Blekinge Tekniska Högskola (BTH) and HOCHTIEF ViCon

Digital Collaboration and Automized Tracing of Information (D-CAT)

Final report

Michael Unterkalmsteiner, Waleed Abdeen, Krzysztof Wnuk (BTH), Jan-Derrick Braun, Alexandros Chirtoglou, Christoph Schimanski, Heja Goli (HOCHTIEF ViCon)

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2 Introduction

Client organizations in the infrastructure industry are transitioning from formulating constructive design requirements to functional requirements for the design and implementation of a facility. The idea of this paradigm shift is to allow for the flexibility to develop an optimal facility by placing requirements on the dimensioning of infrastructure facilities, building components and essential properties instead of pre-emptying solutions with a constructive design. The functional requirements for the facility must be traceable to enable their procurement, validation and verification. Knowledge of methods for describing, procuring, validating and following up the infrastructure's functionality needs to be developed.

This research project investigates methods that can improve the traceability of functional requirements in different stages of infrastructure projects. Functional requirements must be linked to a digital copy of the facility so that it can then be followed up on the physical facility. By researching working methods that make it easier for the industry to cooperate in the exchange of digital information, methods must be developed that can facilitate the coordination of functional requirements.

For the project, three aims have been defined:

1. Study existing work processes for requirements management at various actors in the infrastructure industry through the life cycle of a project.
2. Identify opportunities for automation of activities (reduce manual handling) for verification and validation of requirements and to investigate opportunities for implementing these methods in established work processes.
3. Demonstrate developed methods in a practical context.

These aims form the three cornerstones of the project. To achieve the project's aims, three main goals and associated sub-goals have been developed. The main goals and their sub-goals form the basis for the direction of the research work. The aims are fulfilled with the implementation of nine work packages that have been defined for the research project.

The work in the nine work packages was distributed between representatives from academia (Blekinge Institute of Technology, BTH) and the construction industry (HOCHTIEF ViCon GmbH). BTH led the research and carried out the work in close cooperation with industry, which contributed with its practical expertise and supported the project in its ambition to demonstrate the application of the research results in practical contexts. The division of labour is reflected in the work packages, which were managed by the participating project parties. Section 2.3 reiterates the purpose and deliverables of each work package, and provides also a description of the actual implementation and outcomes of the work. The Swedish Transport Administration acted as a supervisor in the research work and contributed with reference material.

The results of the research project are summarized in this report in Sections 3-9. All the deliverables are available online at:

https://www.bth.se/eng/research/research-fields/software-engineering/requirements-engineering/digital-collaboration-and-automized-tracing-of-information-d-cat-deliverables/

2.1 Background

Infrastructure projects have been, and still are to a large extent, controlled and driven by a comprehensive set of rules and regulations that are strongly focused on detailing the implementation of a facility. However, this approach to specify a facilities' requirements is changing since Trafikverket is moving from a design and build role towards an ordering organisation [1].

The role of an ordering organisation implies that requirements need to be defined on a functional level [2]: prescribe, in measurable terms, the characteristics of a building, plant or part thereof at a given time or the change of properties over time.

A central enabler for this paradigm change is the efficient and effective exchange of information between the ordering and executing partners throughout the lifecycle of a project [3]. The construction industry strives towards digitalizing information management, working towards defining common processes and standards, such as ISO 19650 (Organization of information about construction works - Information management using building information modelling) or common classification systems such as CoClass.

Figure 1 illustrates, using the generic systems engineering process, how Trafikverket as a client interfaces with a supplier. While the systems engineering process is under control of the supplier, both parties need to agree on *what* information is exchanged *when* and *how*. A seamless exchange of data reduces the risk of cost overruns and minimizes the risk of misunderstandings particularly in the early phases of a project. Studying, analyzing and improving the interfaces between client and supplier is at the core of this research project, with the vision to use functional requirements as a key component for creating downstream traceability, enabled by the digital information exchange between the requested and the implemented facility, thus creating a digital twin than can be used for planning, analysis and verification.

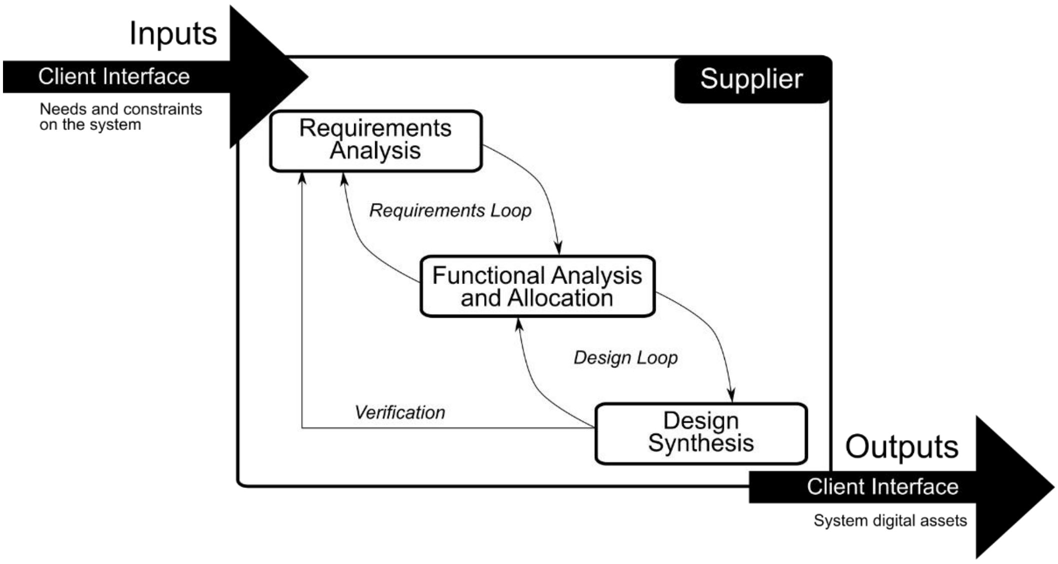

Figure 1 Systems Engineering Process with Client - Supplier Interfaces

2.2 Aim, objectives, and goals

The aim of this research and development project is to design methods for the exchange and archival of digital information and to streamline the communication between different stakeholders throughout the life cycle of an infrastructure project. This overall is achieved by realizing the following objectives:

O1. Study existing work processes related to requirements management that involve varying stakeholders during the life-cycle of a project.
O2. Identify opportunities for the automation of verification activities, develop techniques to reduce manual work, and integrate them in established work processes.
O3. Demonstrate the practical application of the adapted processes and designed methods.

From these objectives, we have derived a set of goals and subgoals.

G1. Assess state of practice
  G1.1 Describe work processes related to requirements engineering, product design and verification & validation, from clients' and suppliers' perspective, and assess them with respect to best practices from literature.
  G1.2 Identify obstacles, related to process, policy and technology, that limit the efficiency of coordination among stakeholders.
  G1.3 Develop strategies to address the identified obstacles. These strategies can include, but are not limited to, the adoption of open data formats and digital processes, traceability recovery, and machine-supported transformation of unstructured information into structured data.
G2. Systematically develop solutions to the identified obstacles, based on the outlined strategies from G1. We group sub-goals according to the assessed work processes,
  G2.1 Requirements engineering:
    - Evaluate to what extent functional requirements can be transformed into a machine readable, structured language.
    - Develop semantic analysis of functional requirements that allows tracing to digital assets.
  G2.2 Product design:
    - Define open digital processes to enable communication between stakeholders.
    - Realize the analysis of functional requirements (e.g. by clustering of related requirements) to increase their value for product design decisions.
  G2.3 Verification & Validation:
    - Automate the verification of functional requirements and properties specified in product design and digital assets.
    - Support the validation of digital assets w.r.t. client needs.
G3. Evaluate the performance of the developed solutions and processes in a setting that corresponds to realistic conditions.
  G3.1 Statically assess the developed processes from both the clients' and suppliers' perspective.
  G3.2 Implement demonstrators that illustrate the viability of the solutions.
  G3.3 Apply the demonstrators on realistic artefacts to evaluate their practical utility.

Each of these goals is addressed by one or more work packages. Table 1 illustrates this mapping.

	G1.1	G1.2	G1.3	G2.1	G2.2	G2.3	G3.1	G3.2	G3.3
WP1	X	X	X						
WP2					X		X		
WP3					X		X		
WP4				X				X	X
WP5					X		X		
WP6						X	X		
WP7						X		X	X
WP8				X	X	X		X	X
WP9	X	X	X	X	X	X	X	X	X

Table 1 Mapping between goals and work packages

2.3 Organisation, implementation, and outcomes

We provide an overview of the original work package definitions, established at the beginning of the project in 2019, and the actual outcomes as of September 2022. The project was conducted in collaboration between Blekinge Institute of Technology (BTH) and HOCHTIEF ViCon. BTH took the role as main coordinator for the project and led the research work overall, while HOCHTIEF ViCon contributed essential domain specific knowledge. The project was organized around nine work packages, each with a brief statement of its purpose, a main responsible for implementation (leader) and a list of deliverables.

The project was scheduled to start with a kick-off meeting in Stockholm in March 2020. However, due to the pandemic, no physical meetings between the project partners could be conducted. While certain aspects of research, in particular data collection and the discussion/demonstration of results have been less efficient in virtual settings, the coordination of work could be managed by regular (bi-weekly) meetings between BTH and HOCHTIEF ViCon. Overall, while the need to work from home, in particular in 2020 and 2021 has somewhat slowed down progress due to the lack of workplace interaction, the project partners have compensated the additional workload that came with the shift in mode of working.

In the remainder of this section, we look back at the original work package definitions, reflect on the implementation and goal achievement (see Table 1), and discuss eventual deviations from the original plan.

2.3.1 WP1 – Coordination needs assessment

Purpose: Assess processes, working practices, artefacts and information systems that are involved in the interfaces (input/output) between client and supplier, and in verification and the requirements / design loop. The observations shall be made on an actual project (or set of projects) in order to elicit the experienced challenges in client-supplier coordination.

Leader: BTH

Deliverables: A report, containing:

- A process, artefact and information system (PAIS) inventory
- Prioritized (by client and supplier) list of challenges to address
- Recommendations to implement existing solutions and research plan for solutions that require further evaluation

Implementation and outcome: We have implemented this work package by conducting interviews with domain experts from HOCHTIEF ViCon, a subcontractor, and Trafikverket. The data collection was conducted virtually and was limited to expert opinion (i.e. we did not get access to project documentation or examples). The prioritization of challenges (G1.2) was performed by BTH together with HOCHTIEF ViCon. The report provides a non-representative snapshot how requirements are communicated between client and supplier (G1.1), and identified support for our initial assumption that traceability between requirements and deliverables is a key issue for the systematic verification at the supplier and acceptance of deliverables by the client (G1.3). The results of this work package were written up as a scientific paper and sent to a journal where it is currently under peer review.

2.3.2 WP2 – Traceability through classification

Purpose: Evaluate the feasibility of using a common vocabulary and classification of construction objects (e.g. CoClass) for tracing functional requirements to digital assets developed by the supplier and handed over to the client.

Leader: BTH

Deliverables: A report, containing:

- Recommendations for using a classification system and suggest structure and content improvements (if any are required)
- Recommendations for the adoption of the classification system in the PAIS inventory

Implementation and outcome: We split the work in this package into two parallel tracks. In the first track, BTH conducted a study to answer the fundamental question how a classification system can be evaluated and compared (G2.2). It turned out that answering this question was far from trivial and the scientific literature did not provide a single best method or a commonly agreed set of objective quality attributes and measurements. The results of this work are already published in a scientific journal. In the second track, we investigated the feasibility of the idea of taxonomic trace links in practice (G2.2). This investigation was conducted together with HOCHTIEF ViCon, using requirements and early-stage BIM models from project Eastlink (G3.1). Collecting the data needed for analysis from Trafikverket turned out to be time consuming, but we eventually received four design models. The results of this work have been written up as a journal publication which is currently under peer review.

2.3.3 WP3 – Digital asset design and analysis

Purpose: Suggest the Project Data Structure (PDS) for infrastructure projects which will enable the linking of model elements to the asset database. Data clustering approach shall be the guide, which will facilitate the information flow from the supplier to the client in a meaningful level of detail.

Leader: HOCHTIEF ViCon

Deliverables: A report, containing:

- Initial PDS guidelines for a test project
- Recommendations for client Asset Database development
- Classification requirements analysis approach

Implementation and outcome: We implemented this work package by analysing the existing structure of the early design models received by Trafikverket. While considering the need to define open digital processes to enable communication between stakeholders, we proposed based on HOCHTIEF ViCon best practice experience a multidimensional data structure which would enable the linking of the data (G2.2). We considered both the client and the supplier perspective, aiming at the feasibility of the Project Data Structure applicability on all required data sets (requirements, digital model, other digital artifacts) (G3.1). The potential to extend the use of the suggested data structured within the BIM models for other use cases of possible interest for Trafikverket, as well as more details for its concept and application have been reported within a document deliverable. The applicability of existing classifications (f.e. SB11 or CoClass) has been analysed as well within the document deliverable.

We could not make any recommendation on the Asset Database development since the Trafikverket project lead could not grant us with access to the database due to restriction of Trafikverket.

2.3.4 WP4 – Client input interface

Purpose: Develop a software supported solution that traces client input to supplier produced digital assets. Implement a demonstrator that is aligned with the recommendations from WP2.

Leader: BTH

Deliverables: A demonstrator that traces functional requirements to a classification system and a screencast illustrating the demonstrators' operation.

Implementation and outcome: One of the key insights from the feasibility study from WP2 was that human classifiers exploit the hierarchical structure of a classification system when making the decision to what class a requirement belongs. That observation from the feasibility study led us to investigate the area of hierarchical classifiers, in particular the approaches that are based on one-shot learning (G2.1). In a previous project (KREDA), we implemented a classifier that used CoClass and did not consider hierarchical information. We extended this implementation, supporting in addition SB11. In order to evaluate the performance of the improved implementation, we had to establish a so-called ground truth. The ground truth consists of a set of requirements, each of which is associated to zero or more classes from a classification system, representing the trace links. This ground truth was created in a collaboration between BTH and HOCHTIEF ViCon and verified with input from Trafikverket. We summarized the evaluation of the improved recommender against the ground truth in a report (G3.3), and plan to write a scientific publication on the process of developing the ground truth as well as the recommender evaluation. The improved recommender itself is part of the deliverable for this work package, as well as part of the demonstrator in WP8 (G3.2).

2.3.5 WP5 – Supplier output interface

Purpose: Evaluate existing open data formats for data exchange from supplier to client.

Leader: HOCHTIEF ViCon

Deliverables: A report, containing:

- An evaluation report for data exchange format processes
- Guidelines for data exchange structure
- Input for Employer's Information Requirements (EIR)

Implementation and outcome: Based on the results from the previous work packages and identified bottlenecks, as well as concerns and input received by the requirements engineering experts of Trafikverket, the BIM-supported use case description and process (G3.1), including the exchange requirements (G2.2) have been document with the current deliverable document. The necessary organisational adjustments to international norms (ISO) have been suggested, a step which will enable the open data format information exchange. Our suggestion was to consider the proposed use case description as basis for the creation and later on the extension of the EIRs. The suggested process map was the basis for the implemented verification process within the next work packages.

2.3.6 WP6– Handling results from requirements validation

Purpose: Apply existing standards to approval workflows and design coordination.

Leader: HOCHTIEF ViCon

Deliverables: A report, containing:

- A Procedural description (guideline) of approval workflows
- Recommendations for further development of Asset database structures in order to allow an automated requirements-based verification of construction designs

Implementation and outcome: During the project, we found it difficult to access information and expertise from Trafikverket. In the project budget, we have not allocated resources for such interaction with Trafikverket, which, in hindsight has been a mistake. Therefore, when we were planning the execution of this work package in the beginning of 2022, we decided to focus on WP7 instead, where we the necessary resources and data were under control of BTH and HOCHTIEF ViCon. As a result, this work package was not completed.

2.3.7 WP7 – Digital asset verification

Purpose: Investigate the feasibility of requirements-based verification of construction design

Leader: BTH

Deliverables: A report containing an evaluation of the accuracy of requirements-based verification and a demonstrator.

Implementation and outcome: As part of this work package, we conducted two studies. First, BTH conducted a literature review on the scientific research on automated compliance checking in the construction industry. The goal was to better understand the current state-of-art. Second, BTH and HOCHTIEF ViCon analysed a sample of requirements from TRFInfra and Eastlink w.r.t. to their verifiability as well as whether they share fundamental commonalities that could be exploited to define verification archetypes (G2.3). The results of this work package are summarized in a report and the demonstrator, illustrating the automated verification of one particular type of requirement, is shown in the demonstrator that is part of WP8 (G3.2, G3.3).

2.3.8 WP8 – Digital asset visualization

Purpose: Create a demonstrator with dynamic data dashboards for management overview of digital assets and their status (traces to client information, verification, export readiness).

Leader: HOCHTIEF ViCon

Deliverables: A demonstrator to visualize management information on digital assets, accompanied with video documentation.

Implementation and outcome: The deliverable of this work package displays and synthesizes the findings and the proposed workflows of all the previous work packages (G3.2). Within a demonstrator, consisting of presentation slides and live demonstration of the systems developed during the period of the DCAT project for real Trafikverket data (G3.3), HOCHTIEF ViCon and BTH display how with the use of their developed tools the verification process of requirements within the digital assets can be facilitated.

2.3.9 WP9 – Guidelines and recommendations

Purpose: Summarize the results of all WPs by presenting new guidelines and proposing updates of existing guidelines.

Leader: BTH

Deliverables:

- A report containing an action plan for standardisation of information exchange between client and supplier.
- A final report of the project outcomes.

Implementation and outcome: All work packages, except WP8, have resulted in at least a written report and/or a scientific publication. We have summarized these reports in this document using a common structure (motivation, results, conclusion). In addition, BTH and HOCHTIEF ViCon have conducted a workshop to elaborate the action plan for standardisation of information exchange between client and supplier, presented in Section **Error! Reference source not found.**.

2.4 Action plan

We outline here the next steps we deem consequential from the results of D-CAT. We present these steps as concrete actions that Trafikverket can choose to implement, as well as new research questions that emerged from our studies.

2.4.1 Concrete actions

The research in D-CAT was designed as a funnel, with WP1 having the widest scope that was narrowed down in the following work packages. With the focus on a particular issue in client-supplier coordination in a selected project (Eastlink), we traded off generalizability with specificity and concrete examples. While we deem the recommendations from the work packages to be generalizable, we deem it also necessary to validate them on a wider spectrum of project types at Trafikverket. Hence, concrete next actions are:

- Communicate the recommendations from this report (WP3, WP5) and replicate the studies (WP2, WP4, WP7, WP8) in a variety of projects (scale and type).
- Analyze and understand the differences between the pilot implementations in order to refine the technical solutions we propose, as well as develop guidelines that are adapted to all scales and types of projects.
- Contractually require open data exchange standards as they are the key element that enables automation in general and automated compliance checks in particular.

2.4.2 New research questions

The investigations in this project have also uncovered a series of new research questions that we deem valuable to answer in the future:

- How can requirements quality be improved, in particular consistency in terminology and verifiability?

- To what extent is the corpus of technical product requirements (TRVInfra, system- and project specific requirements) verifiable?
- To what extent is the set of verification archetypes identified in WP7 generalizable to the complete corpus of technical product requirements?
- To what extent are the identified verification archetypes automatable with rule checks?
- How can information, required for automated rule checks, be integrated into design models (preferably open standards such as IFC) and made accessible for verification?
- What is the best strategy to develop, validate and distribute organization-wide Information requirements (OIRs)?

Finally, based on the experiences from D-CAT, we recommend that future research projects, that aim at investigating tangible and practical improvements of the state-of-practice, plan for the active involvement of all stakeholders, including Trafikverket, in the research process. Both expertise and data (models, requirements, project documentation) from Trafikverket is essential for the ability to design and evaluate solutions that have the potential to impact real life problems.

3 WP1 - Coordination needs assessment

3.1 Motivation

The goal of this work package is to create a baseline that describes how clients and suppliers communicate throughout the life-cycle of a project. Establishing such a baseline is essential as it allows to purposefully design and implement improvements that address any identified challenges. We have focused our investigation on processes that typically require extensive coordination between clients and suppliers:

1. Requirements validation: the process of ensuring that the requirements formulated by the client are correct.
2. Requirements communication: the process of conveying the requirements to the supplier.
3. Digital asset verification: the process of ensuring that the deliverables, created by the supplier, fulfil the initially stated requirements.

While one could study these processes on a theoretical level by analyzing process documentation, such an investigation would not lead to a picture that reflects current work practices at Trafikverket and their suppliers. Hence, we decided to anchor the investigation in concrete projects, allowing us to elicit and describe the processes as they are implemented, not as they are prescribed. The advantage of this approach is that we can identify concrete challenges that were experienced in the execution of the studied processes. One disadvantage is that the identified challenges are specific to the studied context and may or may not be pertinent in other projects.

We have interviewed 10 experienced engineers and managers, working in two projects (Eastlink and FSE101) at Trafikverket. The interviewees work for Trafikverket, a contractor and a subcontractor. Table 2 summarizes the demographics of the interviewees. In the remainder of this chapter (WP1), Trafikverket will be referred to as the “Client”.

ID	Role	Company	Project	Experience
A1	Design manager	Contractor	FSE101	20 years
A2	Tender manager	Contractor	FSE101	10 years
A3	BIM manager	Contractor	FSE101	7 years
A4	Design manager	Contractor	FSE101	10 years
B1	Discipline leader	Subcontractor	FSE101	15 years
B2	Head of design	Subcontractor	FSE101	25 years
C1	BIM specialist	Trafikverket	FSE101	9 years
C2	Requirements specialist	Trafikverket	Eastlink	11 years
C3	Requirements Engineer	Trafikverket	Eastlink	8 years
C4	Head of Technology and Environment	Trafikverket	Eastlink	24 years

Table 2 Interviewee demographics

The interview questions were targeted at eliciting how requirements validation, requirements communication and digital asset verification are conducted in the FSE101 and Eastlink. The roles were selected based on this selection of processes.

3.2 Results

We report here our findings from the interview. First, we describe the processes how they are conducted in FSE101 and Eastlink. Then we describe the challenges, related to the processes, as they were described by the interviewees.

3.2.1 Requirements Validation

Figure 2 depicts the requirements validation process in FSE101. The tender manager and their team at the contractor conduct a review process. The inputs to this process are the technical description and the general regulations in the country that apply to the project. The output of this process is a cost estimation in the form of a spreadsheet. The purpose is to come up with an estimation for the cost of the project to use when tendering for the project. Another review process for the requirements is conducted at the subcontractor by the discipline leaders and designers. They take as input the technical description from the contractor and the general regulations. The output of this process is the design guidelines document that helps designing the models for the project.

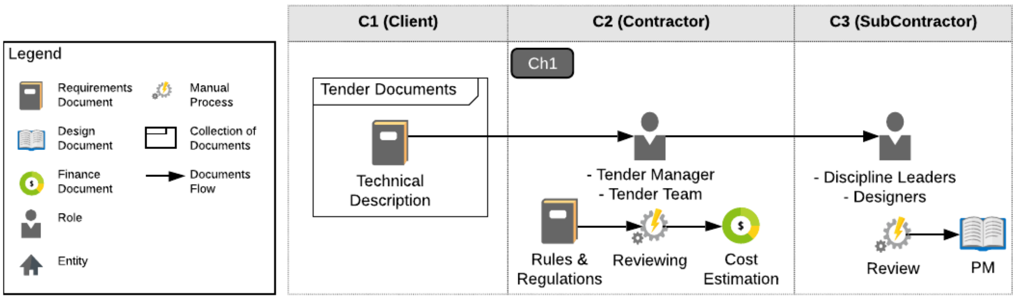

Figure 2 Requirements validation process - FSE101

Figure 3 shows the requirements validation process in Eastlink. The client conducts a partial check on the requirements. The inputs to this check are the railway regulations and technical system standards. The output is the validated requirements. Since the people we interviewed in case two are from the client-side, we do not have information about the requirements validation process on the contractor side.

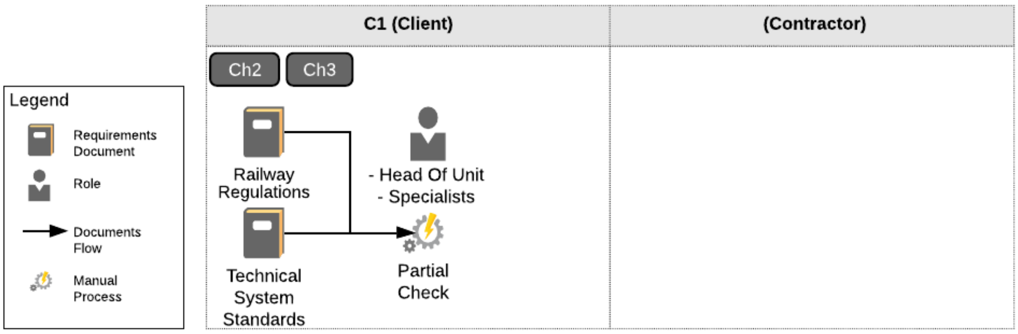

Figure 3 Requirements validation process - Eastlink

3.2.2 Requirements Communication

Figure 4 shows the requirements communication process in FSE101. The project's technical requirements, called technical description document, are a part of the tender documents. The project leaders and tender manager on the contractor side get the technical description from the client, and then they communicate these documents to the discipline leaders and designer on the subcontractor side. Additional requirements apply to the project in form of Rules and Regulations. The contractor and subcontractor are responsible for finding those additional requirements that apply to the project.

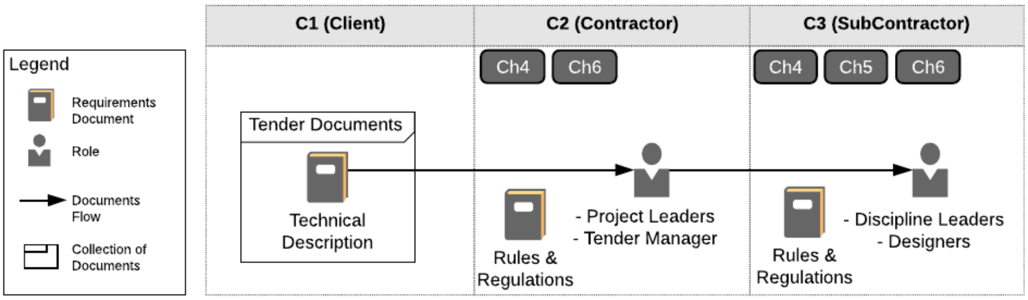

Figure 4 Requirements communication process - FSE101

Figure 5 shows the requirements communication process in Eastlink. In this case, there are many sources of requirements which are of three main types: 1) documents, e.g., technical system standards, or railway regulations; 2) internal or external departments, e.g., local government or maintenance department; and 3) people who reside or work in the project area and who could be affected by the project outcome, e.g., property owners. The client compiles the requirements from all the mentioned sources into project-specific requirements for the railway. Those requirements are stored in a software called Lime, which is used to negotiate requirements between the client and the contractor. After the client and the contractor have agreed on the requirements, those requirements are stored in DOORS NG.

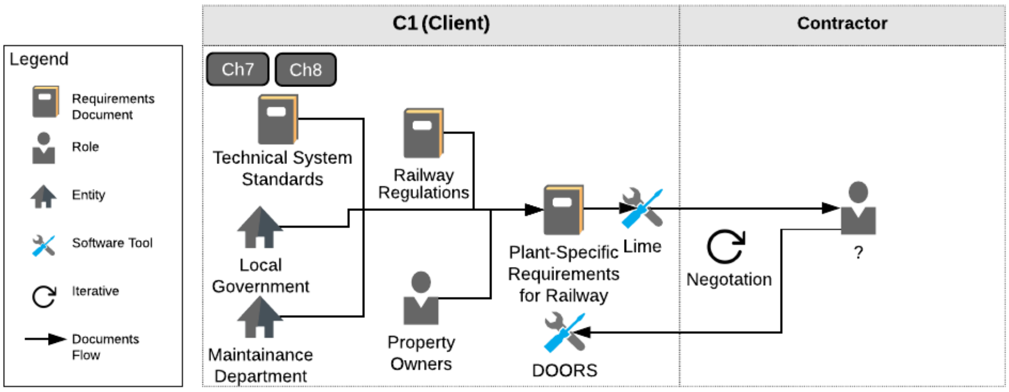

Figure 5 Requirements communication process - Eastlink

3.2.3 Digital Asset Verification

Figure 6 shows the digital assets verification process in FSE101. There are two verification processes present in the figure. The technical check is the process of verifying the produced digital assets' conformity with the specified technical requirements. The consistency check is the process of verifying the conformity of digital assets with the BIM requirements. BIM requirements specifies how the design models should be delivered (e.g., the file's extension to be used for delivering a model, or the units of measure used).

As the subcontractor designers produce the model, a review process is conducted by those designers and the head of design. The process takes as input 1) the produced model, which could be 2D drawings/3D models/BIM, 2) a checklist that is prepared by the designers based on the technical requirements before the implementation, 3) the technical requirements of the project. The output model of this process, along with BIM requirements, goes into a clash detection tool, which checks whether the models have any conflict in design objects. After that, a manual review process is made by the BIM manager.

At the contractor, a similar verification process on the model is followed. First, a technical check is done with the design manual, which is produced at the beginning of the project. This check is done by a checking engineer and is mainly based on experience with verification of similar models. The model is sent to the BIM expert who conducts pre-configurated semi-automated checks on the attributes of the BIM objects based on the client's BIM requirements, using internal tools with customizable configuration possibilities. The technical and consistency check is an iterative process.

Then the model is sent to the client for approval. At the client, there are technical specialists who do their own technical checks while taking technical requirements as input. After that, a series of consistency checks are conducted: clash detection, BIM requirements check, and partial check by BIM specialists. When the model passes all those checks, it is stored in the appropriate database.

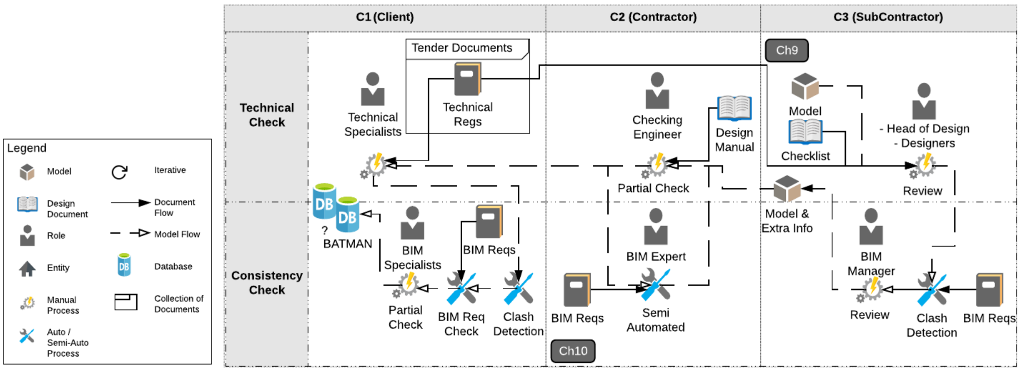

Figure 6 Digital asset verification process - FSE101

Figure 7 presents the digital assets verification process in Eastlink. When the models are delivered to the client for approval, the specialist in the domain conducts a manual review process to verify those models. We also know that there is some kind of check being done by the contractor. However, as we did not conduct any interviews with contractors in Eastlink, we do not have any more details on the verification process.

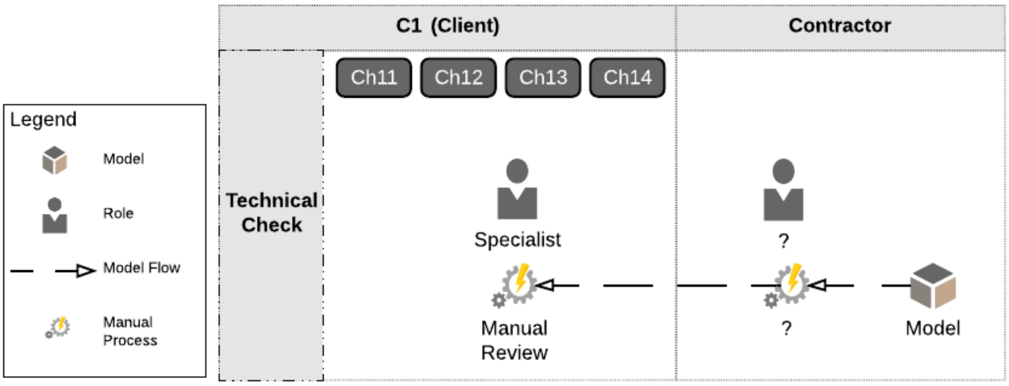

Figure 7 Digital asset verification process - Eastlink

3.2.4 Identified challenges

From the interviews, we identified 14 challenges, summarized in Table 3. We briefly discuss now each challenge, using statements from the interviewees by referring to the IDs introduced in Table 2.

ID	Process	Challenge
CH1	Requirements validation	Requirements validation time
CH2	Requirements validation	Identify conflicts early
CH3	Requirements validation	Prioritizing the requirements validation process
CH4	Requirements communication	Miss-interpretation of requirements
CH5	Requirements communication	Time to communicate the requirements (changes and questions)
CH6	Requirements communication	Finding the correct information
CH7	Requirements communication	Requirements elicitation and validation with non-technical stakeholders
CH8	Requirements communication	Requirements abstraction
CH9	Digital asset verification	Requirements are impossible to build
CH10	Digital asset verification	Difficulty understanding BIM requirements
CH11	Digital asset verification	Requirements management tool related
CH12	Digital asset verification	Granularity of traces
CH13	Digital asset verification	Lack of experience using tools
CH14	Digital asset verification	Verifying all requirements

Table 3 List of identified challenges

Requirements validation time (CH1)
The tender manager (A2) reported that the time to validate the requirements by the contractor was experienced as too short in FSE101. When the tender project is announced, the contractor has to respond with the cost estimation in a matter of weeks. This makes it challenging for the contractor to validate the requirements in such a short time. The major problem is that the contractor has to take responsibility if the cost estimation is inaccurate due to ambiguous or conflicting requirements: "The client spends four years coming up with the design (presented by the requirements), and we have to price it in four or eight weeks, coupled with a tender model that is purely price-driven. It is a very unhealthy situation" (A2).

The cause of this challenge is the ambiguous and conflicting requirements. The requirements validation process could take more than a couple of months when the supplier finds requirements that need clarification or revision by the client.

Added responsibility to the contract is seen as a consequence of this challenge. Since the contractor submits the bid to the project based on the requirements, the contractor takes the responsibility if they have not validated the requirements properly: "Do not put all the risk on us if we can't find the problem in such a short time" (A2).

Identify conflicts early (CH2)
It could be difficult to identify conflicts in the requirements early as seen in Eastlink by the requirements engineer (C3) and head of environment (C4). Although there is a partial check being

conducted on the requirements at the client side, some conflicts may go undetected until later at the design stage, for example, when verifying tunnel related requirements, requirements engineers or designers may not be able to identify water pipes intersection with an obstacle due to the land geometry. "It is hard to see that before when you haven't drawn the lines for the pipes or the tunnel" (C3).

The main cause of this challenge is not clear. When we asked C3 whether the lack of information or having too much information is the cause of difficulties identifying those conflicts, they answered "it depends" (C3).

Prioritizing the requirements validation process (CH3)
The requirements validation process requires experience and knowledge in the discipline, which makes it difficult for the client to prioritize this process and find the right people to do the validation. "When you talk about validating requirements, it is not our top priority." (C2).

Lack of resources is a cause of this challenge. As C2 said "there are not enough railway specialists in the company". The people involved in Eastlink are involved in other projects and have other responsibilities at the client, making it difficult to find the right people to validate the requirements.

The requirements validation process is overlooked as a consequence of not prioritizing the said process. Since it is not always feasible to allocate resources for the validation process, it gets less priority over other activities, leading to the process not being performed in many cases.

Miss-interpretation of requirements (CH4)
Although all parties working on the project have access to the same requirements documents, each party has their interpretation that could differ from the other parties' interpretation. This happens in both projects, as reported by the design manager (A1), tender manager (A2), and discipline leader (B1). The requirements could be unclear or difficult to understand. As one interviewee on the subcontractor side mentioned, "we have had a whole lot of discussions regarding these requirements in the technical description, and it is constantly not crystal clear, so it is very much up to interpretation" (B1). Also, the client thinks that their writing can be improved; as C4 said, "we often think that we are quite clear in our communication, but often it's not the case" (C4).

Lack of knowledge in local projects and requirements are open for interpretation are of the causes of this challenge, as seen by the interviewees. Some people working on the project could lack experience in the projects done in this specific country, which could lead to a different interpretation of the requirements. "If you have any country A engineer and you want to make a bridge design, his background is slightly or completely different from the country B engineer" (A2). The subcontractor sees it as one of the causes of misinterpretation of requirements as put by one interviewee "There is never really a correct answer. There is not just one solution that you can do" (B1).

The misinterpretation of requirements could lead to additional work and extra cost. If the subcontractor's interpretation is different from the client's interpretation, then additional work should be done by the subcontractor. As B1 said, "if our interpretation of the requirements is not that what the client wants us to do, then there is some additional work for us" (B1). In special cases, the misinterpretation of requirements could lead to extra costs paid by the contractor, as confirmed by A1, "I was not informed at all what a requirement (temporary use of land for the project) means".

Time to communicate requirements (CH5)
The requirements communication process between the different parties (client-supplier) takes a long time. This process includes requirements change requests and any requirements-related questions raised by the contractor or subcontractor. This challenge was seen by the discipline leader (B1) in FSE101 and the head of environment (C4) in Eastlink.

All requirements-related communications between the client and subcontractor go through the contractor, which takes a long time: "it could take quite a bit of time" (B1). The client also sees that the change process takes a long time from the contractor side as well. C4 gave an example of a case, "one occasion we did a very big change of the requisition of the whole project ... but then it took like a year for the consultants to respond and tell us how the changes would be interpreted and implemented" (C4).

The interviewees did not explicitly identify the causes or consequences of this challenge.

Finding the correct information (CH6)
The documents communicated by the client do not include all the requirements that apply to the project, and it is challenging by the contractor and subcontractor to find the correct information. This challenge was reported in FSE101 by the design manager (A4) and head of design (B2). As illustrated in Figure 4 and Figure 5, there are additional requirements documents that are not communicated by the client as part of the tender documents. Those documents are local rules and regulations. The client only refers to those documents, and the contractor and subcontractor need to find those documents. "The tricky task to make sure you have all requirements that have to be followed" (A4).

One cause of this challenge is the lack of knowledge in local projects, similar to the cause of miss-interpretation of requirements. Some people with different background could lack experience in how the projects are done in a specific country. In this case, people with experience in local projects are consulted to find the right information.

Requirements elicitation and validation with non-technical stakeholders (CH7)
The requirements elicitation and validation process is a challenging task since many stakeholders are involved. This challenge was reported in Eastlink by a requirements engineer (C3). The client elicits requirements from many sources and stakeholders, as seen in Figure 5. Therefore, the way the client communicates the requirements to different parties needs to be adapted to the audience. "We can have a super model to communicate with the supplier, but we can't use that one when we meet the restaurant owner in the city" (C3).

The cause of seeing the requirements elicitation and validation process as a challenging task is because there are different parties and many stakeholders with different backgrounds involved in the process.

This challenge adds additional work to the client, as the client needs to adapt the requirements to the audience. For example, sketches and drawings need to be done so the client can communicate the requirements with the property owners.

Requirements abstraction (CH8)
The requirements communicated by the client have variations in abstraction levels. The challenging part is to find the right level of granularity for these requirements. This is reported in Eastlink by the head of environment (C4). A too specific requirement could constrain the supplier in developing the solution, "sometimes we were getting the wrong answer when we are too specific in demands" (C4), and a too abstract requirement is open for miss interpretation "often we have to explain more to make the requirements more specific" (C4).

We did not identify clear causes or consequences for this challenge from the interviews.

Requirements are impossible to build (CH9)
In some cases, during the verification of digital assets, engineers detect requirements that are impossible to build. This challenge was reported in FSE101 by the discipline leader (B1). The contractor and subcontractor are limited by what they can change in the requirements. Then, during the verification of digital assets, some requirements appear to be impossible to build. "The solution that company C stated simply can't be done" (B1). Although the client may be validating the requirements, it is still the contractor's and subcontractor's responsibility to make sure those requirements are sound and possible to build.

The client specifies solutions rather than requirements was one cause of this challenge. The requirements provided by the client do not have much room for the contractor or subcontractor to come up with a solution. Rather the requirements specify an actual solution that the contractor and subcontractor need to follow. Therefore, if those requirements/solutions have conflicts, they will likely show during the verification process (since they might be overlooked in the requirements validation process).

The consequence of this challenge is extra work to be done by the subcontractor. During the verification process, if some requirements were detected to be impossible to build, then the subcontractor needs to come up with a new solution, verify it, and request a change for requirements.

Difficulty understanding BIM requirements (CH10)
Some consultants working on the project are not fluent or familiar with the language in which the requirements documents are written, as reported in FSE101 by the BIM manager (A3). It is difficult for those consultants to understand the BIM requirements. Although the consultants translate those documents into their language, they are not confident that the translation is accurate.

Long time spent at the beginning is the consequence of this challenge. At the beginning of the project, it took a while for both the client and the contractor to coordinate and make sure that they were on the same page; as mentioned by A3 "It took some time coordinating with the client to understand the requirements" (A3). This challenge is not specific to BIM requirements only. The project has many people (requirements engineers and designers) with different language proficiency, who may find it difficult to interpret the requirements if the translation is inaccurate.

Requirements management tool related (CH11)
In Eastlink, one of the identified challenges is related to using the requirements management tool DOORS. This challenge was reported by the requirements specialist (C2). People would prefer to use conventional tools like spreadsheets over a specialized new system like DOORS; as mentioned by C2, "specialists don't really like new systems" (C2). It is challenging to get people working on the tool. Another part of this challenge is related to reaching models from within DOORS. "When specialists review stuff, they need to go to the specific document in the specific models to look, and they can't just click on the link, which is annoying" (C2). The delivered models are verified in a different system, and it could be difficult to find the model and the related requirements during the review process by the client's engineers.

The causes we identified for this challenge are use of yet another new tool and the limitation of the tool DOORS. The requirements management tool DOORS is new for many specialists working on the project, and they are not familiar with it; also, some specialists already maintain different systems. "It is a lot for people that already maintain like fifteen different systems so that was an issue to make them like DOORS" (C2). Also, DOORS has its limitations, e.g., "you can't do hyperlinks in the attribute in DOORS" (C2). Currently, using the tool to link the requirements to a specific attribute or part of the model is not possible.

This challenge leads to additional work for the requirements specialist and extra effort by the people verifying the models. Since DOORS is a new system for the people to use, the requirements specialist does spend time preparing views and arranging requirements to make it easy for people involved in the review process. "I have to be involved quite a bit just for them to know where to look" (C2). Additionally, since the tool has a limitation in linking requirements to the detailed model implementations, model verification requires an extra effort. As explained by C2 "they need to be ready to open several different models which take time to load" (C2).

Granularity of traces (CH12)
The traces created between the requirements and the models are of high abstraction. This was reported in Eastlink by the requirements specialist (C2). There is information used in DOORS to trace requirements to the created models. However, this traceability information is not detailed

enough, which makes it difficult to do the verification process. It is challenging to create those kinds of traces as it is seen to be an expensive practice.

Requirements are not linked to objects is seen to be as the cause of this challenge, "even though they give you a specific place to look there will be lots of places to look at" (C2). The current traces are created between requirements and models rather than requirements and the objects.

One consequence of this challenge is that an extra effort is required to verify the model as C2 explained "it just takes some time and effort" (C2). Since the requirements are linked to models rather than objects within the model, it takes extra effort and time from the specialist to verify the model.

Lack of experience using tools (CH13)
There is a lack of experience in using the modeling tools by the people verifying the models. This challenge was reported in case two by the requirements specialist (C2). The manual model review process at the client in Eastlink depends mainly on the specialists' experience. Although DOORS contains traces between requirements and models, the specialists verifying the model must know where in the model the requirements apply. The specialists lack experience verifying those models, as (C2) put it "We are not very experienced using the model, so that's a challenge for all specialists".

The use of different models in the project is the cause of this challenge. There are too many model types used in the project; these models require different tools for viewing. It is difficult for specialists to cope with all these tools. C2 said, "we can not choose exactly what they are going to use; unfortunately, some consultants use different BIM modeling programs" (C2).

Difficulty navigating the models is a consequence of lacking experience verifying the models. Since the digital assets verification process at the client in Eastlink is an experience-based process, it gets difficult to navigate the models to verify them. The specialist needs to figure out where in the model the specific requirements apply.

Verifying all requirements (CH14)
The client finds it challenging to verify all the requirements in the delivered model. This was reported in Eastlink by the requirements specialist (C2). There are many generic and project-specific requirements that apply to the models; it becomes troublesome to verify whether the models conform to all requirements.

The absence of risk analysis for the requirements makes the verification of all requirements difficult. There exists no classification of requirements nor a risk analysis based on severity or importance. Therefore, the client has no basis on which to base the prioritization for verification and resource allocation.

As a consequence, there is an uncertainty in the verification process at the client side. Currently, it is not determined whether a complete model verification for all requirements that apply should be performed or not. "There is a debate at the client whether or not we are supposed to do a complete verification or just sample verification and see" (C2).

3.3 Conclusions

Based on these challenges, identified from FSE101 and Eastlink, we suggest addressing the following main problem areas[1]:

- ***Customer-supplier communication.*** Requirements negotiation should not be neglected, but considered equally important as the implementation of requirements processes and

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[1] Note that this list is not reflect any prioritization.

routines. We believe that requirements engineering could benefit from exploring various negotiation and conflict-resolution techniques from other disciplines, e.g. finance or organizational theory. This could result in reshaping the requirements process from a passive expression of wants, needs and demands to a more active negotiation and conflict resolution between the client and supplier.

- ***Requirements quality.*** Requirements verification and validation are required to ensure the quality of the specified requirements, as recommended by INCOSE (International Council on Systems Engineering). Requirements validation can reduce the risk of mis-interpretation. However, as observed in the two projects, requirements validation is currently down-prioritized, mostly due to lack of resources. The quality of requirements can be verified with the help of automated NLP (natural language processing) techniques. An earlier FoI project (ERSAK, 2015-2017, coordinated by Peter Axelsson), has conducted research in this direction by formalizing manual quality controls into an automated tool.
- ***Trace links.*** The lack of links between requirements and objects in other digital assets requires experienced engineers and domain experts to perform a asset verification. This reliance on manual verification renders compliance checks against rules and regulations (e.g. TRVInfra) extremely costly or even impossible. The cost of establishing and maintaining trace links needs to be weighed with the benefits of more efficient and complete compliance checks. This is not a pure technical question, but political (standardization) and commercial (business incentives) factors affect this analysis too.
- ***Project management.*** There are a couple of improvements that emerged from the interviews. First, the current tender process conditions should be rethought to 1) allow more time for requirements validation, and 2) reduce the time to communicate the requirements to the contractor. Second, for design and build contracts, certain consideration shall be given to the risks allocation between contractor and client associated with the challenges arisen from timing challenges of the requirements evaluation. Third, we need to give people more time to gain experience in using the different tools verifying different types of design models.

Are more detailed discussion of the above findings, including references to the relevant scientific literature can be found in the paper listed in Section 3.4.

3.4 References to publications and reports

1. Challenges of Requirements Communication and Digital Asset Verification in Infrastructure Projects. Waleed Abdeen, Krzysztof Wnuk, Michael Unterkalmsteiner, Alexandros Chirtoglou, 2022, submitted to a journal.

4 WP2 - Traceability through classification

4.1 Motivation

Traceability is the ability to relate data that is stored within artifacts to each other and to use these relationships to conduct analyses, such as coverage and impact analysis. In essence, trace links between artifacts increase the value and usefulness of the information recorded in them. In requirements traceability, the most common usage scenarios for trace links are finding the origin and rationale of requirements, tracking requirement implementation state, and developing test cases based on requirements [4].

However, implementing traceability in practice is challenging due to: (1) high manual effort to create and maintain trace links, (2) no systematic approach to establish traceability, (3) lack of tool support, (4) creator and user of trace links are often not the same roles, (5) lack of support for traceability beyond organizational boundaries.

Trace links are most commonly implemented with general purpose tools, such as spreadsheets and wikis, as well as configuration management tools [4]. This means that traceability is established by storing identifiers of linked artifacts or other data elements within artifacts in some sort of table or matrix. These links can become difficult to establish if the traced artifacts contain information on different abstraction levels [5].

We propose therefore the novel idea of *taxonomic trace links*. A trace can be defined as a triplet consisting of a source and target artifact, and a primary and a reverse link associating the two artifacts. Figure 9 illustrates the fundamental concept of traditional trace links.

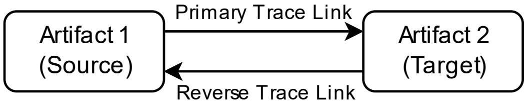


Figure 9 Traditional trace link

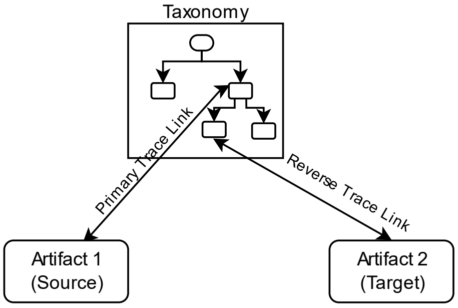


Figure 8 Taxonomic trace link

The principal idea of taxonomic trace links (TTL), shown in Figure 8 is to introduce indirection between a source and target artifact through an auxiliary artifact. We argue that any knowledge organization system, such as an ontology, taxonomy, classification system or controlled vocabulary, can be used as an auxiliary artifact.

In order to test the idea of TTL in practice, we have designed and implemented a validation study. The study material consists of system requirements, digital 3D models, and a domain-specific classification system, SB11. The requirements are written in natural language and consist of two subsets. Project-specific system requirements (240 in total) describe, at varying degree of detail, the product needs. The generic system requirements (TRVInfra) consist of 150 documents, each containing dozens to hundreds of requirements. We randomly sampled 27 requirements (10 generic from a document describing how animal fences shall be constructed, and 17 project-specific) for this study. The 3D models contain the design of the railway track, illustrating the location, dimension and orientation of the physical objects that need to be constructed. The design engineers involved in developing the 3D models have already associated each object with codes from SB11.

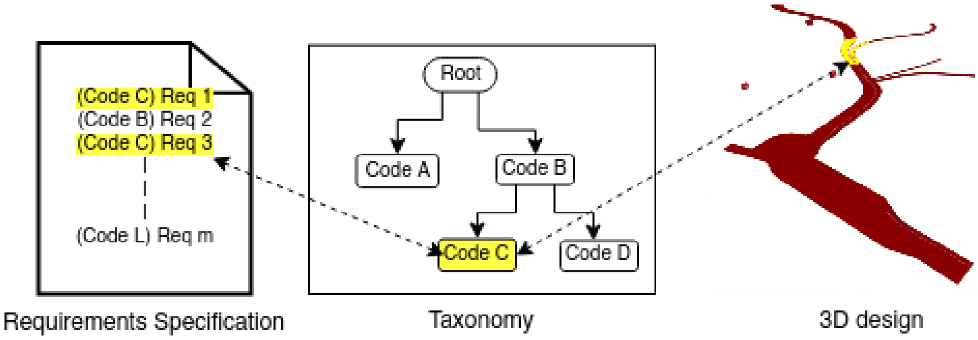


Figure 10 Requirements to design objects tracing

The study was designed and conducted as a series of workshops in the form of online meetings. To establish trace links between 3D models and requirements, we first had to associate requirements with SB11 codes, and then we investigated how comprehensive and consistent the associations of model objects to SB11 codes were. Furthermore, we verified the design model against the traced requirements, trying to find defects in the model. Figure 10 illustrates how the codes in SB11, already existing in the design model on the right side, and associated by us to requirements on the left side, implement the idea of taxonomic trace links.

In addition to the above empirical study, we conducted a literature study on classification system quality attributes. The goal was to identify a set of quality attributes that are commonly agreed by the scientific community and can be applied to objectively compare different classification systems used in the construction industry, such as OmniClass, UniClass, CoClass and SB11.

4.2 Results

Sections 4.2.1-4.2.3 report on the results of the validation study (i.e. the use of taxonomic trace links in practice), whereas section 4.2.4 reports on the results of the literature review (i.e. the identified classification system quality attributes).

4.2.1 Association of codes to requirements

We randomly picked 27 requirements coming from two different requirements documents and associated them with codes in our workshops. Ten of these requirements were sampled from a document related to wild and game fences while 17 were sampled from the project specific requirements of Eastlink. Overall, 26 out of the 27 requirements could be associated with at least one code from the SB11 classification. Table 4 shows six representative requirements which illustrate the full set of challenges faced during this activity. In the remainder of this section, we discuss those challenges.

Challenge 1: Vagueness

R1 is a safety requirement specifying the minimum distance between two objects. One type of objects refers to "buildings where people are more than just temporarily present", which is an ambiguous formulation as the timing aspect can be interpreted in different ways and therefore results in an unclear set of building types that are affected by this requirement. The second object, the railway track, is implicit and not mentioned in the requirement. Using only the information that is stated in the requirement, it was not possible to identify any relevant codes from SB11.

Challenge 2: Compound requirements

R2 specifies two independent requirements on the same object, i.e., who can open the gate and where it shall be located. This, in turn, means that the requirement contains several objects of interest that need to be associated with the classification system. Compound requirements are not necessarily a problem, can however lead to increased effort in determining all relevant objects in a requirement.

ID	Requirement	SB11 codes
R1	The distance to buildings where people are more than temporarily present should be 30 meters in general, taking into account the risk of derailing and other factors. If this distance is not met, the situation should be assessed and choices of departure be justified.	-
R2	It shall be possible to open the gate to the track from inside the track area by both rescue and evacuation personnel and from outside by rescue personnel. The gate should not be placed closer than 50 m from the tunnel entrance.	18B, 32QG
R3	The opening and closing device must have a width of at least 25m.	32QG
R4	Fencing should be placed behind the engineering building, seen from the railway, if the property boundary allows this.	32GDC
R5	Auxiliary power (three-phase, 22 kV) shall be provided along the entire route.	63N
R6	Emergency lighting shall be provided in service and access tunnels.	18B, 63FH

Table 4 Sample requirements illustrating classification challenges

Challenge 3: Context dependency

R3 refers to an opening and closing device, without however specifying what shall be opened and closed. In this particular case, the requirement was accompanied by a figure that made clear that the device refers to a gate in a fence. In general, however, for requirements in this group, the textual description alone was not sufficient to understand what objects are relevant. These need to be deduced from the context in which the requirement is mentioned, for example, a particular section in a document or a complete document that covers certain objects of interest. In addition, we could not associate the opening and closing device mentioned in the requirement with any SB11 code. This particular issue is covered under challenge 6: high specificity.

Challenge 4: Similar classes

R4 refers to the placement of fencing behind technical buildings. SB11 contains classes related to fences in general, but also in the particular context of road facilities. The correct SB11 class can therefore only be deduced by understanding that R4 refers to railway tracks. Furthermore, the decision of association cannot be based solely on the class definitions (they are ambiguous in SB11), but needs to take the hierarchical structure of the taxonomy into consideration.

Challenge 5: Varying terminology

R5 specifies that auxiliary power shall be provided along the train track. However, the particular term "auxiliary power" does not appear in the SB11 taxonomy. It instead contains a code for "backup, uninterruptible or emergency power" which, one could argue, are either synonyms or more specific instances of auxiliary power. Therefore, associating objects in a requirement with the taxonomy requires domain knowledge on synonyms and specializations of concepts.

Challenge 6: Low specificity

R6 refers to emergency lighting in service and access tunnels. While emergency lighting exists in SB11 (63FH), there is no code for service or access tunnels, the other relevant objects in the requirement. Hence, we associated these objects with the more generic code for concrete tunnels which is potentially not correct. SB11 is, in this case, not specific enough.

4.2.2 Verification of design models

The purpose of this analysis is to determine whether the subcontractors' application of SB11 to 3D models is comprehensive and reliable. First, to evaluate comprehensiveness, we check if all objects in a 3D model have been associated with an SB11 code. Second, to evaluate reliability, we evaluate whether the same objects have been associated with the same code throughout all 3D models.

We use for this analysis 3D models of two constructions segments which represent a part of the whole facility. For each model, two versions are available: a pre-verification model, as supplied by the sub-contractor to the client, and a post-verification model that contains changes by the sub-contractor after it has been verified by the client. We use letters to refer to the two modeled segments and sub-contractors, i.e. *A* and *B*, and numerical subscripts to refer to the different versions (A1, A2, B1, B2). Table 5 summarizes the properties of the models.

Model	Sub-contractor	Nr. of objects
A1	A	8435
A2	A	1584
B1	B	306
B2	B	380

Table 5 3D model properties

A comprehensive and reliable classification of objects is a crucial pre-requisite for the verification of those objects against the stated requirements. If the object classification is inconsistent or incomplete, the classification of requirements may still be useful for analyzing the requirements w.r.t. their completeness and correctness. Regarding the evaluation of comprehensiveness and reliability of the classification, we observe the following. Due to the high number of classified objects, either an automated process or sampling is required. An automated evaluation was not possible as the necessary meta-data to trace objects throughout different model versions was not available. Sampling and manual evaluation reduces the confidence in the results, in particular if there is no objective way to ensure the representativeness of the sample. Due to the few faults and inconsistencies we identified in the classification of objects in the two models, we conclude, within the limited context of this study, that the creation of taxonomic trace links is feasible, considering however that the challenges reported in Section 4.2.1 need to be addressed.

4.2.3 Model verification based on traced requirements

We have now the information in place to verify the models against the requirements we traced to SB11. The procedure we followed was:

1. Select a requirement from the traced requirements and extract criteria that can be used to verify that the design complies to the requirements. For example, requirement R3 in Table 4 specifies the minimum width of an object.
2. Filter the model objects by the SB11 code(s) associated with the requirement; in the case of R3, the code is 32QG (gates, gateways).
3. Verify that the filtered objects comply to the requirement.

Out of the 26 requirements we have classified, 11 were associated with codes that were also present in the models. Ten of these requirements did not reveal any problem with the inspected model objects. For one requirement (K29674), shown in Figure 11, we could however identify a potential issue in the inspected models. The requirement defines the areas adjacent to the train tracks where is not allowed to place a fence. Five meters on both sides from the middle of the train tracks (area E) is not allowed to place a fence. In addition, if there is a slope (area C) on the ground from either side of the track, then for at least two meters away of the end of the higher side of the slope (area B), a fence shall not be placed as well. Further than two meters from the end of the slope (area A), on the slope itself (area C) and five meters away from the track until the place that the slope starts (area D), the placement of a fence is allowed.

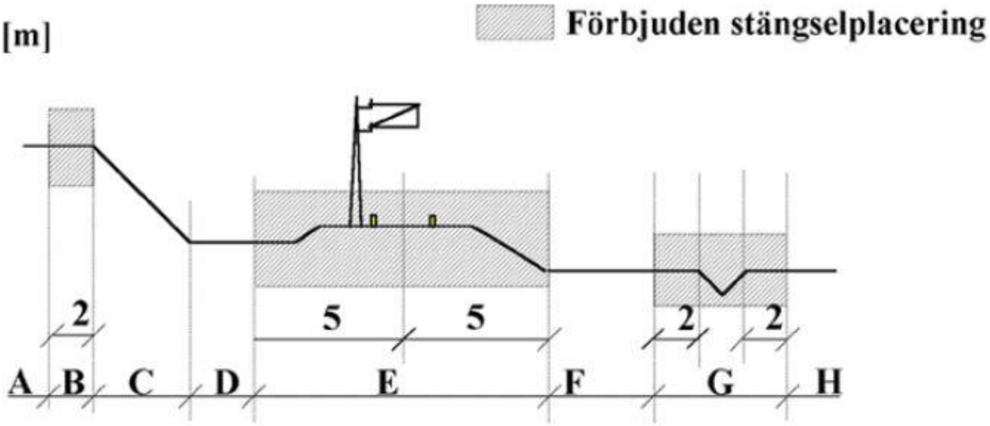


Figure 11 Schematic diagram of the permissible fence position at the surroundings of tracks for requirement K29674.

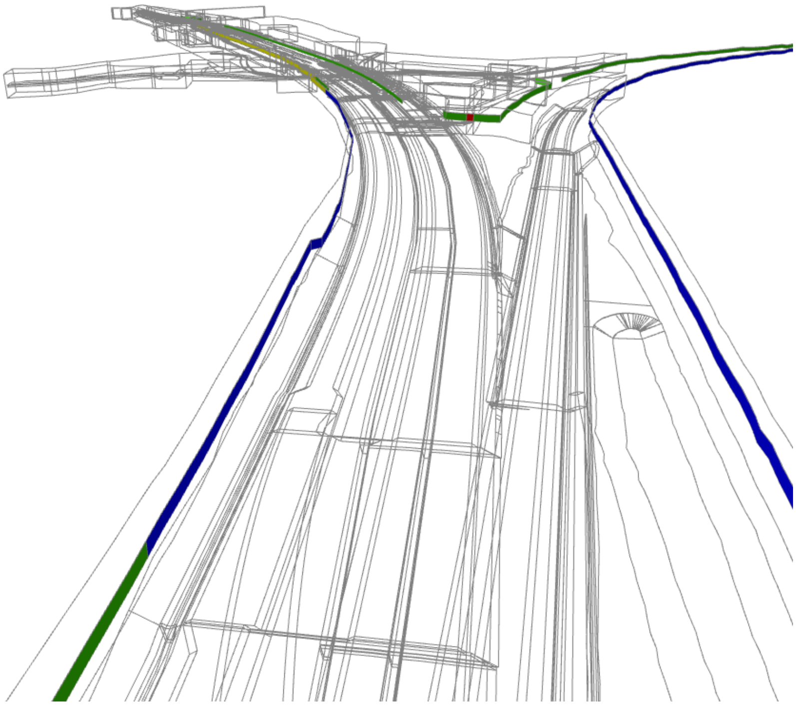
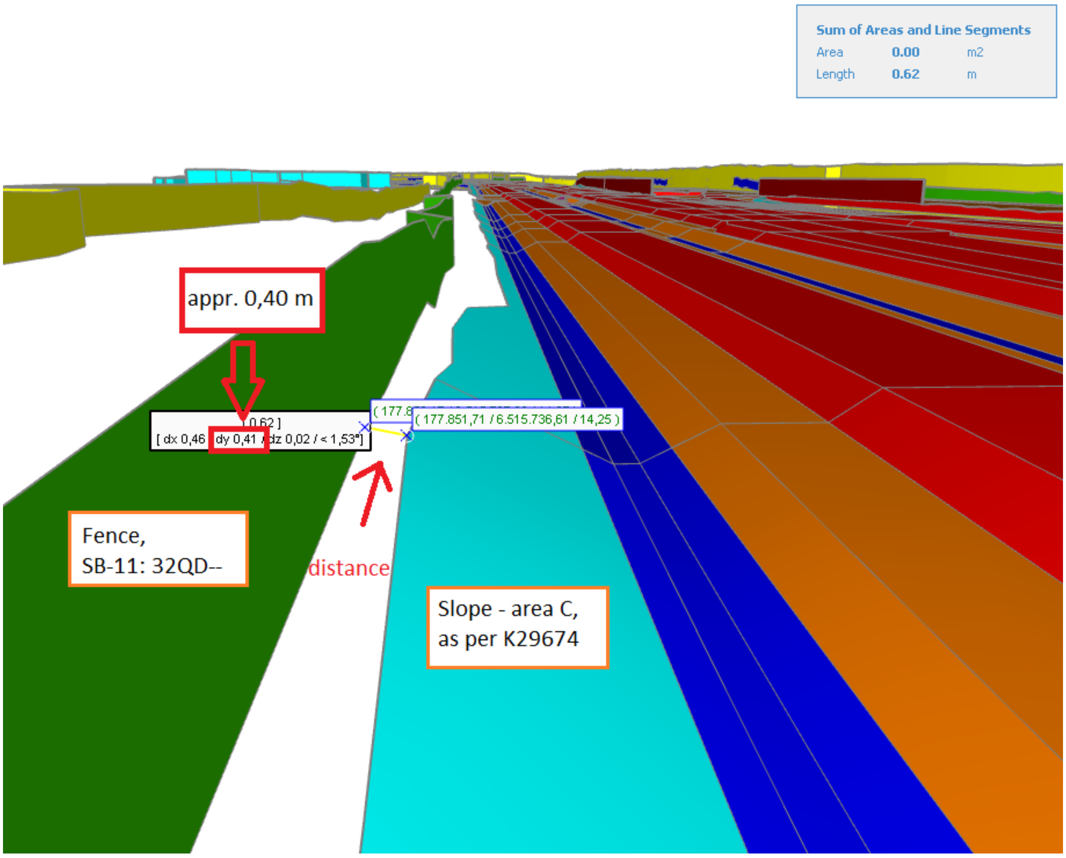


Figure 12 Viewpoint on a BIM Management viewer tool where all elements except the classified as fences object (32QD--) have been wired

Filtering the model (model A, version 2) by fence objects (i.e. SB11 code '32QD--' and leaf nodes), highlighted all objects classified as fences (see Figure 12). We performed a visual inspection of locations that resembled the schematic diagram in Figure 11 and did manual measurements where distances between fence and prohibited areas (B, E, G) seemed to have been violated. We found indeed a few locations where fences were placed within the restricted boundaries of area B. A typical example is depicted in the viewpoint of Figure 13.



Sum of Areas and Line Segments

Area	0.00	m2
Length	0.62	m

Figure 13 Viewpoint on a BIM Management viewer tool where the fence is placed on the restricted area B as per K29674 requirements definition

4.2.4 Classification system quality attributes

We reviewed 324 scientific publications and synthesized the definitions of quality attributes and measurements. By analyzing the original definitions of 43 quality attributes, we found that many quality attributes express the same idea, but are named differently. We could reduce the original number to a manageable seven quality attributes. In addition, we propose for each at least one measurement. The seven quality attributes are:

1. *Comprehensiveness:* the ability to classify all known objects for the domain it was developed for.
2. *Robustness:* the ability to differentiate objects of interest.
3. *Conciseness:* the ability to classify objects of interest with the least possible amount of dimensions, categories and characteristics.
4. *Extensibility:* the ability to allow for changes in its structure, i.e. adding, modifying or deleting dimensions, categories or characteristics.
5. *Explanatory:* the quality to enable the user to locate an object in the classification system based on its characteristics, or to deduce from the location of an object what characteristics it has.
6. Mutual exclusiveness: the ability to identify an object uniquely, i.e. that no object exists in the same dimension under different categories.

7. *Reliability:* the ability to support consistent classification decisions.

In Section 6.2.1, we compare different classification systems from the construction industry and reason which ones are likely to perform better for the use case of taxonomic trace links.

4.3 Conclusions

We demonstrated in our validation study that it is feasible to implement taxonomic trace links to trace requirements to 3D design models and verify those requirements in the 3D design model. However, this comes with challenges that we need to consider when developing a solution that supports engineers in creating taxonomic trace links.

Future work concerns the (semi-)automation for trace links creation by classifying natural language requirements (see WP4 in Section 6). Also, we see a particular interest in requirements based-verification, e.g., the verification of quantitative properties of the design models using the traced requirements (see WP7 in Section 8). Moreover, maintainability of taxonomic trace links through the product life-cycle needs to be investigated.

4.4 References to publications and reports

1. M. Unterkalmsteiner and W. Abdeen, “A compendium and evaluation of taxonomy quality attributes,” Expert Systems, 2022.
2. W. Abdeen, M. Unterkalmsteiner, A. Chirtoglou, C. P. Schimanski, H. Goli, and K. Wnuk, “Taxonomic Trace Links - Rethinking Traceability and its Benefits,” submitted to a Journal and currently under review (September 2022).

5 WP3 - Digital asset design and analysis

The DCAT research project pursues the idea of using structured data to establish digital trace links between formulated requirements and the response to them in terms of digital asset elements. A guideline to realize the establishment of digital trace links based on structured data has been elaborated within WP3.

5.1 Motivation

We consider the use of consistent data structures are the key for bringing multiple project objects in a specific project setup together, or in other words, to create trace links between different digital artifacts. In construction projects, a variety of entities can be referred to as project objects. In addition to requirements and digital asset elements that comprise the focus of the DCAT research project, these include, for example, Bill-of-Quantities (BoQ) positions or schedule activities. Also, any kind of other external documentation can be referenced in this way.

Moreover, the data structure forms the basis for attributing project objects and can provide additional information about attributes, such as sources of information (standards and guidelines), calculation rules (for calculating quantities), and responsibilities (who manages the attribute and can provide further information about it).

The Building Information Models (BIM) are structured data carriers for design information and as such can be the vehicle for a systems engineering approach supporting the processes of allocating, tracing, as well as verifying the functions assignment. The information in the structured and classified digital objects of a BIM model can be the leading component for the forward and backward traceability between the objects and the requirements.

Main precondition for the realization of such an approach is the utilization of a defined **Project Data Structure (PDS)**

This PDS is the subset of the consolidated data structures for project objects that is needed to enable the links between the project objects by means of uniform attributes. Hence, project objects can be linked to each other by associating two project objects with the same attribute and same values.

The PDS must be associated with project objects at least to such an extent that a transfer or link with other project objects can be made solely based on the attributes. The degree of implementation of the PDS defines the granularity of the link and depends on the selected BIM use case as well as the project phase. The attributes used for this purpose are also referred to as PDS attributes.

This WP3 aimed at elaborating PDS concepts for the application within infrastructure measures. Results and conclusions for this elaboration are briefly summarized in the following.

5.2 Results

WP3 resulted in an abstract guideline to develop the PDS on an organizational level and allowing at the same time for a project-specific adaption and concrete application. The PDS provides a consistent coding to various teams, elements, or processes of a project, in order to enable team members to correlate data across different systems and processes.

We propose to base the development of the PDS on the following three common data structures (see Figure 14):

- Location Structure
- Discipline Structure
- Deliverable Structure (The System / Asset Structure).

The PDS serves as the basis for linking relevant project data from different sources in a project for all BIM use cases. It enables a uniform labeling of data even if authors - or even software vendors - usually use different terms and identifiers.

Hence, when all relevant information in a project is originated considering this PDS structure consistently, saying PDS attributes are applied when an information entity is generated, linked information can be found easier, faster and with increased transparency, f.e. by means of a 3D model.

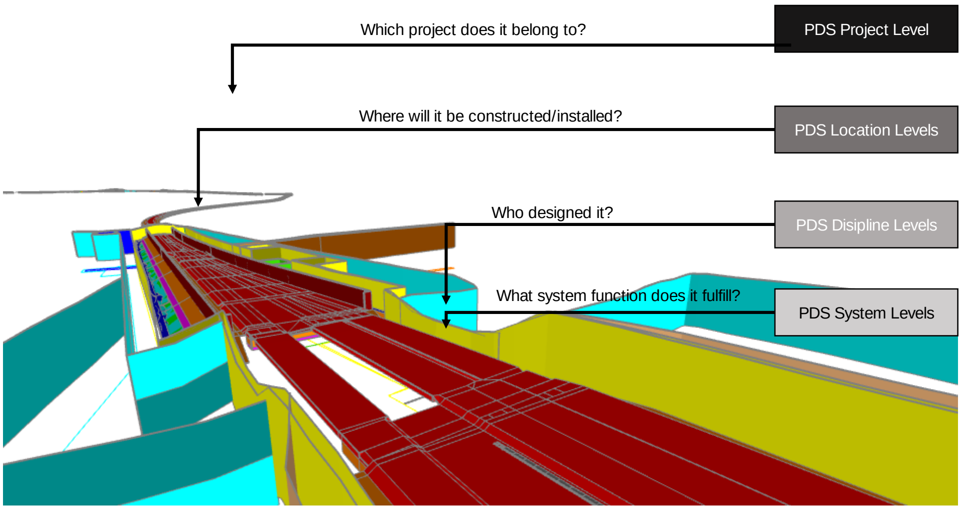


Figure 14 PDS concept

It is suggested that to describe the "systems" dimension, that is, to answer the question of "What system function does an object fulfill?" existing classification systems in the building industry should be used. The previous investigations in the DCAT research project (WP2) included the evaluation of the two classification systems SB11 and CoClass. The results so far have not shown any reasons for exclusion that would deny the suitability of either of the two systems within the PDS for application in the BIM use case of requirements management. Therefore, the system level can be filled with one of the two classification systems. Figure 15 shows the example of a PDS for infrastructure measures using SB11 to describe the system levels.

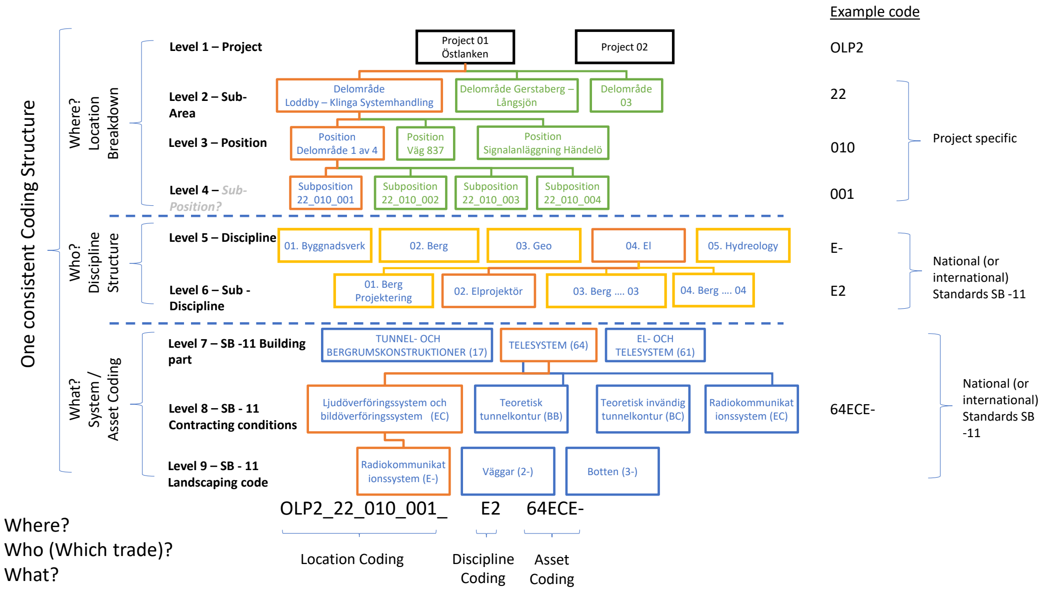


Figure 15 Exemplary PDS using SB11 classification

5.3 Conclusions

Knowledge of trace links between artifacts allows for semantic reasoning and insights. In the construction domain the trace link between technical requirements and delivered digital design data is of vital nature as it allows for streamlined requirements verification. Within the DCAT project we have developed an approach for establishing such trace links based on a common and consistent taxonomy that is supposed to be associated with both artifact types (requirements and design data) to allow for a matching of corresponding items. For this purpose we have introduced the concept of a PDS, that basically is characterized by combination of a set of hierarchical taxonomies allowing to answer the questions of "where are you?", "what are you?" as well as "which function do you fulfil?" when referring to an object of real world that is represented by any kind of digital abstraction.

Since there is not yet an established industry standard for PDS, this must be developed and established at the company level. A guideline for doing so is provided in WP3 deliverable ("PDS Guideline).

The advantages that are hoped to be gained by applying the PDS attributes to the requirements are, the creation of trace links to digital assets and associated documents to foster requirements verification and management processes.

5.4 References to publications and reports

1. J. Braun, "Project Data Structure", 2021.

6 WP4 - Client input interface

6.1 Motivation

We introduced in Work Package 2 (WP2) the Taxonomic Trace Link (TTL) approach that creates trace links between two elements using a taxonomy [6]. TTL can connect elements of the same (e.g., requirements with requirements) or different artifacts (e.g., requirements with design models). The TTL approach aims to overcome the barriers that are faced when introducing traceability between different project artifacts, mainly the misalignment between the documents' abstraction level, structure, and time of creation.

Applying TTL requires the association of requirements and design models with classes from a domain-specific taxonomy. The association of requirements with classes from the taxonomy (requirements classification), needs to be done only once per requirement. This association can be used later for tracing the same requirement to multiple design models (from the same or different project). We use two taxonomies from the construction domain, also referred to as classification systems, to implement our approach, SB11 and CoClass.

In WP2 we validated the TTL approach on a set of 27 requirements, 10 generic from TDOK and 17 from the Eastlink project. The purpose of the validation study was to investigate the applicability and practical challenges associated with TTL when applied in practice. The results of the validation study show that it is possible to implement TTL to trace design models to generic and project-specific requirements. However, this depends on the quality of requirements and the taxonomy, and the proper association of codes with both requirements and design models.

In this WP we build a recommender system to semi-automate the process of requirements classification. The recommender analyses the requirement and proposes classes from SB11 or

CoClass. Then, the domain experts or requirements engineers decide on the correct classification. A recommendation system has two dimensions: 1) *input* fed by the user or imported from other systems, and 2) *output* is the recommendation provided by the recommendation system. In our case, the inputs are a natural language requirement and a classification system, while the outputs are the suggested classes from the classification system.

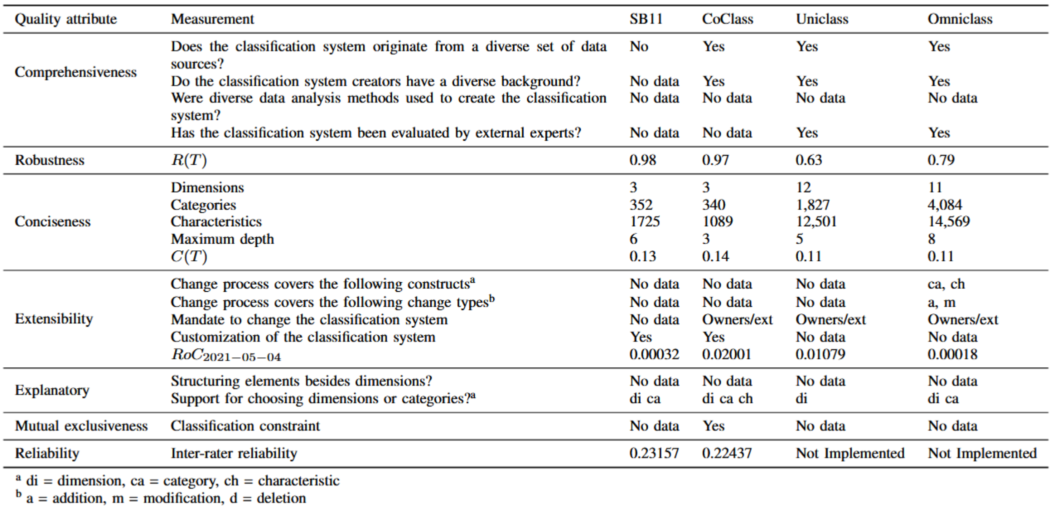
To evaluate the performance of the recommender, we have created a so called “ground truth”. The ground truth consists of 129 requirements that were associated to classes from SB11 and CoClass to establish a baseline against which the automatically generated recommendations can be evaluated. The process how we have constructed the ground truth is explained in detail in the report for this work package.

As part of this work package, we first compare different classification systems using the quality attributes we identified in WP2. Then, we report the results of the recommender evaluation.

6.2 Results

6.2.1 Classification system quality

In WP2, we have defined seven quality attributes for classification systems (see Section 4.2.4). Here, we use these quality attributes to compare four classification systems from the construction industry: OmniClass, UniClass, CoClass and SB11. Figure 16 summarizes the evaluation and we discuss the results of six quality attributes[2] next.



Quality attribute	Measurement	SB11	CoClass	Uniclass	Omniclass
Comprehensiveness	Does the classification system originate from a diverse set of data sources?	No	Yes	Yes	Yes
	Do the classification system creators have a diverse background?	No data	Yes	Yes	Yes
	Were diverse data analysis methods used to create the classification system?	No data	No data	No data	No data
	Has the classification system been evaluated by external experts?	No data	No data	Yes	Yes
Robustness	$R(T)$	0.98	0.97	0.63	0.79
Conciseness	Dimensions	3	3	12	11
	Categories	352	340	1,827	4,084
	Characteristics	1725	1089	12,501	14,569
	Maximum depth	6	3	5	8
	$C(T)$	0.13	0.14	0.11	0.11
Extensibility	Change process covers the following constructs[a]	No data	No data	No data	ca, ch
	Change process covers the following change types[b]	No data	No data	No data	a, m
	Mandate to change the classification system	No data	Owners/ext	Owners/ext	Owners/ext
	Customization of the classification system	Yes	Yes	No data	No data
	$RoC_{2021-05-04}$	0.00032	0.02001	0.01079	0.00018
Explanatory	Structuring elements besides dimensions?	No data	No data	No data	No data
	Support for choosing dimensions or categories?[a]	di ca	di ca ch	di	di ca
Mutual exclusiveness	Classification constraint	No data	Yes	No data	No data
Reliability	Inter-rater reliability	0.23157	0.22437	Not Implemented	Not Implemented

[a] di = dimension, ca = category, ch = characteristic
[b] a = addition, m = modification, d = deletion

Figure 16 Comparison of construction classification systems

Comprehensiveness: CoClass seems to have a slight advantage over SB11 as it originates from a diverse set of sources (standards ISO 12006-2, IEC 81346-1, IEC 81346-2 ISO 81346-12, as explained by Eckerberg [7]) and the developers have a diverse background (illustrated by the

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[2] We omit the discussion on extensibility as for the tasks of requirements classification, we deem that attribute as not relevant.

partners that have contributed to CoClass[3]). We could not find information on whether CoClass and SB11 has been evaluated by external experts, in contrast to UniClass and OmniClass.

Robustness: For the task of classification (whether manual, semi-automated or fully automated), the ability to differentiate objects of interest is very important. Both SB11 and CoClass have scored a significantly higher result than UniClass and OmniClass in this quality attribute. We were suspicious of these rather high differences, and found that it can be explained by a weakness how we calculate the score, in particular the language model we use as a basis for the analysis. In short, we suspect that both SB11 and CoClass contain many domain-specific terms that do not appear in the language model that stems from a general purpose document corpus. Hence, the metric is overly optimistic, compared to the results from UniClass and OmniClass (for which use the same language model, but we observed that the terminology uses less compound, domain-specific terms). To conclude, further work is needed to increase the confidence in the achieved evaluation results for robustness.

Conciseness: SB11 and CoClass are very similar with respect to the number of dimensions and categories. However, SB11 has more characteristics (i.e., leaf nodes in the hierarchy of the classification tree) and a higher tree depth. This means that SB11 is likely more specific, fine-grained, while CoClass has a higher abstraction level. Both SB11 and CoClass are significantly more concise than UniClass and OmniClass, which makes them more amenable for manual and semi-automatic classification tasks.

Explanatory: We did not find any information regarding structuring elements besides dimensions that would help to understand the classification systems. CoClass is unique among the studied classification systems in that it provides definitions for all characteristics and commonly used synonyms.

Mutual exclusiveness: Only CoClass mentions explicitly [7] that an object can be member in one class only.

Reliability: We have evaluated intra-rater reliability based on the data we collected when developing the ground truth. The reliability of SB11 is slightly higher than CoClass, despite CoClass being more concise. The annotators have observed that it was easier to find an exact match in SB11 than in CoClass because the terminology used in the requirements text was similar to the class names in SB11.

Based on this comparison between SB11 and CoClass, we have not found a clear advantage of one classification system over the other. Other, non-technical factors may in this case provide further guidance. For example, the current and future plans for adoption of a classification system.

6.2.2 Classifier performance

We used the ground truth that we prepared to evaluate the performance of the hierarchical classifier (HC), that we developed in this project. Furthermore, we compare the HC with the flat classifier (FC), from our previous work [6]. The main difference between the classifiers is how the nodes of the classification system are analyzed. In the HC, the hierarchy of the classification system is considered during the analysis of the nodes. On the contrary, in the FC each node is analyzed alone regardless of its place in the hierarchy.

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[3] https://coclass.byggtjanst.se/about#owners

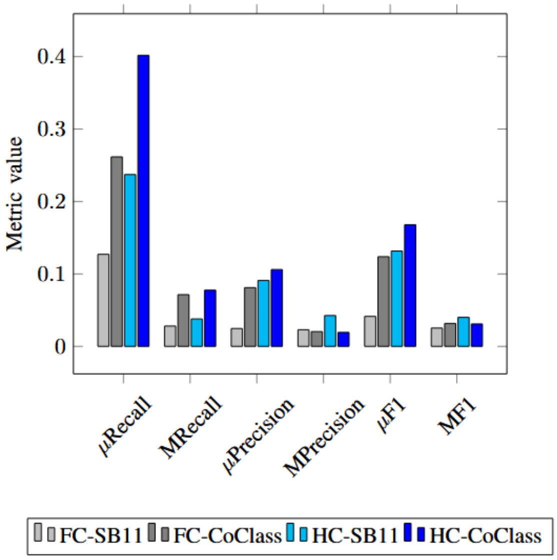


Figure 17 Comparison of classifier performance

Figure 17 illustrates the results of comparing the HC with the FC using SB11 and CoClass. The x-axis represents the metrics used for evaluations, while the y-axis represents the value of the metric with maximum value of 1. The ground truth contained 129 requirements. However, not all requirements were considered when calculating the evaluation metrics. We used the requirements labeled using the Byggdelar table from SB11 (123 requirements) and from CoClass we used those labeled using Tillgångssystem (81 requirements).

Overall, the higher recall compared to the precision indicates that the classifier produces fewer false negative than false positive results. That means that the number of true labels that are not retrieved is lower than the number of wrong labels retrieved. In practice, an expert would therefore have to review and exclude wrong suggestions but can, on the other hand, rely on that the suggestions are complete.

In all metrics except the MPrecision and MF1, the use of CoClass showed a significant improvement in performance of the flat and hierarchical classifiers compared to the use of SB11. Therefore, CoClass is a better choice as a classification system to classify requirements.

The low value of MPrecision, averaging of precision per-class, means that the recommender is better at retrieving some labels but worse at retrieving others. Here, further analysis needs to be done to understand if the attributes of the nodes (e.g., level of depth and number of words in the description) has any correlation with the per-class precision.

6.3 Conclusions

The comparison between SB11 and CoClass, based on classification system quality attributes did not identify a clear superiority of one classification system over the other. Hence, for a manual classification, both are a good choice. However, when using the recommender, CoClass yields better classification results than SB11. These results can be attributed to CoClass being more concise (less categories and characteristics than SB11), but longer textual descriptions of the classes.

6.4 References to publications and reports

1. Waleed Abdeen and Michael Unterkalmsteiner, "Client Input Interface – The Recommender System", 2022.
2. Demonstrator of the classifier: http://dcat.diptsrv003.bth.se/labeled-data
3. Source code of the classifier: https://github.com/munterkalmsteiner/DatalessClassification/tree/SB11Classifier
4. Source code of the demonstrator: https://github.com/waleedabdeen/dcat-demonstrator

7 WP5 - Supplier output interface

7.1 Motivation

The idea was to generate a document, which could be considered as input for developing organization-specific Exchange Information Requirement (EIR) templates. The document is not a set of guidelines that must be followed, but rather recommendations that can be followed. EIRs comprise vital definitions in the context of the organization of information about construction works using Building Information Modeling (BIM).

In particular, the assumptions made in the report concentrate on a broad and industry-wide adoption of the information management principles in accordance with ISO 19650. In essence, information management is needed to steer and control the field of tension between requiring digital information and delivering them in BIM projects. Therefore, the report of WP5 contextualizes with the principles of ISO 19650 the role of a public authority as the lead appointing party in BIM projects. More precisely, the report elaborates on how such a public authority needs to require information from their suppliers in the right way and quality assure the delivery accordingly in order to comply with international standard mentioned above.

7.2 Results

Analyses were carried out and the results recorded in the report how information is currently requested from suppliers and what possible improvements in the light of information management according to ISO 19650 can be implemented. Furthermore, recommendations for requiring and processing information for the BIM-use case "BIM-supported requirements management" are elaborated and documented in the form of a so-called "Information Delivery Manual" (IDM) according to ISO 29481-1. This comprises also the suggestion of a new BIM use case to Trafikverket, which could potentially be implemented in upcoming projects. The process required is elaborated in detail with a flow chart including and describing the roles and responsibilities. The exchange requirements and functional parts required for the use case implementation are suggested within the document and the LOIN concept has been suggested. Finally, suggestions for the Quality Assurance process have been made in accordance with the suggested process.

Prerequisite for the adoption of the recommendations in the use case "BIM-supported requirements management" in future BIM projects is a completed requirements engineering process, including:

Definition of the phase when the requirements shall be verified ("during design" vs. "during construction")

The mapping of each requirement to a project data structure (PDS) according to the guidelines from Work Package 3 (WP3) of the DCAT project.

In the course of investigating the supplier output interface and the analyzation of the existing BIM Standards at Trafikverket it was clear that they already request BIM models from their suppliers by formulating so-called BIM requirements (BIM-Kråv in Swedish) within the document TMALL 0423 PM v1.0. In addition, a supplementary document is provided to the suppliers for the locations (subareas and positions) of Ostlänken project, which has been used as reference for the D-CAT project. These two documents have been the basis for the current document's analysis of existing information and BIM standards within the organization of Trafikverket. The existing BIM standards of Trafikverket define various requirements related to the BIM data delivery which are categorized in the accompanying report.

The existing BIM standards of Trafikverket, define various requirements related to the BIM data delivery.

Evaluation of the data formats used within Trafikverket has shown that they are not sufficient to fully meet the information management principles of ISO 19650 in the context of information deliveries from the supply chain. Therefore, in addition to enabling BIM-based requirements validation, another goal of this document is to promote the use of open data formats for information exchange with suppliers.

7.3 Conclusions

Based on the information included in the above-mentioned BIM standards of Trafikverket, it can be realized that the requirements for the BIM models are not conforming to the ISO 19650 standard series as they do not sufficiently detail out on an object-basis what the required level of information need for the appointing party is. In addition, no detailed processes for the information exchanges with the suppliers have been identified. For the future further development, it is assumed that Trafikverket will adopt the ISO 19650 standard eventually as the industry, following the tendencies across other public authorities and will show more and more acceptance and commitment in following the underlying concepts. In order to enable BIM-based requirements verification, not just the fully commitment to the ISO 19650 is necessary but also the use of open data formats for information exchange with the suppliers.

Based on the above, the following actions are recommended:

- Develop organization wide PDS template and define specific PDS for each project
- Annotate the technical requirements which will enable their linking through the PDS to model and facilitate their verification
- Commit to ISO 19650 norm for the structured information exchange processes, including:
  - Setting up CDE standard processes on organizational level
  - Develop EIR overall template which can be adjusted on project scale specific needs
  - Sharpen process definitions for BIM supported Requirements Management UC considering also required roles and functions
  - Mobilize resources and assign BIM roles on organizational as well as project level
  - Develop LOIN definitions for Trafikverket Assets according to ISO 17412 norm and incorporate as part of the EIR that are submitted to the suppliers

- Require information deliveries by Trafikverket suppliers in open formats, which allow for rich metadata assignments and enhance collaboration
- Setup and conduct predefined and structured QA processes on exchanged information
- Consider the implementation of the use case within a pilot project of limited scope for testing and refining the theoretical approach and establish lessons learned mechanisms

7.4 References to publications and reports

1. J. Braun, “Exchange Information Requirements recommendations”, 2022

8 WP7 - Digital asset verification

8.1 Motivation

In this work package, we analyze to what extent Trafikverket’s requirements are automatically verifiable. The motivation for this analysis origins from the work by Beach et al. [8] who developed a roadmap with 24 capabilities that are necessary for the industry adoption of automated compliance checks. The first capability is the “cataloguing and prioritizing regulations that are suitable for automation” [8].

One fundamental quality attribute of a requirement is its verifiability, that is, the quality that allows one to decide whether the requirements has been fulfilled or not. Requirements verifiability is a complex requirements quality attribute that can be further broken down, i.e. a requirement must be understandable, complete, unambiguous, and atomic to be verifiable [9].

Trafikverket has hundreds of regulatory documents (TRVInfra), each containing dozens to hundreds of requirements. Furthermore, each project elicits specific requirements originating from the different stakeholders and the goals that are targeted with the project. Hence, in order to render this task tractable within the scope of this project, we have analyzed a sample of project specific requirements (Eastlink) and TRVInfra requirements. The overarching goal was to gauge the potential for automated verification of the sampled requirements.

To drive the analysis, we asked the following questions:

- Q1: Is the requirement verifiable?
- Q2: If the requirement is not verifiable, why not?
- Q3: Is the requirement, in principle, automatically verifiable?
- Q4: If the requirement is not automatically verifiable, why not?
- Q5: Can we identify archetypes of verification procedures?

We analyzed in total 129 requirements. One researcher (BTH) performed an initial review of the requirements and classified each requirement as automatically verifiable or not (Q3). In addition, he provided a brief description to motivate this decision (Q4). Furthermore, he extracted the information that is needed to verify the requirement and formulated a simple procedure how the requirement could be verified. That procedure was then used to identify verification archetypes, i.e. common procedures that can be used a variety of different requirements (Q5). The information extracted for Q3-Q5 was reviewed by a practitioner (HOCHTIEF Vicon) and amended in case the feedback required a change in the assessment made by the researcher. Upon inspection of the answers to Q4, the researcher found that it would make sense to differentiate between requirements that are not verifiable at all and requirements for which an automated verification seems difficult or impossible. We added therefore Q1 and Q2, as it makes sense, from a reporting perspective, to start with these questions, even though they were analyzed last.

8.2 Results

8.2.1 Verifiable requirements (Q1, Q2)

Out of the 129 requirements, 122 (95%) were verifiable whereas 7 (5%) were assessed as not verifiable. Seven out of 129 requirements is a relatively low number and is acceptable if the requirements are clarified or made more specific in other related requirements. If this is the case (we did not investigate that), it should still be ensured that the non-verifiable requirement has an explanation/qualification where the more specific requirement(s) can be found. While some of the non-verifiable requirements are associated with advisory text (råd), this additional information should rather be encoded in a requirement that can be verified.

8.2.2 Automatically verifiable requirements (Q3, Q5)

Out of the 122 verifiable requirements, we classified 103 (84%) as automatically verifiable. While analyzing the requirements, we have developed a set of six verification archetypes. A verification archetype is a fundamental check that describes *what* should be verified to ensure that the requirement is fulfilled. Please note that, as we analyzed only a sample of 129 requirements, these archetypes may be incomplete and more can be added at when a larger of requirements is analyzed.

Verification archetype	Example	Occurrences
Localization of an object	*Fences* must be **placed behind the technology building, seen from the railway**, if the property boundary allows this.	9
Distance between objects	*Cross-connections*, between up and down tracks, shall be provided with a **maximum distance of 40 km**.	9
Internal attribute(s) of an object	If the support layer thickness is greater than 120 mm, a **coarser 0/45** *support layer* should be selected for stability reasons.	14
External attribute(s) of an object	*Railings on railway bridges* shall be designed with **safety nets**.	31
Geometrical attributes of an object	The *hardened walkways* in the track tunnel should be **1,2 m wide** (minimum free width).	20
Existence of an object	There should be *emergency lighting* in service and access tunnels.	20

Table 6 Verification archetypes and their occurrences in the studied requirements

Table 6 provides the names of the six archetypes, an example requirement and the occurrences we counted in the 129 analyzed requirements. In the example requirement, we highlight the object which needs to be verified in *italics* and the property of that object that needs to be verified in **bold**.

The **location** on an object describes where an object shall be placed within a model. The **distance** is similar, describes however the relationship between objects in terms of distance. An **internal attribute** is a property of an object that can likely be modeled as part of the digital building model. An **external attribute** is a property that can likely be found only in external documentation, linked to from the model. **Geometrical attributes** are physical dimensions of objects, as they are either specified in the model as attributes (a special case of an internal attribute) or derived from the actual object geometry. The **existence** of an object describes that an object must exist in a model.

Note that the verification archetypes are a simplification and capture only the essence of what needs to be verified in the requirement. For example, a requirement may specify that something is *not* located at a particular place. Another, more complex requirement may specify that the distance between two objects shall be a certain value, *only if* certain conditions exist. Exactly how these semantics can be captured and extracted from requirements, as to determine which automated verification techniques shall be applied, is a matter of future research.

8.2.3 Not automatically verifiable requirements (Q4)

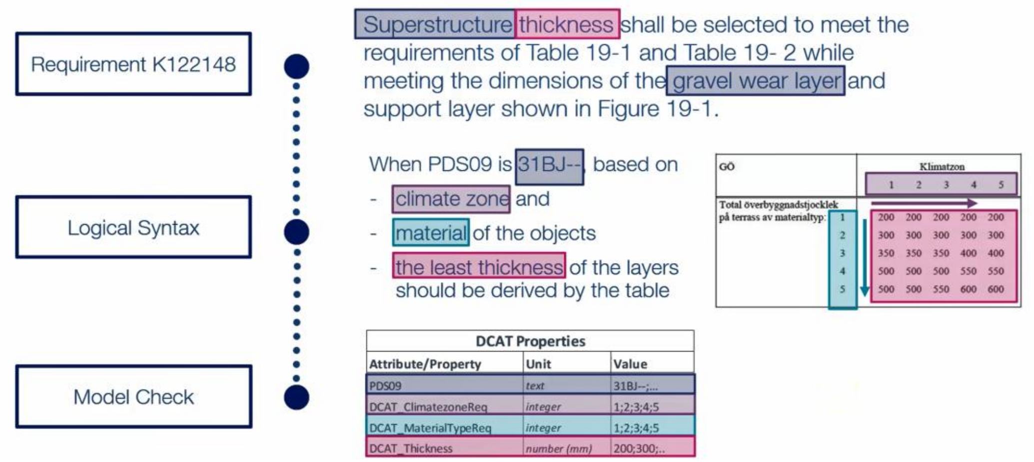
Out of the 122 verifiable requirements, we found 19 (16\%) to be not automatically verifiable. We believe that, with help of domain experts, these requirements could be clarified to a degree that an automated verification is possible or at least established whether the requirements should rather be verified during or after the construction, instead of the design phase.

8.2.4 Automated compliance checks – an example implementation

To demonstrate automated compliance checks, we have transferred the textual requirements description into a logical syntax, which can be verified with a model-based rule check.

As an example, we used the requirement K122148. At first, we had to identify those objects which must be addressed to verify the requirement. The identification of these objects was enabled with the translation of the textual description “superstructure” into the classification value, which is the PDS 09 value “31BJ--“.

Furthermore, the reference to a table (Table 19-1 in TRVInfra-00224) of the requirement description defined the attributes that needed to be used for the verification. For our example, the climate zone and the material type would define the least thickness of the related road layers. That meant that two attributes were required to be assigned to all relevant model objects with the classification values “31BJ--“. These are the suggested attributes “DCAT_ClimatezoneReq” and “DCAT_MaterialTypeReq” as shown in Figure 18 under the DCAT properties section of the Model check definition.



Superstructure thickness shall be selected to meet the requirements of Table 19-1 and Table 19- 2 while meeting the dimensions of the gravel wear layer and support layer shown in Figure 19-1.

When PDS09 is 31BJ--, based on
- climate zone and
- material of the objects
- the least thickness of the layers should be derived by the table

GÖ	Klimatzon 1	2	3	4	5
Total överbyggnadstjocklek på terrass av materialtyp: 1	200	200	200	200	200
2	300	300	300	300	300
3	350	350	350	400	400
4	500	500	500	550	550
5	500	500	550	600	600

DCAT Properties		
Attribute/Property	**Unit**	**Value**
PDS09	*text*	31BJ--;...
DCAT_ClimatezoneReq	*integer*	1;2;3;4;5
DCAT_MaterialTypeReq	*integer*	1;2;3;4;5
DCAT_Thickness	*number (mm)*	200;300;..

Figure 18: Logical syntax for requirement K122148 and model check attributes

These attributes, for the sake of the test purpose of project, were assigned manually to the test models.

In addition, the Table 19-1 indicates the minimum thickness of the relevant road layers based on the assigned material type climate zone. This geometrical attribute was calculated using basic scripting functions within the 3D BIS demonstrator tool (more details for the tool to be found in Section 9.2.2) and the property "DCAT_ThicknessReq" was automatically calculated and assigned to the proper model objects.

Moreover, the outcome of the table 19-1 conversion into a pivot table (extract) was the following:

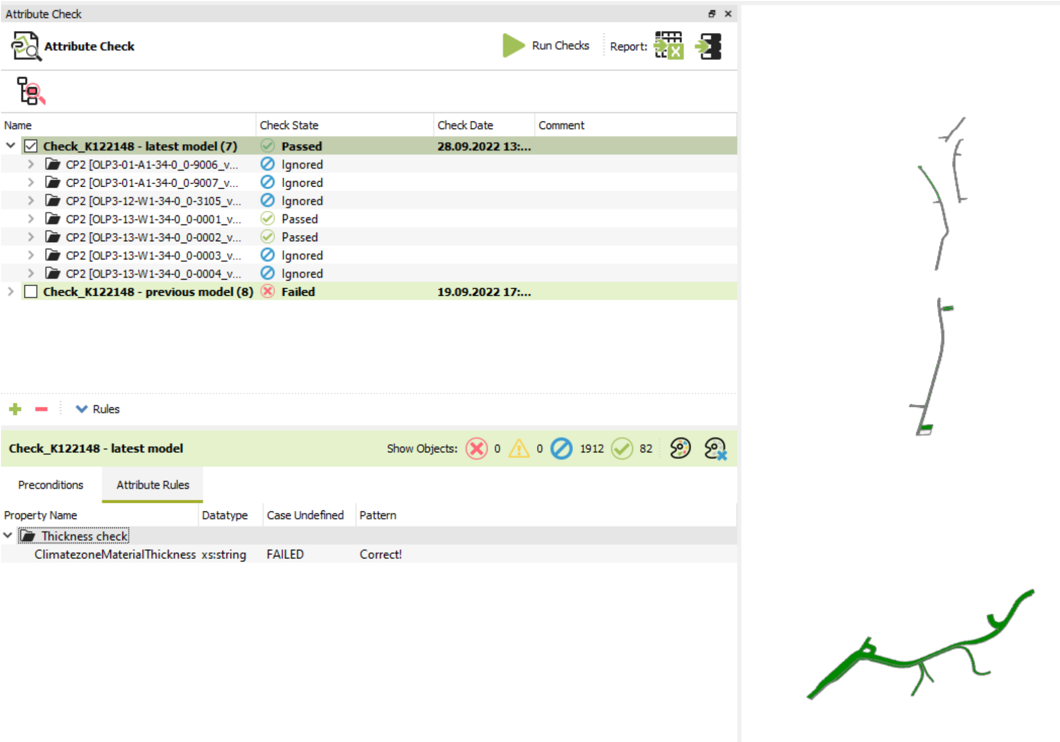
DCAT_ClimatezoneReq (integer)	DCAT_MaterialTypeReq (integer)	DCAT_ThicknessReq (mm) - minumum
1	1	200
1	2	200
1	3	200

This conversion was used as input and within 3D BIS, we setup once the model based rule which:

- Identifies the objects that need to be checked (PDS09 value "31BJ--") and ignores the rest
- Uses the pivot table information above and cross checks for the combination of the specific DCAT_ClimatezoneReq and DCAT_MaterialTypeReq attributes which is the DCAT_ThicknessReq calculated property.

If the DCAT_ThicknessReq is equal or more than the indicated in the pivot table value (in mm), then:

- the checked objects were highlighted green in the model area
- if all objects were fulfilling the defined rule, the check state was set to "Passed"



Name	Check State	Check Date	Comment
☑ **Check_K122148 - latest model (7)**	✓ **Passed**	**28.09.2022 13:...**	
CP2 [OLP3-01-A1-34-0_0-9006_v...	⊘ Ignored		
CP2 [OLP3-01-A1-34-0_0-9007_v...	⊘ Ignored		
CP2 [OLP3-12-W1-34-0_0-3105_v...	⊘ Ignored		
CP2 [OLP3-13-W1-34-0_0-0001_v...	✓ Passed		
CP2 [OLP3-13-W1-34-0_0-0002_v...	✓ Passed		
CP2 [OLP3-13-W1-34-0_0-0003_v...	⊘ Ignored		
CP2 [OLP3-13-W1-34-0_0-0004_v...	⊘ Ignored		
☐ **Check_K122148 - previous model (8)**	☒ **Failed**	**19.09.2022 17:...**	

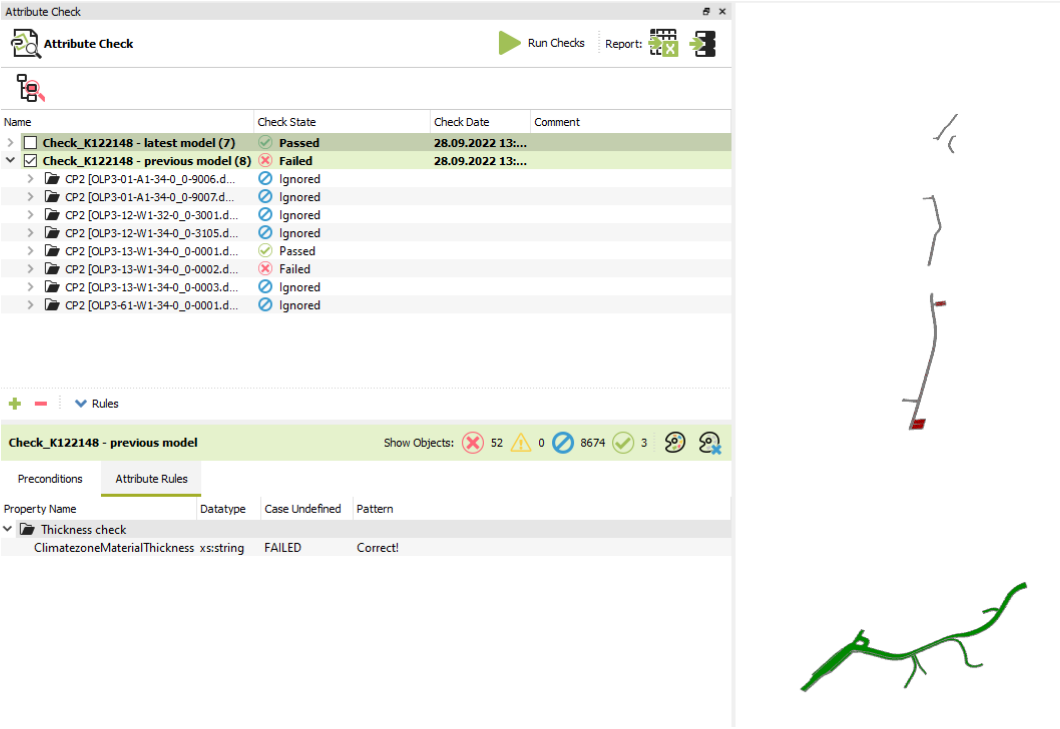
Check_K122148 - latest model Show Objects: ☒ 0 ⚠ 0 ⊘ 1912 ✓ 82

Property Name	Datatype	Case Undefined	Pattern
Thickness check			
ClimatezoneMaterialThickness	xs:string	FAILED	Correct!

Figure 19:Rule-based model check example where check state is passed

If the DCAT_ThicknessReq is not equal or more than the indicated in the pivot table value (in mm) for at least one object for, then:

- the check state was set to “Failed” and the respective object is highlighted red in the model view area.



Name	Check State	Check Date	Comment
☐ Check_K122148 - latest model (7)	Passed	28.09.2022 13:...	
☑ Check_K122148 - previous model (8)	Failed	28.09.2022 13:...	
CP2 [OLP3-01-A1-34-0_0-9006.d...	Ignored		
CP2 [OLP3-01-A1-34-0_0-9007.d...	Ignored		
CP2 [OLP3-12-W1-32-0_0-3001.d...	Ignored		
CP2 [OLP3-12-W1-34-0_0-3105.d...	Ignored		
CP2 [OLP3-13-W1-34-0_0-0001.d...	Passed		
CP2 [OLP3-13-W1-34-0_0-0002.d...	Failed		
CP2 [OLP3-13-W1-34-0_0-0003.d...	Ignored		
CP2 [OLP3-61-W1-34-0_0-0001.d...	Ignored		

Property Name	Datatype	Case Undefined	Pattern
Thickness check			
ClimatezoneMaterialThickness	xs:string	FAILED	Correct!

Figure 20: Rule-based model check example where check state is failed and a few objects are red highlighted

8.3 Conclusion

One of the key root causes for not adopting automated compliance checks in industrial practice is the lack of precise, digitalisable regulations [8]. To understand if this is also the case for the regulations in use at Trafikverket, we have studied a sample of requirements drawn from TRVInfra and Eastlink. We found that the vast majority (95%, 122 out of 129) are verifiable, and 83% (103 out of 122) of these are probably automatically verifiable with existing technologies. Furthermore, we identified a set of six verification archetypes that cover the 122 analyzed requirements. This means that the implementation of one archetype can already cover a large set of requirements. For example, the check for the existence of an object was found in 20 out of 103 requirements (19%). We have also implemented the automated check for verifying the geometrical attributes on an object. While this requires initial investment in developing the logic for rule checks and discipline by suppliers to provide the needed information in the delivered models, the implementation can be reused in different projects and be executed on demand, allowing for quick feedback on the deliverables.

These initial results are encouraging and call for a more in-depth study of the complete corpus of requirements at Trafikverket. However, a manual assessment of thousands of requirements is prohibitively expensive. Therefore, future work can investigate the feasibility of such analysis through clustering [10], i.e. by grouping requirements by their similarity and then analyze these clusters, presumably less in number than the original requirements, w.r.t. to their verifiability.

8.4 References to publications and reports

1. M. Unterkalmsteiner and A. Chirtoglou, “Digital asset verification - State-of-the-art and feasibility study”, 2022

9 WP8 - Digital asset visualization

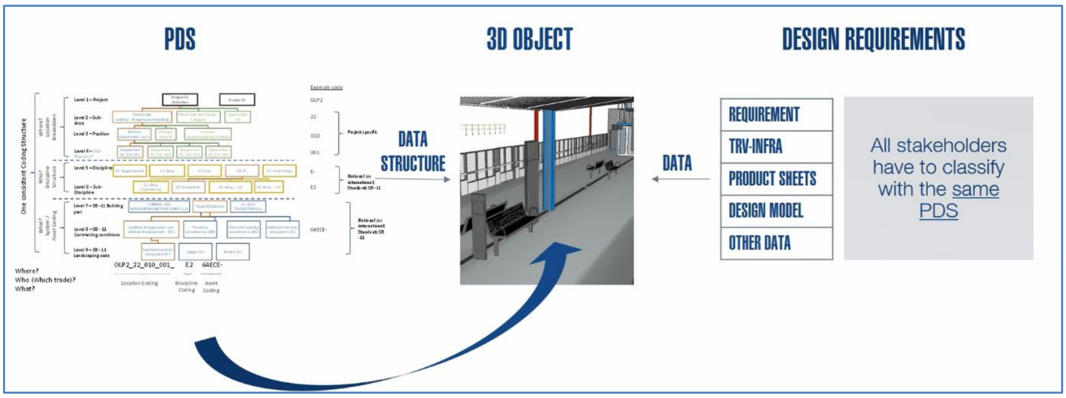
This is an accompanying text to the video that has been provided as DCAT project deliverable for Trafikverket. The demonstrator presented in that video displays in general the findings and proposed workflows for the BIM supported requirements management use case, while this text gives further explanations and a static description.

More details about the proposed process for this use case can be found at the **Work Package 5 deliverable**, where it is described in detail.

9.1 Process introduction / PDS introduction

The main objective of the use case is to support the designers and the requirements managers, to verify specific requirements in an automated way within the digital assets, by linking necessary information and with the use of rule-based model checks.

To achieve this, the approach was to use structured data to establish digital trace links between the formulated requirements and the digital asset elements. In particular, this common structure, the Project Data Structure or else PDS has been introduced and used to enable this link. The PDS can partly consist of classification systems, which are used already in the construction industry.



When the requirements and the design models are classified using the same classification system, then the relevant requirements can be associated to the specific design objects. It is therefore of significant importance to use a common language, for the requirements, the design models or even other data with important information for the verification. In this proposal, the common language is the same classification system as part of the PDS.

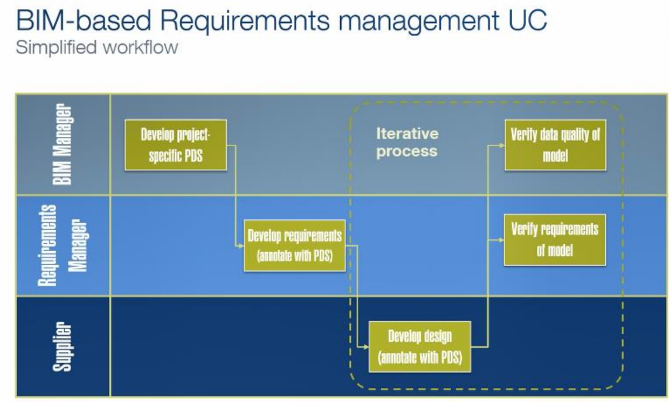


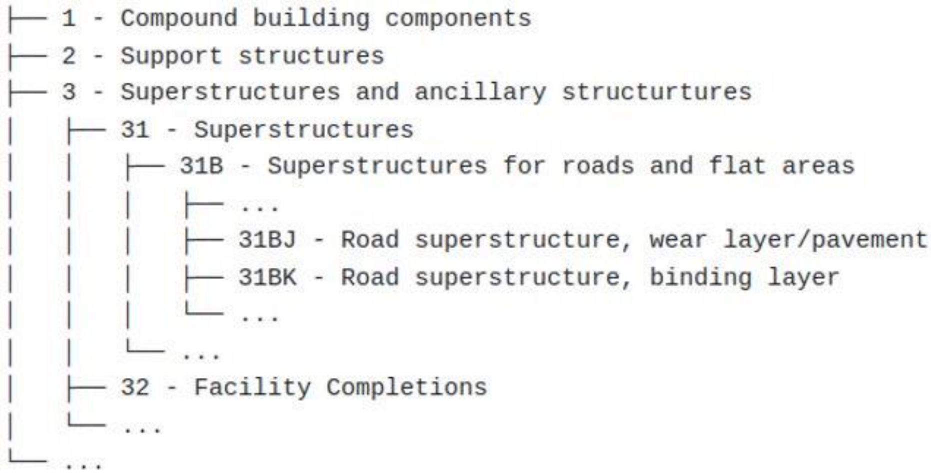
Figure 21 Simplified flowchart of the use case as per WP5 deliverable

The PDS guidelines have been the input for the development of the project specific PDS, a task which shall be led by the project BIM manager. As shown in Figure 21 “simplified flowchart of the use case”, the project-specific PDS structure, is the basis for the next steps. The same PDS is assigned by the requirements manager to the requirements and by the supplier to the digital assets. This will allow the verification of the requirement within digital asset in an automated way.

More information about the PDS development can be found at the **Work Package 3 deliverable** document.

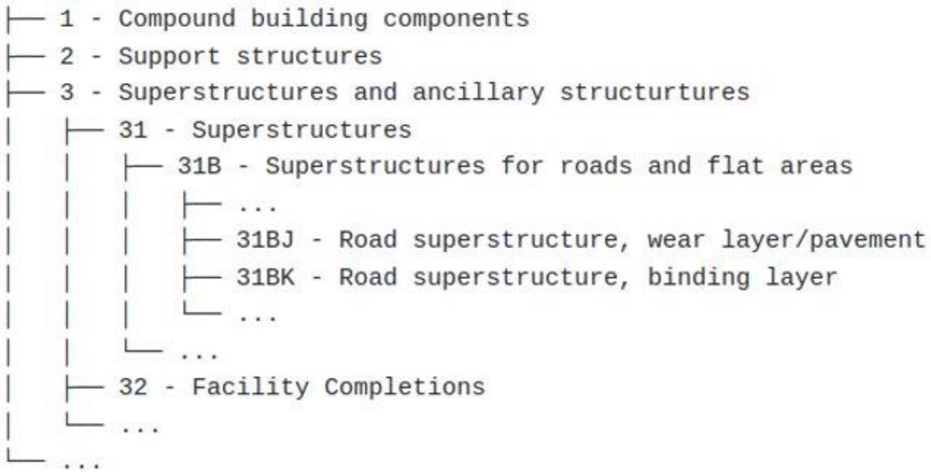
The important step of developing and classifying the requirements is what comes after the development of the project specific PDS. Two classification systems have been considered for the DCAT project: CoClass and SB11.

In the requirements classification, we used the classification system SB11 to recommend labels for TRV-Infra and Eastlink requirements, which is used to classify objects in the parts OLP2 and OLP3 of the project Eastlink.



```
├── 1 - Compound building components
├── 2 - Support structures
├── 3 - Superstructures and ancillary structurtures
│   ├── 31 - Superstructures
│   │   ├── 31B - Superstructures for roads and flat areas
│   │   │   ├── ...
│   │   │   ├── 31BJ - Road superstructure, wear layer/pavement
│   │   │   ├── 31BK - Road superstructure, binding layer
│   │   │   └── ...
│   │   └── ...
│   ├── 32 - Facility Completions
│   └── ...
└── ...
```

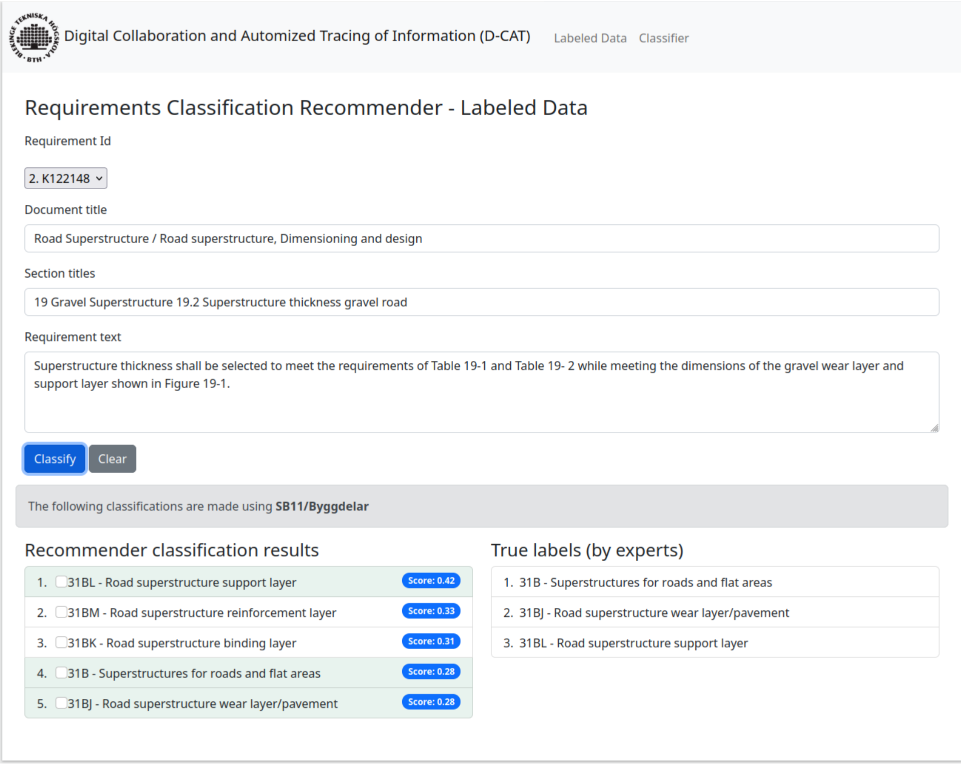
Figure 22 Example classes from SB11



```
├── 1 - Compound building components
├── 2 - Support structures
├── 3 - Superstructures and ancillary structurtures
│   ├── 31 - Superstructures
│   │   ├── 31B - Superstructures for roads and flat areas
│   │   │   ├── ...
│   │   │   ├── 31BJ - Road superstructure, wear layer/pavement
│   │   │   ├── 31BK - Road superstructure, binding layer
│   │   │   └── ...
│   │   └── ...
│   ├── 32 - Facility Completions
│   └── ...
└── ...
```

Figure 22 shows an example of SB11 classes that are arranged in a hierarchy. The node with code 3 – superstructures and ancillary structures – has multiple child nodes: 31, 32, and others. Node 31 has children 31B and others, each of which has more children until we reach the leaf nodes without children.

Trafikverket has hundreds of TRVInfra documents, each containing dozens to hundreds of general requirements that potentially apply to any infrastructure project. The manual classification of all these requirements would require a lot of time and would need to be repeated when requirements change or new ones are added.



Requirements Classification Recommender - Labeled Data

Requirement Id

2. K122148

Document title

Road Superstructure / Road superstructure, Dimensioning and design

Section titles

19 Gravel Superstructure 19.2 Superstructure thickness gravel road

Requirement text

Superstructure thickness shall be selected to meet the requirements of Table 19-1 and Table 19- 2 while meeting the dimensions of the gravel wear layer and support layer shown in Figure 19-1.

The following classifications are made using **SB11/Byggdelar**

Recommender classification results

1. ☐ 31BL - Road superstructure support layer Score: 0.42
2. ☐ 31BM - Road superstructure reinforcement layer Score: 0.33
3. ☐ 31BK - Road superstructure binding layer Score: 0.31
4. ☐ 31B - Superstructures for roads and flat areas Score: 0.28
5. ☐ 31BJ - Road superstructure wear layer/pavement Score: 0.28

True labels (by experts)

1. 31B - Superstructures for roads and flat areas
2. 31BJ - Road superstructure wear layer/pavement
3. 31BL - Road superstructure support layer

Figure 23 Screenshot of the classification recommender

Classifying a requirement using the recommender requires that we enter the requirements information (document title, section titles, and requirement text). Figure 23 shows a screenshot of the demonstrator that shows the recommender output and compares it with the results from the ground truth annotations.

We initiate the process of classification (by clicking classify). Then, the recommender retrieves the five labels, from SB11, with the highest similarity score. In the demonstrator, the recommender also shows the true labels from the ground truth, which we developed earlier. However, when using the recommender to classify requirements, these true labels do not exist. Each classification result is represented with the label/code, description, and score. The score represents the similarity between the chosen label description and the requirement.

An expert needs to select the labels that he/she sees as correct, and the system will store these labels as the correct ones. We can use these classifications later to trace requirements to objects in the design models.

9.2 Demonstrator walkthrough

9.2.1 Model explanation

The BIM models that have been used for the demonstrator (OLP2 and OLP3 projects) have been brought close to each other for the sake of demonstration. The models (as shown in Figure 24) are both from early design phase and there are two versions of them included: an original version called 'previous' and an updated version shown as 'latest'.

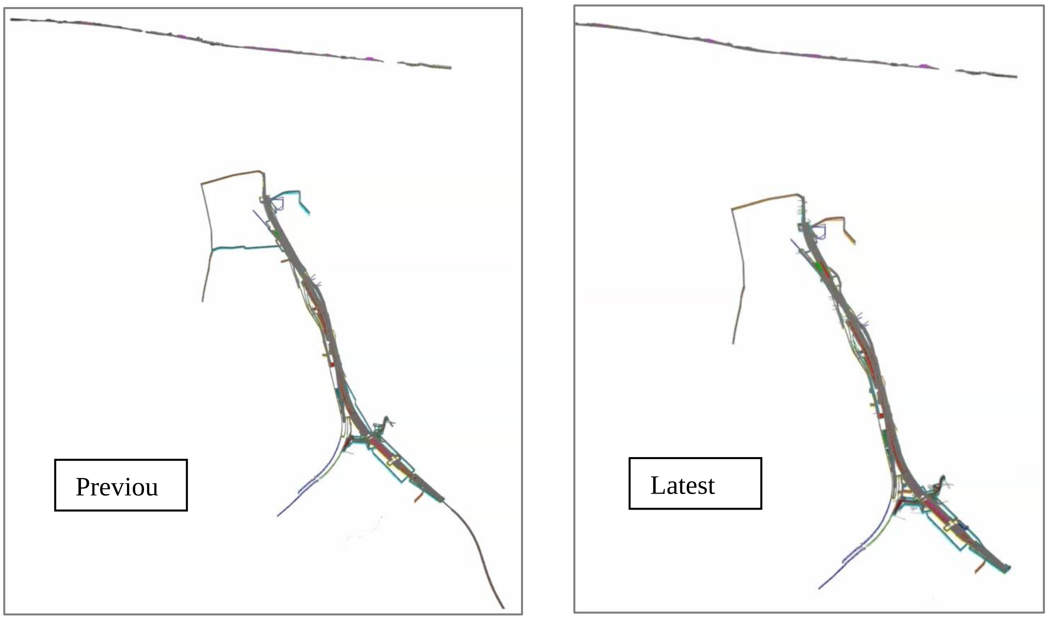
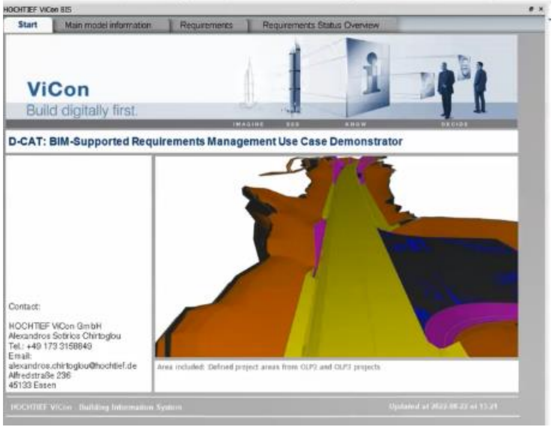


Figure 24: Viewpoints on OLP2 and OLP3 model versions used for the demonstrator

9.2.2 Software

The software that has been used for the demonstrator is the HOCHTIEF ViCon 3D BIS, a BIM management software tool, which links bi-directionally the 3d objects of a BIM model with the associated information of the data analysis dashboards.



D-CAT: BIM-Supported Requirements Management Use Case Demonstrator

Contact:

HOCHTIEF ViCon GmbH
Alexandros Sotirios Chirtoglou
Tel.: +49 173 3158849
Email:
alexandros.chirtoglou@hochtief.de
Alfredstraße 236
45133 Essen

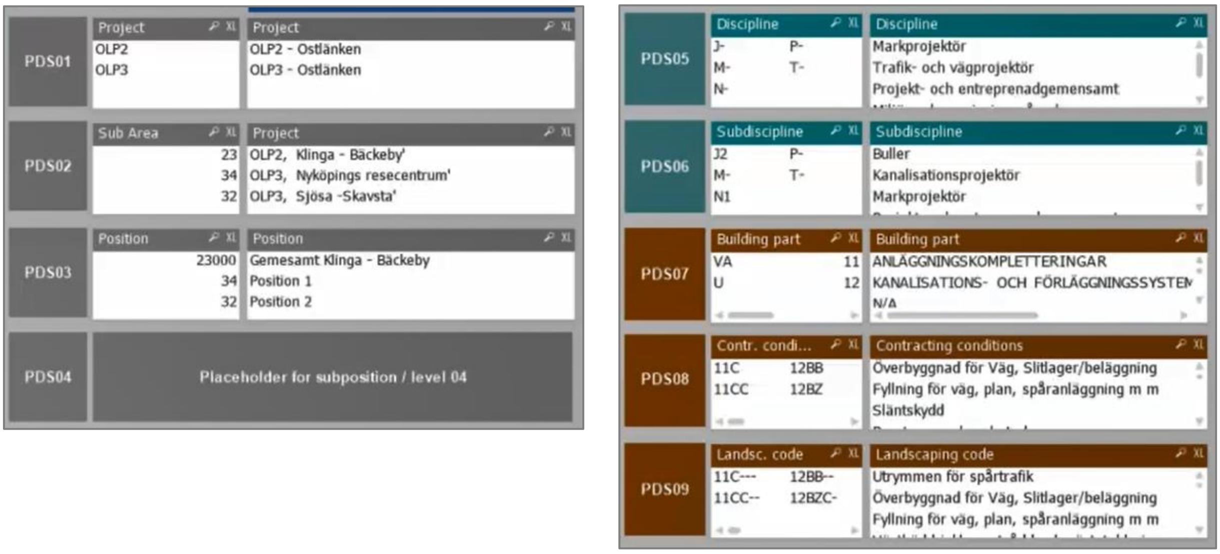
Area included: Defined project areas from OLP2 and OLP3 projects

HOCHTIEF ViCon · Building Information System

Updated at 2022-08-22 at 13:21

9.2.3 3D BIS - PDS assignment to model

We describe now the assignment of the PDS values to the digital assets by the designers. In the left part of the first data part tab of the demonstrator (see Figure 25), the PDS levels are shown, split into three common data structures. These are namely the location (grey), discipline (green) and asset structure (brown). All these structures are applied to each model object.



PDS01
Project: OLP2, OLP3
Project: OLP2 - Ostlänken, OLP3 - Ostlänken

PDS02
Sub Area: 23, 34, 32
Project: OLP2, Klinga - Bäckeby', OLP3, Nyköpings resecentrum', OLP3, Sjösa -Skavsta'

PDS03
Position: 23000, 34, 32
Position: Gemesamt Klinga - Bäckeby, Position 1, Position 2

PDS04
Placeholder for subposition / level 04

PDS05
Discipline: J-, P-, M-, T-, N-
Discipline: Markprojektör, Trafik- och vägprojektör, Projekt- och entreprenadgemensamt

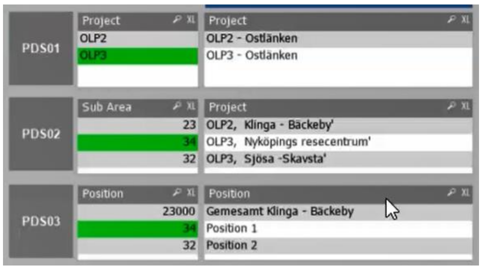
PDS06
Subdiscipline: J2, P-, M-, T-, N1
Subdiscipline: Buller, Kanalisationsprojektör, Markprojektör

PDS07
Building part: VA 11, U 12
Building part: ANLÄGGNINGSKOMPLETTERINGAR, KANALISATIONS- OCH FÖRLÄGGNINGSSYSTEM, N/A

PDS08
Contr. condi...: 11C, 12BB, 11CC, 12BZ
Contracting conditions: Överbyggnad för Väg, Slitlager/beläggning, Fyllning för väg, plan, spåranläggning m m, Släntskydd

PDS09
Landsc. code: 11C---, 12BB--, 11CC--, 12BZC-
Landscaping code: Utrymmen för spårtrafik, Överbyggnad för Väg, Slitlager/beläggning, Fyllning för väg, plan, spåranläggning m m

Figure 25: PDS values assigned at the demonstrator models



PDS01
Project: OLP2, OLP3
Project: OLP2 - Ostlänken, OLP3 - Ostlänken

PDS02
Sub Area: 23, 34, 32
Project: OLP2, Klinga - Bäckeby', OLP3, Nyköpings resecentrum', OLP3, Sjösa -Skavsta'

PDS03
Position: 23000, 34, 32
Position: Gemesamt Klinga - Bäckeby, Position 1, Position 2

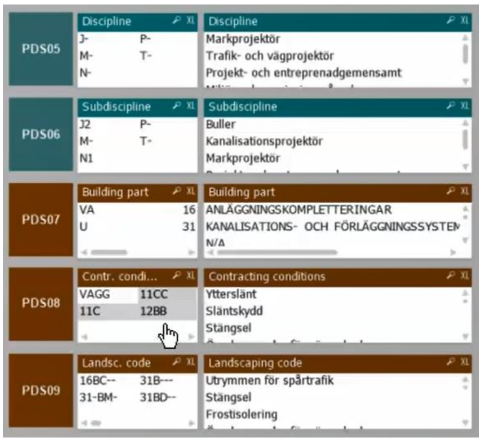
First, the 'previous' model version will be selected and a specific position can be filtered:

- PDS01 filters for the **OLP3** project,
- PDS02 will select **sub area 34** and
- PDS03 selects **position 34** in this example.

It needs to be noted that the values shown in the PDS list for the levels 01 to 09, include the relationships between them following their assignment to the model elements.

Therefore, as shown in Figure 26 the other structures (discipline (green) and asset (brown)) are also being narrowed down as long as the location is defined through the location data structure. The values with the grey background are the ones that are not assigned at the digital assets of the location that were previously selected.

The data model is narrowed down to the specific filtered location, which can also be synchronized with the model.



PDS05
Discipline
J- P-
M- T-
N-
Discipline
Markprojektör
Trafik- och vägprojektör
Projekt- och entreprenadgemensamt

PDS06
Subdiscipline
J2 P-
M- T-
N1
Subdiscipline
Buller
Kanalisationsprojektör
Markprojektör

PDS07
Building part
VA 16
U 31
Building part
ANLÄGGNINGSKOMPLETTERINGAR
KANALISATIONS- OCH FÖRLÄGGNINGSSYSTEM
N/A

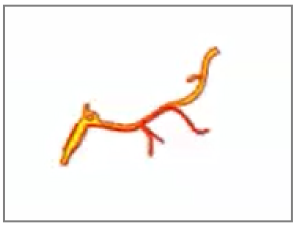
PDS08
Contr. condi...
VAGG 11CC
11C 12BB
Contracting conditions
Ytterslänt
Släntskydd
Stängsel

PDS09
Landsc. code
16BC-- 31B---
31-BM- 31BD--
Landscaping code
Utrymmen för spårtrafik
Stängsel
Frostisolering

Figure 26: Discipline and Asset Data Structures with values filtered for the previously selected Location Data Structure values

A further filter for specific asset types of a discipline is also possible (for example the T- as discipline and sub discipline which is the traffic), and the PDS09 31BJ- which is the top layer of the road superstructure.

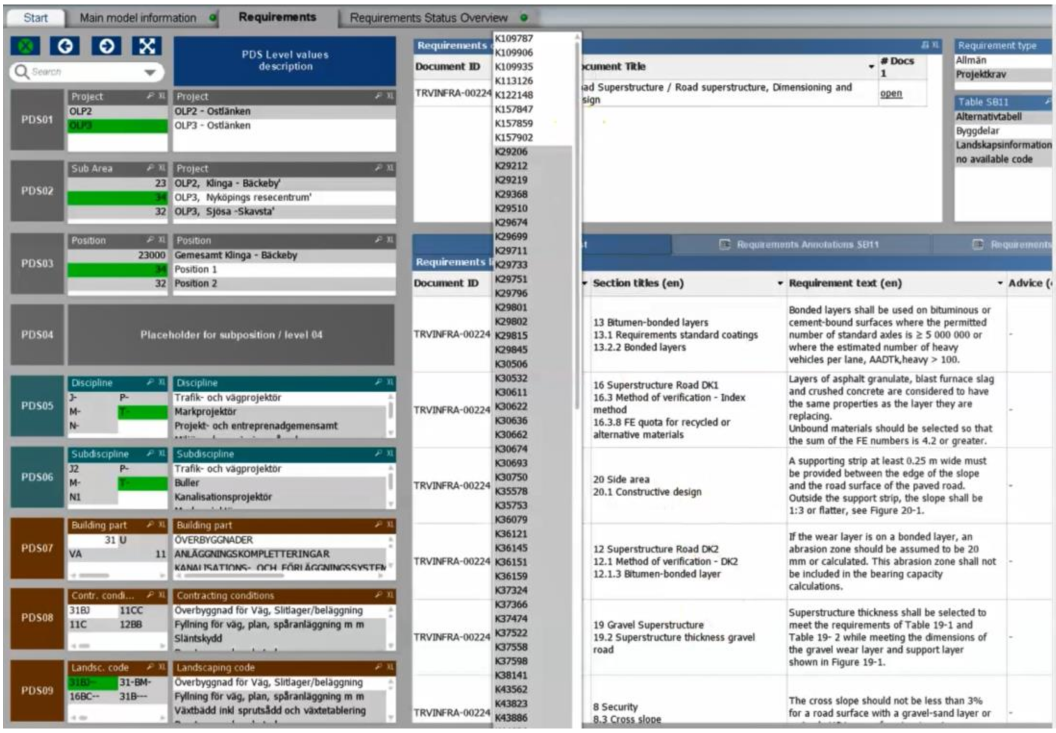
After manually synchronizing the associated digital assets to the 3d area can be visualized. All highlighted objects are the elements, which have been associated with the selected PDS values. By clicking on 'Reduce model' all the other model objects can be hide.



9.2.4 Requirements page

After defining the objects that are of interest, the verification process can start and be further monitored through one integrated system. Under the tab "Requirements", all requirements coming from another systems, f.e. Doors, are displayed and linked with the digital assets through the PDS concept and the common classification.

Figure 27 shows the filtered requirements for the selected PDS values.



PDS01
Project: OLP2, OLP3
Project: OLP2 - Ostlänken; OLP3 - Ostlänken

PDS02
Sub Area: 23, 34, 32
Project: OLP2, Klinga - Bäckeby'; OLP3, Nyköpings resecentrum'; OLP3, Sjösa -Skavsta'

PDS03
Position: 23000, 34, 32
Position: Gemesamt Klinga - Bäckeby; Position 1; Position 2

PDS04
Placeholder for subposition / level 04

PDS05
Discipline: J-, P-, M-, T-, N-
Discipline: Trafik- och vägprojektör; Markprojektör; Projekt- och entreprenadgemensamt

PDS06
Subdiscipline: J2, P-, M-, T-, N1
Subdiscipline: Trafik- och vägprojektör; Buller; Kanalisationsprojektör

PDS07
Building part: 31 U, VA 11
Building part: ÖVERBYGGNADER; ANLÄGGNINGSKOMPLETTERINGAR; KANALISATIONS- OCH FÖRLÄGGNINGSSYSTEM

PDS08
Contr. condi...: 31BJ, 11CC, 11C, 12BB
Contracting conditions: Överbyggnad för Väg, Slitlager/beläggning; Fyllning för väg, plan, spåranläggning m m; Släntskydd

PDS09
Landsc. code: 31BD-, 31-BM-, 16BC--, 31B---
Landscaping code: Överbyggnad för Väg, Slitlager/beläggning; Fyllning för väg, plan, spåranläggning m m; Växtbädd inkl sprutsådd och växtetablering

Requirements

Document ID	ocument Title	# Docs 1
TRVINFRA-00224	ad Superstructure / Road superstructure, Dimensioning and sign	open

Requirement type: Allmän; Projektkrav

Table SB11: Alternativtabell; Byggdelar; Landskapsinformation; no available code

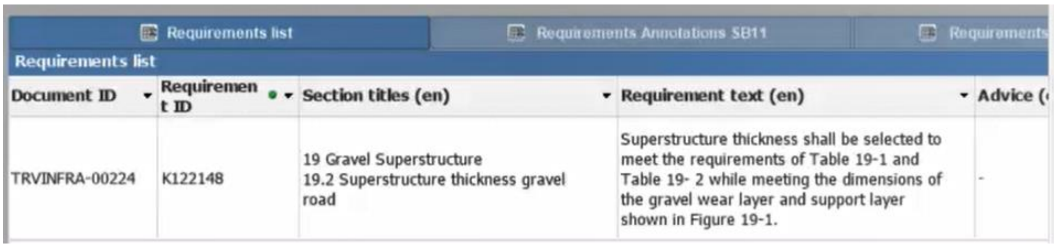
Requirements l

Document ID	Section titles (en)	Requirement text (en)	Advice (
TRVINFRA-00224	13 Bitumen-bonded layers 13.1 Requirements standard coatings 13.2.2 Bonded layers	Bonded layers shall be used on bituminous or cement-bound surfaces where the permitted number of standard axles is ≥ 5 000 000 or where the estimated number of heavy vehicles per lane, AADTk,heavy > 100.	-
TRVINFRA-00224	16 Superstructure Road DK1 16.3 Method of verification - Index method 16.3.8 FE quota for recycled or alternative materials	Layers of asphalt granulate, blast furnace slag and crushed concrete are considered to have the same properties as the layer they are replacing. Unbound materials should be selected so that the sum of the FE numbers is 4.2 or greater.	-
TRVINFRA-00224	20 Side area 20.1 Constructive design	A supporting strip at least 0.25 m wide must be provided between the edge of the slope and the road surface of the paved road. Outside the support strip, the slope shall be 1:3 or flatter, see Figure 20-1.	-
TRVINFRA-00224	12 Superstructure Road DK2 12.1 Method of verification - DK2 12.1.3 Bitumen-bonded layer	If the wear layer is on a bonded layer, an abrasion zone should be assumed to be 20 mm or calculated. This abrasion zone shall not be included in the bearing capacity calculations.	-
TRVINFRA-00224	19 Gravel Superstructure 19.2 Superstructure thickness gravel road	Superstructure thickness shall be selected to meet the requirements of Table 19-1 and Table 19- 2 while meeting the dimensions of the gravel wear layer and support layer shown in Figure 19-1.	-
TRVINFRA-00224	8 Security 8.3 Cross slope	The cross slope should not be less than 3% for a road surface with a gravel-sand layer or	-

Figure 27: Requirements list linked through the PDS with the selected model objects

9.2.5 Requirements Status Overview page

Even while the development of the design is ongoing, the system can support the tracking of the requirements verification process. In the described process, the BIM manager together with the responsible design manager can track the design status based on the requirements. In the demonstrated example, the K122148 requirement is selected that has been used previously with the annotation recommender presentation. This is one of the requirements that are associated through the common classification language with the digital asset objects that were filtered.



Requirements list

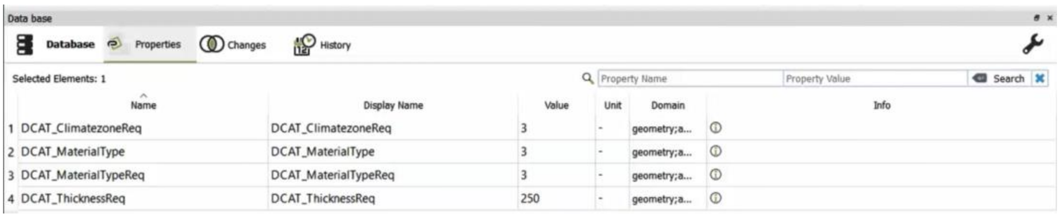
Document ID	Requirement ID	Section titles (en)	Requirement text (en)	Advice (
TRVINFRA-00224	K122148	19 Gravel Superstructure 19.2 Superstructure thickness gravel road	Superstructure thickness shall be selected to meet the requirements of Table 19-1 and Table 19- 2 while meeting the dimensions of the gravel wear layer and support layer shown in Figure 19-1.	-

Before the verification process starts, the requirement is previously translated into a "logical syntax" where all necessary properties and attributes have been considered and are displayed.

The K122148 requirement defines that the superstructure thickness shall be in accordance with the information coming from two tables. This requirement is going to be translated into a logical syntax. With the addition of the table, the attributes that are required for the verification can be defined: the classification, the climate zone, the material and the thickness that define the requirement. More details on the requirement model based rule check setup can be found at the section 8.2.4.

The model based check is setup once within a system and can be reused for other design models that the user wants to verify against this requirement.

Within the 3D model the required attributes for this requirement are already included. In the given example shown in Figure 28, the selected object has a **climate zone 3**, **material type 3** and the **thickness of the layers is 250 mm**.



Selected Elements: 1

	Name	Display Name	Value	Unit	Domain	Info
1	DCAT_ClimatezoneReq	DCAT_ClimatezoneReq	3	-	geometry;a...	ⓘ
2	DCAT_MaterialType	DCAT_MaterialType	3	-	geometry;a...	ⓘ
3	DCAT_MaterialTypeReq	DCAT_MaterialTypeReq	3	-	geometry;a...	ⓘ
4	DCAT_ThicknessReq	DCAT_ThicknessReq	250	-	geometry;a...	ⓘ

Figure 28: DCAT assigned properties for a model object (example)

By setting up the corresponding model check and running the verification process of this requirement in the “previous” model version, the model turned red and the check state reported is 'failed'.

In fact, the attributes of the example object of **material type (3)** and **climate zone (3)** require that the minimum thickness of the layers should be 350 mm. However, these layers whose verification failed, had a **total thickness of only 250 mm**. The automated rule based model check showed within a few seconds all model objects, which do not fulfill the requirements. This task would require otherwise much effort and manual review by design experts.

Name	Check State	Check Date	Comment
☑ Check_K122148 - previous model (9)	☒ Failed	14.09.2022 16:24:23	

Check_K122148 - previous model

Show Objects: ☒ 52 ⚠ 0 ⊘ 8678 ✓ 3

In the given scenario, which is depicted in the demonstration, the verification result has been communicated to the designer team and a new model has become available. Once again the derived model is filtered and the related objects are visualized now. After running the verification check on the latest model, it results to a verified requirement within the BIM model. As illustrated in Figure 29, all the model elements are now green, which means verified and the check state is 'passed'.

By checking the attributes of the latest model, it can be observed that the requirement criteria of at least 350 mm thickness for the same material type and climate zone is now met for the same object.

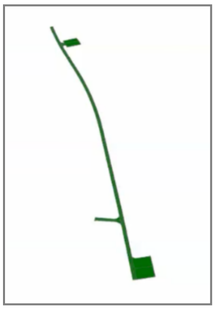
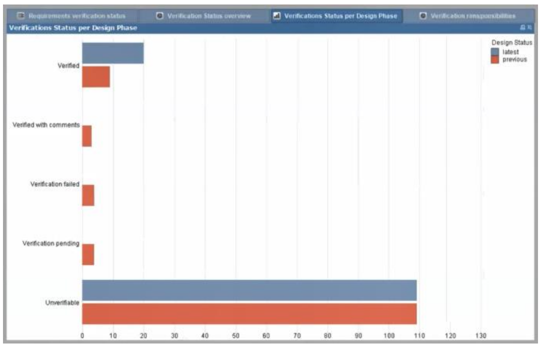
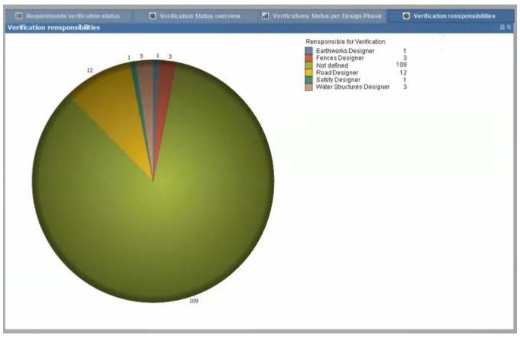


Figure 29: Verified objects against the example requirement (colorized green)

The verification results of all different model versions are available within the dashboard. The digitalization of the information can further support with KPIs related to the verification process. By reviewing the tab with the requirements verification overview, the design and requirements managers can see KPIs with the status of the requirement per model version, information about the overall verification status, the status per design phase or per responsible department.





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