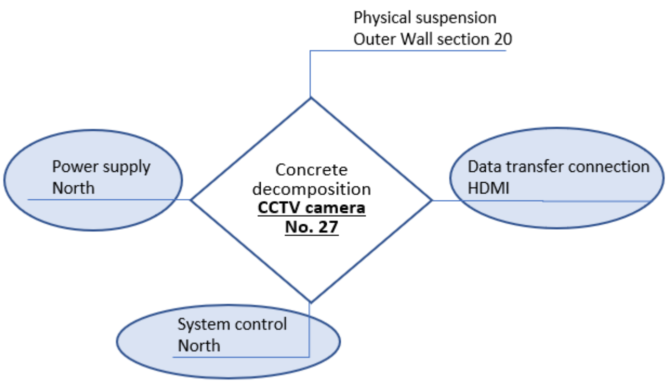
Despite the improvements proposed in this paragraph, there could be an abundance of information presented on the object page. Filtering of information is a solution that can be implemented. A filter can be applied on the system decomposition to present the system of interest. Furthermore, there are other possibilities to filter based on categories such as the type of requirements or the type of relations between objects depending on the information required by the specific specialty engineer. Such analysis is to be conducted based on the tasks of the specific specialty engineer.



Schematic presentation of system of interest (blue circle)

- Domain – relations

Each specialty engineer has a specific domain of interest related to the tasks that have to be performed and related to the objects that needs to be designed. The domain could be applicable to any entity managed on the object page, however, in this example the fields of interests in the relations are considered. An object has several relations with other objects in any way. Therefore, an example is given of the relations possible.



Relations of interest of a specific specialty engineer

- Hyperlinks to related pages

Problem	End users do not have the possibility to quickly browse relational objects as hyperlinks are not presented
Goal	Improve information retrieval by establishing relations so that users are able to find their information in 2 clicks
Requirements	Hyperlinks are to be presented to all information that is relevant but not frequently needed for the specialty engineer
Contribution	Ability to quickly understand context by browsing to other pages from e.g., the object page

- Relevant entities on object page

Problem	Entities such as interfaces, design decisions, standards, relations, directives, object subtypes and specific objects are not collectively presented on the object page

Goal	Improve obtainability by presenting all relevant entities on the object page so that the object page functions as a single stop page
Requirements	The object page should present the following entities: - Object attributes (...), - Design decisions, - Standards & directives, - Relations, - Constraints - Requirements (Parent), - Object- or part sub types - Parent object, - Overview of concrete objects or abstract objects
Contribution	Reducing information underload as all information is in one place leads to overview

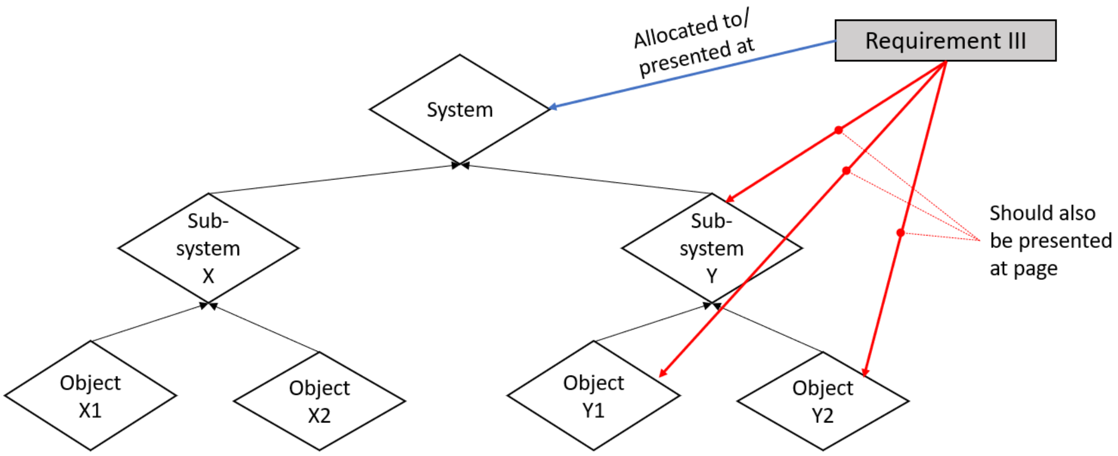
- Relevant attributes on object page

Problem	Entities such as interfaces, design decisions, standards, relations, directives, and object subtypes are not collectively presented on the object page
Goal	Improve obtainability by presenting all relevant entities on the object page so that the object page functions as a single stop page
Requirements	Present relevant attributes of the entities on the object page: - Design decisions (Notes, dimensions of object, material, status of decision, firmness of decision) - Constraints (properties depending on the object) - Requirements (Code, Title, Text, Status) - Interface (Phase, relation text, 'relation requirement', discipline, owner) - Physical relation (Type of relation, related object, corresponding requirement, owner of object)
Contribution	Reducing information underload as all information is in one place leads to overview

- Relevant information allocated parent objects

Relevant requirements allocated to parent objects are to be clearly presented on object pages.

Problem	Applicable requirements allocated to parent objects are not (clearly) presented on the (child) object page
Goal	Improve obtainability by (clearly) presenting relevant requirements allocated to parent objects on the object page the (child) object of interest
Requirements	Present relevant information allocated to parent objects on the child object page
Contribution	Reducing information underload as all information is in one place leads to overview



Requirements allocation and presentation current practice and preferred practice

- <u>Present 'date of modification' and preliminary information</u>

Problem	Not able to easily check the up to dateness of the information
Goal	Simplify the ability to check the up-to-dateness of information by presenting the modification date to the specialty engineer in an easy manner
Requirements	Present the date of modification within a few seconds when hoovering over an entity
Contribution	Improve the ability to assess whether valid information is used

Appendix L – Results and analysis expert panel

Topics to discuss	Comments	Remarks by	Agreed by	Action comment
One stop page (Goal 1 & 2 & 3)				
Information elements	Potentially too much information in a specific information element which consequently lead to information overload	Specialty engineer TTI	All	Future research
	Interface management needs to be presented	Specialty engineer TTI	All	Add to the solution
Information elements metadata	In design decisions, the firmness of decisions should be stated on both object type and instance level	Specialty engineer TTI	All	Add to the solution
	The metadata presented in the information element tables is relevant. But relevance of metadata could differ per role and specialty	Specialty engineer TTI / Specialty engineer Infra	All	Future research
	Design decisions are made object specific and are therefore very relevant. However, this information is dynamic so in order to let this information function as single source of truth direct connections need to be made between the end products such as 3D models or drawings. In case the end product change, the associated design decision should change as well	Specialty engineer Infra	All	Future research
	The discipline for which the requirements is applicable should be added	Specialty engineer Infra	All	Add to the solution
Recency check (Goal 4)				
Up-to-dateness of information	Information field should also present the preliminary information so that traceability is improved and easily checkable on the differences including date	Specialty engineer TTI	All	Add to the solution
Information tailoring (Goal 5&6)				
Information presented not of interest	Each table should have the possibility to filter information, that is saved by the information system	Specialty engineer TTI	All	Add to the solution
Coherent structuring (Goal 7&8)				
Logical coherence of information	Decomposing the line objects into instances raises the questions if all objects need to be decomposed to the smallest level or if a consideration is to be made on the most relevant objects.	Specialty engineer Infra	All	Future research
Relation structuring (Goal 9)				
Ability to quickly switch to relational objects	The decomposition develops through time so it should be possible to change the structures and relations along the way	Specialty engineer TTI	All	Future research
Overview of underlying objects (Goal 10)				

Presenting object overviews	The child objects are relevant when considered whole objects, however other specialty engineers could require parts and components of the specific object instead of instances	Specialty engineer TTI	All	Future research
Interactive data presentation (Goal 11)				
Interactive data presentation	More detailed explanation required on the query (viewpoint) and views.	System engineer / specialty engineer	All	Add to the solution
Conceptual data model (Design of solution)				
Conceptual data model	Intended functionalities properly described. Inheritance should be linked between each sub model	System engineer	All	Add to the solution