
(ASPE Pipeline, 2021)

IMPROVING THE DATA QUALITY CHECKING PROCESS DURING THE DESIGN PHASE

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28th August 2023

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IMPROVING THE DATA QUALITY CHECKING PROCESS DURING THE DESIGN PHASE

Development of a design-integrated data checking and reporting tool

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In partial fulfilment of the requirements for the Master´s Degree programme of

Master of Science in Construction Management & Engineering

at Delft University of Technology

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Preface

This graduation thesis is written in partial fulfilment to the Master of Science in Construction Management and Engineering at the faculty of Civil Engineering and Geoscience of the Delft University of Technology. This research was carried out from February 2023 to August 2023 in collaboration with Hercuton and the Delft University of Technology.

My interest in BIM data came as a result of previous research at the Delft University of Technology. In that case, research and development was focused on collecting and analysing usage data of visual programming scripts across a team to enable data driven decisions in BIM automation strategies. I was fascinated by how data driven approaches can help steer and improve current practices in the industry. After several insightful conversations with Daan Arts from Hercuton, we found a way to contribute not only to the academic world, but also to the workflows of industry professionals by developing a tool that engages designers in the organisational data checking process.

I would like to thank Daan Arts and the team at Hercuton for their countless and insightful meetings and discussions. Your dedication and guidance not only marked the difference in the development of the tool but also brought valuable industry knowledge and expertise to this document. I also enjoyed my time at the office, meeting new people and the conversations with the team.

Additionally, I would also like to express my gratitude to Dr. Ir. G.A. van Nederveen, Dr. T. Wang and Prof. Dr. Ir. J.W.F Wamelink for your feedback and overarching perspective when reviewing my work. Your constructive arguments and comments were a guide and a source of knowledge for this research.

Last but not least, many thanks to my wonderful family, girlfriend and friends for the constant support and always being by my side.

I hope you enjoy reading my thesis as much as I enjoyed working on it.

Jaime Alonso Candau
Delft, August 2023

Executive summary

Introduction

One of the crucial aspects of BIM is the data rich environment connecting project information from different sub-sectors. (Mesároš et al., 2020). Therefore, developing models with consistent and trustworthy building data has gained significant importance in the industry. In contrast, incorrect or incomplete building data in a model could result in chained mistakes across disciplines, rework, or inadequate models for other stages of the building lifecycle.

Most of the improvements in BIM data in organisations take place in data quality reviews by BIM specialists. The lack of integration and complexity of existing data checking tools raised the expertise leading to assessment tools used mostly by BIM specialists. After a specialist reviews a project, corrections are communicated to the designers to solve the data issues in their models. The process is repeated until the desired quality and/or adequacy to requirements is reached by the design team. Furthermore, wrongly defined or missing basic data structure can often lead to incomplete or inaccurate data checking processes.

The higher goal of this research is to produce perceivable benefits in the organisational data checking process. This is approached by facilitating the implementation of BIM standards and increasing the compliance of objects during design periods before entering the organisational review. Previous research and preliminary discussions with professionals showed that they would prefer to use simple dedicated quality checkers that can minimise manual tasks precisely and reliably instead of advanced software solutions. Thus, the goal is not to replace current workflows and practices, but instead to enhance basic data structures in models before entering the data reviews, by developing and implementing a new design-integrated checking and reporting tool. In order to approach the development objective, a main research question was defined:

How can novel design-integrated tools improve the data quality checking process in organisations?

Methodology

To fulfil the development objective and achieve answers to the research questions, the research was structured in 4 phases. This structure is in line with the Delft approach for product development (M. & Eekels, 1996):

- *Analysis* phase: A literature review about the state of the art in BIM quality control and BIM standards was conducted to explore the main challenges in the field. Additionally, how those concepts were applied in practice, is also analysed from the micro level, the data schemas, to the macro level, the organisational process. Finally, based on the analysis and the main challenges found, the user needs and system requirements were introduced.
- *Synthesis and development* phase: The previous analysis was synthesized into a specific concept and approach to features, interfaces and workflows. Next, a selection of rules narrowed down the scope of the development. Lastly, how the research and development project could enhance and support the organisational data checking reviews is explained.
- *Implementation and assessment* phase: The new data checking tool is implemented, verified, and validated in three ongoing projects. The main goal is to determine the

benefits perceived by practitioners involved in the organisational data checking process and validate that the tool fulfils the needs established on the *Analysis* phase.
- *Conclusion* phase: The results from the previous phases are interpreted and assembled into a conclusion to the main research question. Finally, future research in this topic is suggested and a reflection of the research is conducted.

Results

This graduation project aimed at developing a design-integrated solution to enable designers to identify and review data quality issues while modelling on the detail design phase. Data quality is assessed in terms of compliance with a selection of chapters from the BIM Basis ILS. The approach of the BIM Basis ILs, to create a sector level, simple, flexible and easy-to-implement overarching standard, is a positive first step to work with information that is exchangeable, structured and reusable across the industry.

The new system consists of two main components: the designer panel which dynamically checks and reports the issues while the modeller adds or modifies geometry, and the rule definition panel where rules can be added or adapted to potential changes in this or other BIM standards. The main goal was to use the tool as a catalyser to enhance the organisational data checking process. Inherently, it was essential to engage the designers, to enable proactive design, and to achieve fitness for purpose by simplifying effective detection and correction of non-compliant issues with the specified standard.

The new checking process was verified and validated with specialists and modelers in three ongoing projects. This research showed that the developed design-integrated tool can produce the perceivable benefits in the organisational data checking process explained below:

- <u>Enhancements in data quality before and after regular organisational checking reviews.</u> The new data quality checking and reporting tool was perceived to help produce higher data quality models before and after regular organisational reviews.
- <u>Decrease in the duration and iterations in the organisational reviews.</u> The higher data quality of the model before entering the organisational process, led to shorter reviews by the specialists as there were less issues to identify and communicate to the modelers.
- <u>Increase of effectiveness and efficiency in detection and correction of data quality issues.</u> A significant number of quality issues in basic data structures were identified and approached directly by the modeler within their design environment. Otherwise, those issues would have had to be detected and communicated by the specialist and identified and reviewed by the modeler.
- <u>Decrease of personnel frustration in the organisational process.</u> Specialists found that the repetitive process and the obstacles to communicate and specify issues to modelers was sometimes frustrating. As a result of the previous benefits, specialists expressed their contentment with the new tool and the enhancements in the process.

Conclusion

The research fulfilled the main objective to produce perceivable benefits in the organisational data checking process by developing and implementing a dedicated solution that engages designers in the process. The role-specific approach was essential to achieve a solution that meets the specific needs and system requirements of the target group, the designers. The purpose was to add a new prechecking layer to support and enhance existing data quality practices and processes. The result was a steering instrument for modelers working on the detailed design phase to involve them in identifying and correcting data quality issues.

Although a few of the perceived benefits may vary in different contexts and organisations, the new data checking and reporting solution would serve to raise awareness and promote designers' engagement in the organisational data checking process, who are in a dominant position to identify and correct data quality issues. Thus, the new tool was an effective and helpful instrument to achieve successfully perceivable benefits by the practitioners in the organisational process.

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List of abbreviations

AECOO: Architecture, Engineering, Construction, Owner and Operator.

ARC: Automated Rule Checking

BCF: BIM Collaboration Format

BEP: Building Execution Plan

BIM: Building Information Modelling

CAD: Computer-Aided Design and Drafting

CDE: Common Data Environment

EIR: Employers Information Requirement

LOD: Level of Detail

KPIs: Key Performance Indicators

MEP: Mechanical, Electrical and Plumbing

MVP: Minimum Viable Product

1.Introduction

This chapter begins with the context of the research by first introducing the benefits and stages in the transition to BIM. Secondly, critical aspects in BIM quality are analysed and the context of the organisation collaborating in this research is described. Next, a brief literature review supports the problem definition and the development gap. Consequently, the development objective and research questions are determined. Finally, the scope is defined, and the methodology describes how the development process of this research will be.

1.1.Research context

1.1.1.Transition to BIM

The construction industry has been recognized as one of the least digitalized economic sectors. However, the industry is making significant progress with the adoption of BIM which substantially increases productivity. (Mesároš et al., 2020)

BIM can bring benefits to designers with a collaborative and more efficient working environment, to construction companies with an effective synchronisation of design, construction and procurement processes, to maintenance and operation companies with a data rich environment to monitor and maintain buildings more accurately and effectively (Sacks et al., 2018). In Figure 1, a comparison of information exchange with and without BIM is explained. Therefore, advantages are not specific to a role or phase in the industry but rather industry wide and applicable to different lifecycle phases.

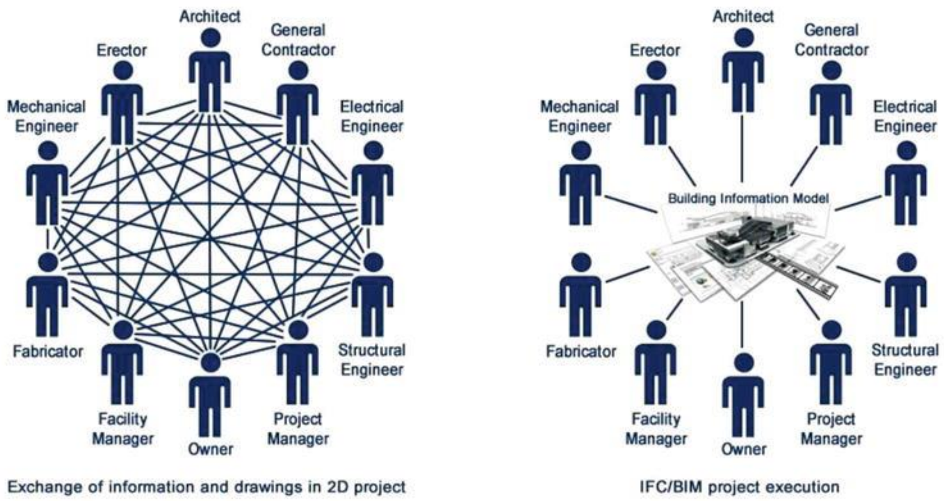

Figure 1: Comparison exchange of information 2D and BIM (Daniotti et al., 2022)

In practice, the potential benefits are constraint to the stage of BIM capability of the organisations involved. According to Succar et al., 2012, three levels of capability can be distinguished:

- Stage 1: Organisations capable of object-based modelling.
- Stage 2: Organisations capable of engaging in multidisciplinary model based collaborative projects.
- Stage 3: Organisations capable of using network-based solutions linking to external databases.

One of the crucial aspects of BIM is the data rich environment connecting project information from different sub-sectors. (Mesároš et al., 2020). Therefore, developing models with consistent and trustworthy building data has gained significant importance in the industry. In contrast, incorrect or incomplete building data in a model could result in chained mistakes across disciplines, rework, or inadequate models for other stages of the building lifecycle.

1.1.2.BIM quality

Generally, “Product quality refers to how well a product satisfies customer needs, serves its purpose and meets industry standards.” (Indeed editorial team, 2021). However, 2D CAD designs needed mostly graphical control before being delivered. With the introduction of BIM, the quality of a model is not only measured in terms of geometry but also in terms of non-graphical contents such as objects´ data (Volarik et al., 2022). According to Choi et al., 2020, BIM quality requirements can be broken down into three subcategories:

- Physical information quality as adequacy to model shape requirements including minimum requirements for geometries, model point of origin and clash detection.
- Logical information quality as adequacy to requirements based on regulations.
- Data quality as adequacy to requirements for model data including checking properties of input data and checking space program.

Nonetheless, how requirements are developed and implemented in a project have a project specific component as a consequence of the Building Execution Plan (BEP) adopted, the nature of the project and the selected BIM standard. A BEP, as a framework for the implementation of BIM in a project, specifies the Level of Detail (LOD) and therefore the Level of Information and the Level of Geometry of the project. Figure 2 explains the level of detail and information in regard to the building lifecycle phase. Thus, a lower LOD in a project does not mean lower quality in a model.

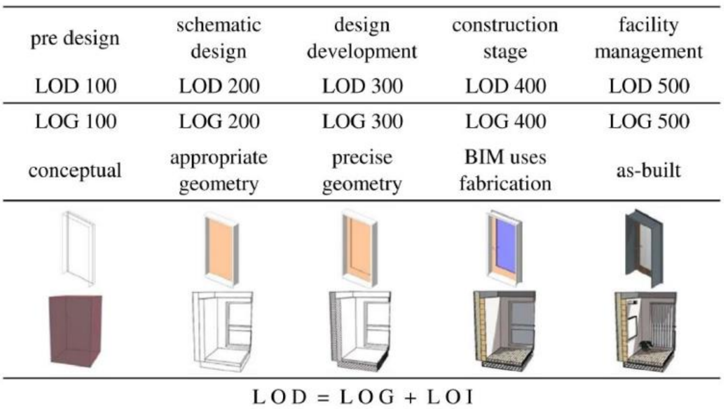

Figure 2: Levels of Detail (Volarik et al., 2022)

Additionally, understanding the development process of BIM models is essential for BIM quality control. In the schematic design phase, project information is still uncertain and therefore models are incomplete, generic and with limited well defined non-graphical information. As a design moves to the detailed phase, the LOD increases. Objects are defined as specific systems as well as geometry and data components become more accurate (van der Zwaag, 2022). As more detailed information and geometry become available, more precise quality checks can be carried out.

1.1.3.Organisational perspective

This graduation project is carried out in collaboration with the company Hercuton at their branch in Nieuwkuijk, the Netherlands. Hercuton is a turnkey contractor employed to plan, design, build and maintain industrial projects. The company is characterised for its practical approach to construction with prefabricated modular building elements.

The design team in this branch consist of:

- The engineering team with structural analysts and MEP professionals.
- The modelling team with BIM modelers, architects and a group of BIM managers and experts who oversee projects and develop BIM standard content and solutions used across the company.

Currently, the modelling team was discontent with the data checking process. According to the BIM lead at Hercuton, “There is a gap between roles in the current data checking process as BIM managers know data requirements and modelers should execute them. This gap often generates frustration and discontent.” Thus, the professionals involved found it inefficient, ineffective and in some cases frustrating. Frustration seems to come because of the simplicity and repetitive nature of the process. As a project progresses, addition and modification of objects take place. Therefore, the same or similar issues discussed for previous objects can be detected again for new objects of the same nature. Simple, repetitive, and limited in the handling of tools tasks can end up in a consequent feeling of discontent and draining interest and energy in the workplace. (Prasanna et al. 2008)

Another factor to consider is that some members of the modelling team were found under time pressure to deliver projects. According to Moore & Tenney, 2012, “Time pressure increases speed at the expense of quality”. This could ultimately lead to lower quality models and/or models non-compliant with requirements.

It is important to underline that the topic of this research was initially proposed by Hercuton. During all phases of this research, the modelling team has been involved through recurrent reviews, meetings and discussions. In the company, only a few specialists have the expertise to use advanced data checking solutions, in this case Solibri. Previous attempts to introduce the software to less experienced professionals have been unsuccessful. The company recognised the high complexity of the tool. According to BIM specialists at Hercuton, “Available data checking tools are way too complex for our designers. We need simple and dedicated solutions to guide our designers during the modeling process.” The aim is to research and develop a new fit-for-purpose tool based on their specific needs. BIM leaders and experts at the company strongly believe that new simplified and dedicated data checking and reporting tools could shorten the iterative BIM data exchange process. The higher goal is to achieve perceivable benefits in the organisational data checking process.

Finally, references to discussions and preliminary interviews with professionals at Hercuton are made throughout this document. Further details about how the information was obtained and the roles involved, are provided in *Appendix A: Information from industry professionals.*

1.2.The problem

1.2.1.The problem statement

Buildings are designed by groups of modelers and engineers from different backgrounds (e.g. architecture, structural and mechanical engineering). While projects are being developed, specialists are very frequently involved in monitoring the progress. One of their responsibilities is to ensure that designs comply, among other aspects, with regulatory or standard requirements in their field of expertise.

The specialisation of the industry and the increasing number of project participants have resulted in numerous iterative BIM data exchange processes. (Lee, Solihin and Eastman, 2019). In the discipline of BIM data, after the specialists review a project, corrections are communicated to designers to improve their models. This process is repeated until the desired quality and/or adequacy to requirements is reached by the design team.

The current organisational data checking process is not ideal. Designing and checking are independent workflows carried out by different stakeholders. In practice, this distinction imposes a burden on designers as they must fix the fail-to-pass issues iteratively. (Sobhkhiz et al., 2021). Consequentially, several drawbacks could follow:

- Decrease in designers' productivity given the continuous interruptions in their work.
- Increase in project delivery time given the number of iterations taking place.
- Frustration and discontent of designers and specialists from repetitive process, miscommunications or misunderstandings.
- Lower quality models and/or models non-compliant with requirements in highly time constraint projects. This could lead to chained mistakes across disciplines and, subsequently, to models that are limited in use in later stages of the building lifecycle.

In contrast, given the variety of lifecycle phases and the cooperation of different disciplines, the industry relies on diverse data accessed by different project stakeholders. Thus, consistent BIM data is a cornerstone for different building analysis and tasks (e.g. sustainability, maintainability and structural analysis) (Lilis et al., 2018, Gomes et al., 2022). However, BIM terms, standards and definitions are continuously evolving and will keep changing in the future. Nonetheless, common reference points should be established to simplify and anchor our approach. (Jensen & Gade, 2022).

In the Netherlands, it is extended that BIM standardisation is a slow, difficult, and not a very exciting process. (van Nederveen et al., 2010). From preliminary interviews at Hercuton, BIM standardisation has usually been the responsibility of BIM managers and experts while most modelers have limited knowledge on how to implement standards in projects (see *Appendix A: Information from industry professionals*). The required level of expertise to implement and monitor BIM standardization is slowing down a wider industry adoption.

In practice, wrongly defined or missing basic data structure could often lead to incomplete or inaccurate data checking processes. According to the BIM lead at Hercuton, "Well defined basic data structures are essential for the checking process. For example, if objects are not correctly identified as types or names, rule checks could be missed for certain objects or applied to the wrong set of objects." For instance, a data check could be if a door object contains certain standard data. However, if several door objects are not defined as such, the check is simply not run on them. In contrast, if a wall object is defined as door, the previous check could raise a false positive issue. Establishing a reliable basic data structure is essential not only to ensure accurate data checking processes but, most importantly, to enable data driven approaches in the building industry.

Data driven approaches can have a significant positive impact in the industry at various levels and fields by allowing smart and informed decisions. (van der Zwaag, 2022) It is about having facts and metrics that, for instance, guide business decisions to align with higher goals, or steer professionals to produce optimised and more sustainable designs. (Sacks et al., 2018)

Thus, in literature (Hjelseth et al. 2016, Sacks et al., 2018, Jensen & Gade, 2022) and in preliminary interviews to professionals (see *Appendix A: Information from industry professionals*), it was found that there is a need of new developments to meet the demands of professionals in the field of BIM data quality.

1.2.2.The development gap

According to literature, model quality significantly relies on the modelling phases and design quality could be improved when quality control requirements are actively utilized. (Volarik et al., 2022; Choi et al., 2020). Additionally, Choi et al., 2020 developed a rule-based quality checking system using requirements for efficient quality control such as the absence of component types in the BIM data or clash checks in geometries. Although the research was not design-integrated, he identified that continuous checks in the design phase should be carried out for adequate quality control. Thus, there was detected improvements in quality by following a step-by-step approach with respect to the detailed checking of results. Nonetheless, existing model quality checking tools such as Solibri or Autodesk Model Checker diverge. Instead, they have been designed as an external corrective process to run at specific points in time and not as a dynamic and design-integrated steering tool to guide modelers. Furthermore, additional research was suggested, by Jensen F. and Gade P. 2022, in terms of how software solutions could adapt and connect to current BIM standards to facilitate standardized data validation workflows and fulfill the needs of professionals in the industry.

The transition to automated rule checking is critical if the quality assumptions of BIM are to be realized. (Sacks et al., 2018). Thus, there are opportunities to provide flexible tools that enable BIM standards and building classification systems to simplify the approach to data validation in the construction industry. (Jensen F. and Gade P. 2022) Rule-based systems have brought flexibility to existing tools but also led to high complex systems difficult to set it up. This has taken model data checking to a specialization area. Therefore, the responsibility of data quality in models fully falls on BIM managers or BIM data specialists who are effectively not designing but instead reviewing the project. This makes the current assessing and correcting processes of data in BIM models ineffective and prompted to misunderstandings. Therefore, an additional design-integrated prechecking layer could make this process more efficient and less subject to error.

After reviewing existing literature in the topic and carrying out preliminary interviews with professionals, the following aspects are extracted:

- BIM data checking has been researched and brought to practice as a post-design corrective process. However, quality control should be approached earlier in projects to potentially reduce errors in basic data structures, chained mistakes across disciplines or rework.
- There is a demand for data checking tools to guide modelers and facilitate the implementation of standards during the design process instead of depending fully on evaluations at specific milestones in the design phase.

- Although BIM quality control has been widely researched before, the approach was on using external checking software solutions. The great majority of the available tools have not had a design-integrated approach that enables modelers to review and work on data quality flaws while modelling. On the other hand, the very few isolated tools focused on the design phase (e.g. Acca software) are full standalone modelling solutions with very limited adoption in the industry compared to the most common modelling solutions. These data checking solutions do not meet the business needs of most professionals who are currently designing with Autodesk Revit.
- The responsibility should partly switch from BIM managers and data specialists to modelers who are in a dominant position to tackle data quality issues effectively while models are being developed.

1.3.The development objective

The higher goal is to enhance the organisational data checking process. This is approached by facilitating the implementation of BIM standards and increasing the compliance of objects during design periods before entering the organisational reviews. From preliminary interviews to professionals (see Appendix A: Information from industry professionals), they would prefer to gain access to simple dedicated quality checkers that could minimise or replace manual tasks precisely and reliably instead of advanced software solutions. Thus, the objective is not to replace current tools and practices, but instead to support them by adding a new dedicated checking and reporting tool to design workflows.

Thus, the new design-integrated solution will be developed enabling BIM modelers to work on the compliance of objects in the model against a set of parameter-based rules. Given the limited time for this research, the purpose is to develop a Minimum Viable Product (MVP) to check a selection of strategic standard rules. The new tool will allow modelers to detect, review and work on non-compliant objects during the design phase. The purpose is to engage designers in the implementation of BIM standards and in the organisational data checking process.

There could be significant benefits in engaging designers in such processes:

- The organisational data checking workflow could reduce the number of iterations and repetitive issues to be corrected. Consequently, this could lead to earlier project delivery, less project cost, reduction in project time pressure and less frustration among professionals.
- In highly time constraint projects, it could improve model quality and/or compliance with requirements that otherwise could be compromised.
- Increase designers´ productivity by reducing the number of interruptions in their work.

1.4.Research questions

The main research question is:

How can novel design-integrated tools improve the data quality checking process in organisations?

Subsequently, this research is guided and structured by four sub questions:

What are the main challenges to improve data quality and compliance with BIM standards?

How can new tools engage and be integrated fluidly in the designer´s and organisational workflows?

To what extent does the developed BIM model checking tool engage designers?

To what extent does the developed BIM model checking tool improve the data quality checking process?

1.5.Scope

Data quality in BIM models could be a multidisciplinary, wide and extensive topic. Therefore, considering the time given for this research, defining a precise scope is essential to focus on specific knowledge in the domain and achieve accurate results. Below, the scope is defined and justified:

Organisational workflows: The validation and verification of the tool is carried out within the company Hercuton from JAJO. Despite the company works using common data assessment processes, it is important to underline that the results of this phase of the research are influenced by their organisational structure and work processes. This will be approached in detail in later sections of this document.

Case studies: The case studies selected are three ongoing projects in their detailed design phase carried out by Hercuton in the Netherlands. Two of them are industrial and the other is commercial. In the selected projects, Hercuton is responsible for the design and coordination of the BIM models at all levels.

Lifecycle phase: Model quality significantly relies on the modelling phases and design quality could be improved when quality control requirements are actively utilized. (Volarik et al., 2022; Choi et al., 2020). Given the uncertainties in project information in early design phases, BIM data may be incomplete or inaccurate at that stage. Furthermore, it is not feasible to evaluate BIM data quality in the pre-design or conceptual phase because the model is still represented in a conceptual manner. Therefore, this research is focused on the detailed design phase in which the level of detail and information in projects increases.

BIM quality: This research is focused on the models´ data quality. Specifically, data quality is approached as the level of compliance to the specified BIM standard. The reason is to facilitate the implementation of standards and reduce project specific factors that could limit the extrapolation of the strategy to other projects in the industry.

BIM standard: The selected BIM standard for this research is the BIM Basis ILS given that it is the most widely supported BIM standard in the Netherlands (Groot, 2022) and the one that the largest Dutch contractors are implementing. This will increase the potential impact of this research. Furthermore, a justified selection of the main chapters to apply from the BIM Basis ILS has been made and explained in later sections of this document.

Software: Revit was chosen as a host software for the new data checking tool developed in this research. Autodesk Revit is estimated to be the market leader with a significant difference to its closest competitors. (Pryer, 2020) Therefore, integrating the new tool in an existing and functional design solution reduces implementation difficulties as professionals are already working within that environment. Furthermore, the wide adoption of this software compared to the competition presents an opportunity to impact the design process at scale.

Target objects: The target elements of this research are those modelled in the project. Families and types not used, meaning that there is not a single object modeled of that type or family, are not examined. The reason is because the focus is on delivering IFC models as the most common and supported openBIM data exchange format (Honti, 2018) which does not includes non-modelled families or types. Specifically, the target objects are those modelled and included in the IFC model and the selected chapters from the BIM Basis ILS.

End-user of the data checking tool: For this research, the tool is targeting designers as the main user with the aim of making them responsible for data quality in models as they are in a dominant position to take effective actions. Nonetheless, BIM managers and data specialists may also be involved in later applications defining and/or updating BIM standard rules in the tool. To achieve a long-term solution that could be implemented widely and have impact in the industry, the tool must also be flexible enough to accommodate addition and edition of rules in the future.

1.6.Methodology

In this section, the process has been broken down into four phases; analysis, synthesis and development, implementation and assessment and conclusion. The structure is in line with the Delft approach for product development (M. & Eekels, 1996). The first three phases of the process are focused on answering different sub questions and, in the conclusion phase, the results are brought together and reflected upon.

1.6.1.Analysis phase

This phase starts with a literature review in which the state of the art in BIM data quality control, BIM standards and its adoption is documented. The purpose is to get a deeper understanding of the theoretical background of existing data quality checking tools as well as explore other relevant research approaches to the adoption of BIM standards.

On the other hand, a preliminary study is carried out about how the previous knowledge is taken to practice in the industry. The approach is reviewed from the microlevel, data schemas and tools, to the macrolevel, focusing on organisational workflows. Additionally, the needs of professionals are explored.

The main goal is to answer the first research sub-question "*What are the main challenges to improve data quality and compliance with BIM standards?"* as well as to achieve specific user needs and system requirements used in later phases of this research.

1.6.2.Synthesis and development

In this phase, the previous needs and requirements are synthesized and translated into the concept, functionality, and features of the new tool. After, a selection of chapters from the BIM Basis ILS is made to apply to this research. Then, the development of the tool takes place. This process could be broken down into two sub processes.

- The development of a flexible rule-based system which defines BIM standard rules and could accommodate future updates of the standard.

- The visualization of the results against the specified set of rules as a system for designers to identify and work on the data quality issues.

Additionally, strategic feedback sessions with BIM modelers and managers take place. The purpose of these sessions is to involve the end-users in the development of the solution to integrate the tool in their workflows and meet their specific needs. Thus, the higher goal of this phase is to develop the new tool and answer the second research question *"How can new tools engage and be integrated fluidly in the designer´s and organisational workflows?"*

1.6.3.Implementation and assessment

The *implementation and assessment* phase begins with the definition of implementation details such as an introduction of the projects to conduct the assessment or the custom mapping of parameters at Hercuton.

Next, evaluation is divided into verification and validation following the concepts introduced by Peffers et al., 2007. On one hand, verification approaches that the tool is functional and operational to fit its purpose through testing in a selection of strategic design processes. On the other hand, validation tackles a more extensive and comprehensive process. In this part, a four-step method for evaluation of design science research is applied from Venable et al., 2012. The goal is to find answers for the two sub questions of this phase:

To what extent does the developed BIM model checking tool engage designers?

To what extent does the developed BIM model checking tool improve the data quality checking process?

Given the dedicated approach of the tool, designers are the main role in this research. Thereby, their engagement is crucial in this evaluation to achieve benefits in the organisational process. In this part, the tool is assessed against the user needs and system requirements found in the *Analysis* phase.

Then, focusing on the implementation of the new tool in the organisational data checking process, the extent of the benefits needs to be evaluated. This is assessed qualitatively by how those benefits are perceived by key practitioners in comparison with previous data checking processes. This is the higher goal of the validation process.

The selection of methods for validation has been based on the framework of Venable et al., 2012. The approach is to conduct surveys and discussions at strategic points in the implementation to the designers and BIM specialists involved.

1.6.4.Conclusion

During this stage, the results from the previous phases are summarised. The main target is to find answers to the main research question, *"How can novel design-integrated tools improve the data quality checking process in organisations?".*

Finally, recommendations for future research in the topic are given and a final reflection over the research is carried out.

2.Analysis

The analysis phase is the first phase of the research. This chapter starts with a brief literature study reviewing the theoretical framework behind BIM data quality control as well as the state of the art of BIM standards. Next, how those concepts are applied in practice is analysed.

The chapter primary goal is to answer the sub-question:

“What are the main challenges to improve data quality and compliance with BIM standards?”

Additionally, considerations on software engagement and perception are briefly introduced to analyse applicable challenges in the field. Then, user needs and system requirements are translated from challenges found in previous sections. This part concludes the analysis phase and establish the theoretical basis for the second sub-question:

“How can new tools engage and be integrated fluidly in the designer´s and organisational workflows?

2.1.Theoretical framework

This section first focuses on BIM data quality control and the theory behind it. Understanding the underlying concepts in the current tools and processes is essential to detect challenges and potential improvements to develop in coming phases. Secondly, the benefits of implementing BIM standards are introduced as well as a closer view to BIM standards in the Netherlands and obstacles found in their adoption.

The purpose is to get a deeper understanding of potential challenges in their theoretical context as well as to explore other relevant research approaches regarding BIM quality control, BIM standards and software engagement.

2.1.1.BIM data quality control

According to Eastman in McGraw-Hill Construction (2012), BIM model checking is the most important requirement to effectively advance the industry, followed by interoperability. BIM models are human created which inevitably leads to missing information or errors non-compliant with the BEP and the established BIM standards. However, model quality reviews are growingly automated because eliminating manual processes is potentially error-free and saves time. Automated reviews are understandably superior to manual checks. (Sacks et al., 2018)

Despite of being inefficient and subject to error, manual model checking forces a series of several checks (Sacks et al., 2018) that with automated means could be taken for granted. The manual process could certainly increase trust and reduce uncertainties in the working tools and end model. Risks and uncertainties were identified by Hou & Jansen, 2022 as a key factor for end-user software trust. Gaining end-user trust is essential to achieve engagement and fitness for purpose in this research.

Furthermore, Lilis et al., 2018 classified BIM data quality checking in three main categories:

- Data consistency: Ensuring that data is compatible with the selected data schema or adopted BIM standard.
- Data completeness: Verifying the existence of the required data across the model.
- Data correctness: Detecting possible errors made when entering the data.

The three categories to check data quality are approached differently in the available applications in the market. Data consistency is the least challenging category to be applied in automated data checks. Formats, data structure or naming conventions could be checked across models with very few technical limitations. On the other hand, data completeness checks are often project and context dependent which may present certain limitations for automated approaches. Frequently, the presence of data is based on varying information requirements. For instance, fire rating requirements are not the same for public buildings than for industrial buildings. Similarly, data correctness is based on its context and meaning. For example, if a door should be two meters or one meter wide depends on the relative position of the door (e.g. main entrance or bathroom) as well as project specific attributes (e.g. hospital or private house). Thus, certain data correctness checks are challenging to be translated into machine readable formats.

Thus, two types of data quality control applications have been distinguished in this research; rule-based applications and issue managers. Both types enable object-based reporting using automated or manual means.

2.1.1.1.Rule-based applications

Automated Rule Checking (ARC) is about capturing and checking a set of rules against a model or design automatically. (Sobhkhiz et al., 2021) Sacks et al., 2018 identified that effective rule checking enables the application of rules to easily represent and reference the parts of the model being checked and all the failing conditions. Rule-based applications apply data quality control in an automated way. The transition to automated rule checking is critical if the quality assumptions of BIM are to be realized. (Sacks et al., 2018)

According to Eastman et al., 2009, ARC consist of several or all of the following phases;

- Rule interpretation and logical structuring of rules: Building design rules and standards are represented in human language such as written text or tables. An extended language for mapping rules to machine readable forms is first ordered predicate logic. This consist of well-defined functions that could be assessed as true or false (or undefined, if data is not specified). They also tackle quantification in terms of whether a function should be checked in one or all instances. (Eastman et al., 2009) Depending on the accuracy and nature of the rules, a deeper level of specification or a more general approach in rules may be required. On the other hand, the development of sets of rules was found a main obstacle for wider industry adoption. The process was defined as complex and time consuming by several authors in literature. (Hjelseth, 2015, Jensen & Gade, 2022). This could ultimately lead to less accurate or incomplete sets of rules.
- Building model preparation: Architects and other professionals designing BIM models, in which rule checking will be carried out, must prepare them as they should provide the necessary information in well-defined data structures.
- Rule execution: During this period, the prepared BIM model is analysed against the applicable rules.
- Rule reporting: Lastly, rule checking tools report the results. In order to understand the completeness of the check, object satisfying with the defined rules need to be included in the report. For a single BIM model, a specific rule may apply to thousands of objects within an object category or type. Those results need to be broken down into identifiable objects. (Eastman et al., 2009) How results are presented, organised and filtered is essential to increase the understandability of the end-user.

In addition to the phases proposed by Eastman et al., 2009, a correction phase should be lastly considered in the workflow. In this stage, the results are interpreted and approached by the responsible professional/s. The goal is to effectively improve model compliance with the set of rules.

Examples of applications of this type are Solibri and Autodesk Model Checker. In both cases, data consistency could be checked in models against a set of predefined rules. Nonetheless, there are context-based limitations in the checking of data completeness and correctness as they may vary on a project specific basis. On the other hand, the specified rules could be added or edited bringing flexibility to the system to adapt to updates in the BIM standards or switch to different standards.

One challenge identified in ARC applications is the intrinsic complexity of set of rules. Given the large number of available BIM standards worldwide (Cheng & Lu, 2015) combined with the possible conditional checks needed to be applied, defining rules is complex and demanding (Lee, Solihin and Eastman, 2019). As there is not an established way of creating BIM standards and codes, an additional level of difficulty is added to translate them effectively to specific rules in machine readable formats. (Jensen & Gade, 2022). In contrast, it is essential to have a method which is effective in translating and distributing rules. (Amor and Dimyadi, 2021). Simplifying this process is key for BIM standard adoption in the industry.

2.1.1.2.Issue managers

Issue manager applications enable issue detection, exploration, and communication among professionals. (Svetel et al., 2020) Some rule-based applications such as Solibri has expanded into issue managers enabling communication and reporting between different project stakeholders.

Solutions include but are not limited to Revizto and BIMcollab (Ham & Yuh, 2023). Even though some of them enable searching for geometry or data using limited rules, the focus of issue managers is on manually creating and communicating issues across teams. This has proved to significantly reduced response time between project stakeholders (Erazo et al., 2020). However, they have not been designed to facilitate the implementation of BIM standards.

Data consistency checks are not possible as the conditions available in rules are limited. It is not possible to detect if data is structured as specified in the standard, such as NL/SfB (e.g. XX.XX), or the format of parameters such as it is boolean, text or number as defined in the BIM Basis ILS (BIMLoket, 2020). On the other hand, data completeness and correctness are manually verifiable within the specified software.

2.1.2.BIM standards

The architecture, engineering, construction, owner and operator (AECOO) industry relies on large amounts of architectural and technical information as a result of the cooperation of many disciplines in distinct design stages for different lifecycle purposes. How information has been brought to practice coherently and consistently has been widely researched and requirements for quality control and ISO standards has been included into BIM guidelines of countries such as Finland, USA, Spain or United Kingdom (Ibrahim & Al-Kazzaz, 2021; Pérez-García et al., 2021 ; Choi et al., 2020). In the Netherlands, there is no compulsory BIM protocol and parties are free to choose and implement any BIM standard. (CMS, 2017).

According to Jensen & Gade, 2022, BIM standards are developed by the international, national and regional organisations but also by businesses for their internal use:

- International BIM Standards are high level standards resulting from the collaboration of several relevant bodies. The main international organisations are International Organization for Standardization and buildingSMART.
- National BIM Standards are developed by governments and/or private initiatives. Additionally, many countries such as the Netherlands, United States or France have made compulsory or set thresholds for the use of national BIM standards in public projects.

By standardizing responsibilities, processes and procedures, companies encourage reliability and consistency of BIM processes and accelerate organisational learning. (Siebelink et al., 2020) Additionally, the use of standard object libraries could ease the design process in BIM models. Furthermore, BIM standards and classification systems establish a consensus on how to carry out a task enabling unambiguous information exchange and promoting better communication between project stakeholders. (Jensen & Gade, 2022) Thus, BIM standards ensure that professionals are working with the same level of detail and consistency, reducing the risk of errors and conflicts. Moreover, BIM standards promote that professionals could easily access relevant information and make informed decisions across projects, leading to reduced delays and improved effectiveness and efficiency.

However, international BIM standardization is a complex process involving many organisations and institutions. Links must be established between ISO, technical committees, geospatial and industrial entities as well as with buildingSmart. (Poljanšek, 2017) In the Netherlands, it is extended that BIM standardization is a slow, difficult, and not a very exciting process. (van Nederveen et al., 2010). Although many standards are already in use for several disciplines, the maturity and fragmentation of standards is called as a point of needed attention. (Siebelink et al., 2020) Siebelink also underlined as a priority the further development and adoption of standards across different subsectors. Therefore, an overarching simplified approach to standards is essential to facilitate wide industry adoption.

2.1.2.1.BIM standards in the Netherlands

BIM Loket, as virtual reference desk for open BIM standards in Netherlands (BIM Loket, 2016) describes several BIM norms and guidelines as industry reference. The goal of these standards is to promote that BIM information that is exchangeable, structured, unambiguous, correct, complete and reusable:

- NL/SfB is a classification system of building and installation elements. From 1980, with the introduction of CAD drawings, it served as the guidelines for organising layers in 2D CAD drawings. NL/SfB is considered the most used classification system for building components in the Netherlands (BIMLoket, 2023). BIM objects are classified using a four-digit standard code based on its function and type. The first 2 digits refer to the category of the object (e.g. mechanical facilities or finishes). The second 2 digits specified in more detail the type of the component and system (e.g. intrusion security system and electromagnetic facilities or exterior wall finishes).
- IFC by buildingSmart is an open and international standard which promotes a vendor neutral data model schema. The schema aims at encoding and standarising objects such as walls, processes such as operations, agents such as architects or suppliers, attributes such as material, identity and semantics such as name or type, relationships such as project location and abstract concepts such as costing. (buildingSMART, 2019). IFC2x3

TC1 is the most widely used version followed by IFC4. As they have a similar structure, many applications are able to use both. (BIM Loket, 2020)

- ILS Ontwerp & Engineering is focused on what information is required, where this information should be found, who provides this information and when in the process this information should be present (BIM Loket, 2019). This standard combines NL/SfB, IFC by buildingSmart and DNR STB 2014 for phasing specification. Thus, it is much more extensive than the previous allowing to specify the phase in which a specific parameter for an object should be filled.

Finally, in the next section, the BIM standard to focus on this research, the BIM Basis ILS, is explained in detailed.

2.1.2.2.The BIM Basis ILS

The BIM Basis ILS is an initiative widely used in construction projects in the Netherlands and it was developed and published in 2016 (Time Graphics, 2016) by BIM Loket in collaboration with fourteen private companies according to professionals at Hercuton. Today, the adoption in the industry is significant, more than 490 companies are considered partners of the BIM Basis ILS.

The BIM Basis ILS consist of 4 main chapters (BIM Loket, 2020).

- Why we exchange information? The target is to define the purpose of the standard which creates an unambiguous exchange of information to use/reuse construction building data efficiently and effectively.
- How we exchange information? The purpose is to use IFC open data standard to exchange information throughout the entire construction life cycle. This ensure that information remains exchangeable in the future by having a vendor neutral solution.
- What we agree on to enable collaboration? This chapter specifies how the data structure of objects and files is configured, so that they remain exchangeable. Therefore, it defines the minimum conditions that each objects must meet. All specifications in this chapter apply to all objects in models.
- Which information is required in one of the aspect models? The purpose of this chapter is to define what information is to be provided. However, it is made clear that the information requirements defined are not relevant for all objects and that project teams should make a careful evaluation about which objects should contain certain information. Finally, each information requirement should be present in at least one of the objects.

Figure 3 and Figure 4 contain an overview of the sub sections included in chapter 3 and 4.

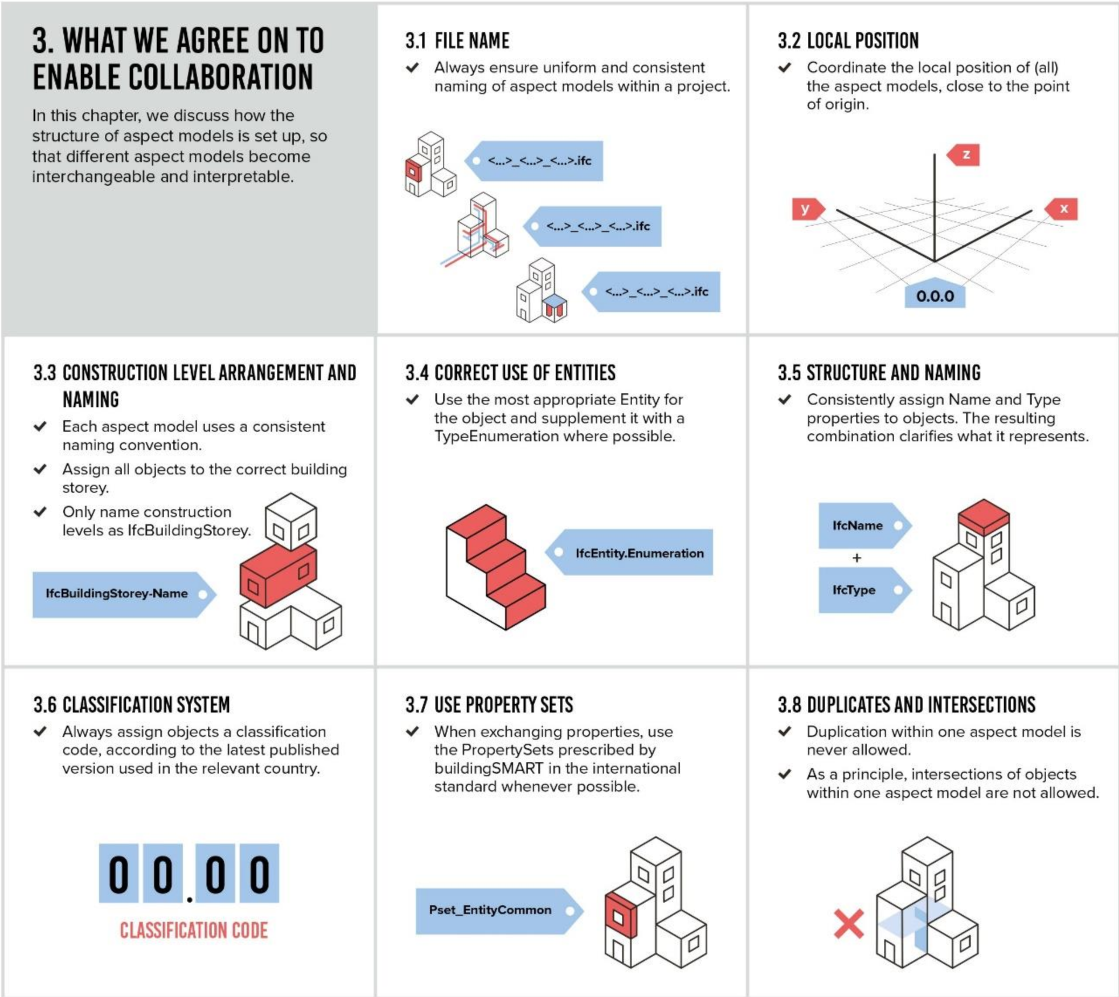

Figure 3: The BIM Basis ILS Chapter 3 (BIM Loket, 2020)

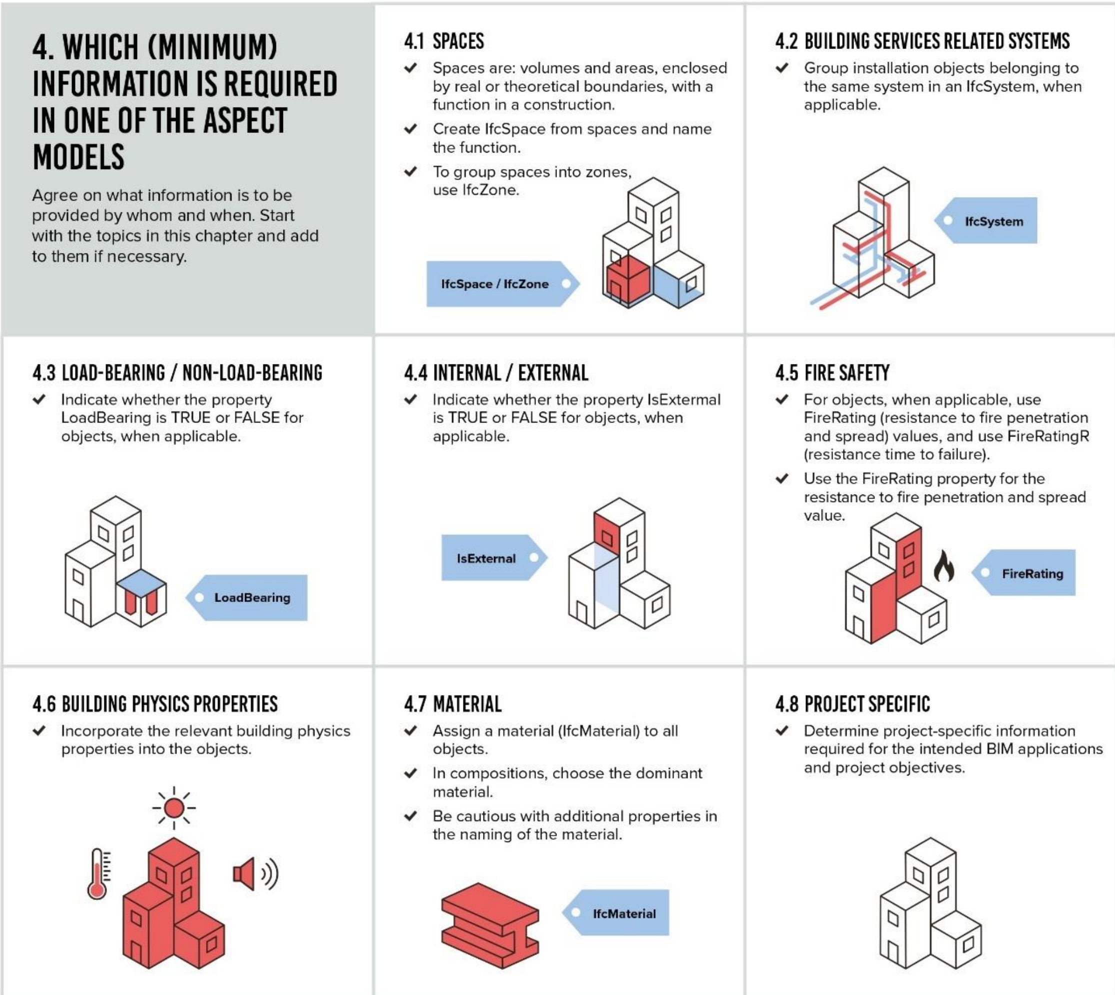

Figure 4: The BIM Basis ILS Chapter 4 (BIM Loket, 2020)

Therefore, the BIM Basis ILS combines several BIM standards such as NL/SfB or IFC by buildingSmart, how models are set up, which information is required and how it is structured. (buildingSMART, 2019). Furthermore, the BIM Basis ILS includes manuals on how to specify and check the delivery of information within different BIM software solutions such as Autodesk Revit, Archicad, VectorWorks and Solibri.

The approach of the BIM Basis ILs is to create a sector level, simple, flexible and easy-to-implement overarching standard. The number of specified rules is kept to the minimum which helps in reducing the level of expertise or knowledge about the standard in order to reach a wider adoption in the industry. Nonetheless, it is important to underline that this standard does not include a standarised manner to work and communicate information requirements by project phasing or by responsible project stakeholder. “The BIM basic ILS alone is not sufficient to achieve all project objectives”. (BIM Loket, 2020). However, it is a positive first step to work with information that is exchangeable, structured and reusable.

Furthermore, according to the BIM studies of Arroyo Ohori et al., 2018 in the Netherlands, it is not realistic to aim at developing a robust process for all IFC geometry types while in practice many of them are rarely used. In their experiments, they develop a solution for only a subset of the IFC standard to simplify the IFC standard. In that line, the BIM Basis ILS could be an impactful alternative to take the industry to the next step in the adoption of BIM standards.

2.2.1.Adoption of BIM standards

Generally, BIM standards have not reached full adoption in most countries. Despite design standards and planning measures are essential for the implementation and delivery of BIM, many countries, the Netherlands included, still fail to offer stakeholders project planning measures such as contracts like Employers Information Requirement (EIR) and BEP documentation, for implementations. (Ganah and Lea, 2021). This represents a challenge to achieve effective implementation of standards in the industry.

BIM guidelines differ when assigning responsibilities (Sacks et al., 2016). The study noted that some opt for a technology center adoption focusing mainly on clash detection, others implement a more construction centered approach considering the purpose as part of the building design. Thus, organisations usually agree on BIM standards per project. (Jensen & Gade, 2022) The previous research introduced that project requirements are adapted to the project specific scopes and services. Although many standards are compatible or similar, this could lead to confusion and mistakes when applying BIM standards.

On the other hand, BIM Standards establish BIM data structure and exchange methods. According to Succar, 2009, a significant portion of AEC companies would benefit from a clear set of guidelines and standards that present a measurable and repeatable methodology at national and organisational level. Nevertheless, although some BIM standards define quality control requirements, overall there is a lack of detailed requirements for quality control. (Choi et al., 2020) Furthermore, there are certain limitations in the adoption of standards in quality control work practices such as the lack of modeling guidelines. (Sobhkhiz et al., 2021) Although IFC has made substantial improvements in data sharing and interoperability, the study noted that there is still a large variety of different IFC formats.

On the other hand, from the moment an IFC is exported, designers are disconnected and pushed away from their usual design environment. (Sobhkhiz et al., 2021) How this is integrated and the impact it has in organisational and designers´ workflows will be covered in a later section of this document. Nonetheless, it is important to underline that this creates a challenge bringing uncertainties in designers who, in many cases, do not have the expertise and knowledge of the IFC standard.

Additionally, given the large number of standards, classification codes and the inherent complexity of their rules (Jensen & Gade, 2022), a simplified and unified overarching approach should be effective to lower the level of expertise and reach wide industry adoption. This was noted in preliminary discussions with professionals at Hercuton, who pointed out that certain BIM standards such as ILS O&E in the Netherlands were too complex and specific to be applied to most of the industrial, residential, or commercial projects (see Appendix A: Information from industry professionals).

The full benefits of BIM standards would only be achieved if a standard is widely adopted. However, in the Netherlands, there is an extended feeling that BIM standardization is a slow, difficult, and not a very exciting process. (van Nederveen et al., 2010) This brings another challenge on the professional side and their inner motivations.

2.2.Application of BIM data quality control

In this chapter, the aim is to explore how the previous concepts are taken to practice. This section starts analysing from a microlevel, looking into the most common data schemas, to a macrolevel, decomposing organisational workflows. The purpose is to first get a deeper understanding of the data structures and specific tools in order to later analyze data correction workflows for designers and break down organisational processes.

First, the benefits and limitations of the most common data schemas are introduced. Then, the focus is on the fundamental relation between data structure and the exporting processes. Additionally, the challenges in existing BIM data quality control tools are analysed. Next, the analysis is about how those tools are integrated in company workflows and obstacles found at organisational level.

2.2.1.Data schemas

2.2.1.1.IFC

In practice, construction projects are usually carried out in a fragmented environment (Sobhkhiz et al., 2021) using a wide variety of software solutions for different purposes; architects and modelers use different software tools such as Autodesk Revit or ArchiCad, building data analysts use Solibri or BIMcollab, structural engineers use Tekla or SAP 2000, …

Generally, the IFC standard is accepted as the main BIM standard in the Netherlands. One of the main goals of IFC has been to enable interoperability between BIM software applications across different disciplines. Additionally, most of the previous research in BIM data quality control have been carried out in IFC (Sobhkhiz et al., 2021).

The most widely used version of IFC certification is IFC2x3 TC1 followed by IFC4. (BIM Loket, 2020). There are a significant number of software solutions that enable working with IFC. These tools have mainly been used by specialists to create an interoperable working environment in projects. However, the export to IFC is often not accurate as exporting tools could be incomplete with certain information from the model. (Lilis et al., 2018)

From preliminary interviews to professional (see *Appendix A: Information from industry professionals*), exporting to IFC from the modelling software (e.g. Autodesk Revit) is usually a time consuming process that requires a wide range of possible different configurations. This could lead to missing objects or unstructured data in exported IFCs.

For that reason, at Hercuton, a custom IFC exporter was developed to schedule the creation of IFC models out of working hours. Nonetheless, if an error is detected in an exported model, they would have to either wait for the time-consuming exporting process or schedule the creation of the file for that night. These interruptions and delays could ultimately have impact in the designers’ productivity and the delivery time of projects.

2.2.1.2.BCF

The BCF format was introduced by Solibri Inc, and Tekla Corp. in 2009 and later adopted as a standard by buildingSmart. BCF file format is usually light and effective to communicate issues. Common use cases for such issues include clash detection or information request in the design phase of a building. A BCF primarily defines views and components in a model, associated with descriptive information about the issue. (Wikipedia, 2023)

Most data checking tools and BIM modelling solutions are compatible with the BCF format. In many cases, BCF files are integrated in issue management workflows that enable not only communicating issues but also monitor and assign tasks in them.

2.2.1.3.Autodesk Revit

Autodesk Revit is estimated to be the most popular BIM modelling software in the world. In this research, Revit was chosen as a host software for the new data checking tool. There are several reasons for this selection:

- The wide adoption of this software means that the research could potentially benefit many BIM professionals and companies in the future from the new solution developed in this research.
- Autodesk offers high product integration for external plugins. Additionally, Autodesk Revit has a well-documented API for external developers to code their own integrated solutions in the software.
- Revit native objects include a significant amount of classification data when included in designs, such as category, family, or type, that could be lost in IFC exporting processes. Although this data could be wrongly filled or lacking in specific objects in Revit, adding a new checking layer in Revit could enhance data quality and the organisational reviewing process.

However, it is important to underline certain weaknesses:

- Autodesk Revit is a BIM solution categorised as Closed BIM. In contrast with Open BIM solutions, Closed BIM solutions are managed by a single vendor and mainly use proprietary formats for data exchange such as .rvt or .rfa (IFC is still an exporting option in the software). Additionally, as Open BIM solutions does not rely on a single developing agent but rather on developers and users spread in the industry, formats and files are future proof and even if specific firms go bankrupt or disappear file formats would still be in use and new tools and software would still be developed by the industry.

Additionally, how data is structured and organized in Revit is critical to create new effective and efficient checking methods. Four different levels of grouping objects´ in models have been identified (Catellier, 2022). Figure 5 explains the different object grouping levels in Revit with the example of a column.

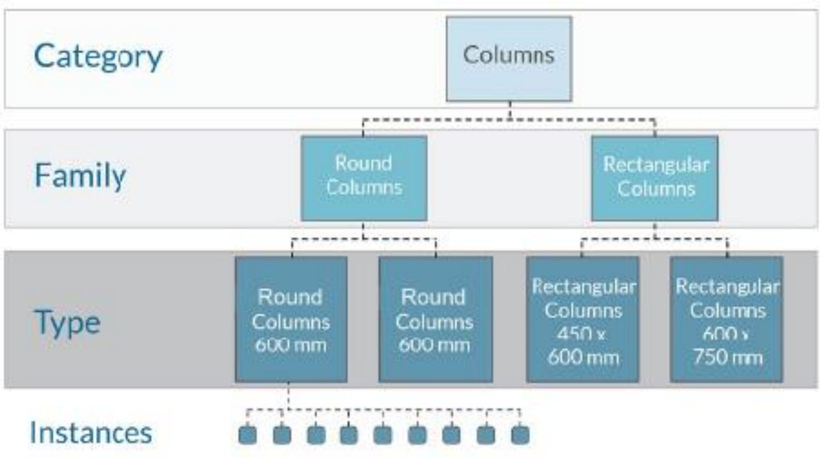

Figure 5: Different levels of grouping objects (Catellier, 2022)

In addition to the previous figure, a higher hierarchical level should be considered. This is the model level. This contains all categories of a model and, in this research, is of relevance given that several of the rules of the BIM Basis ILS apply to all the objects modelled.

In Revit, several key features should be underlined regarding objects´ data or parameters:

- Parameters can be created in objects at different levels; the model level, at the category level or at the type level.
- Parameters can be classified as type or instance. A type parameter has a shared value for all instances of that type. In contrast, an instance parameter can have different values per instance.
- Parameter values can follow different data formats such as text, number, angle, time or material which is critical for designer to input information properly.

According to professionals at Hercuton, the majority of parameters used in companies are:

- Shared parameters given the extended possibility to apply them across families and projects.
- Family parameters as they can be predefined in family libraries at the company level. (Barbini et al., 2019)

2.2.2.Data definition and export workflows

The relation between exporting processes to IFC and the data structure in the modelling software is fundamental to successfully exchange information within and outside organisations. Figure 6 depicts the central position of the IFC exporter between the design and data checking process.

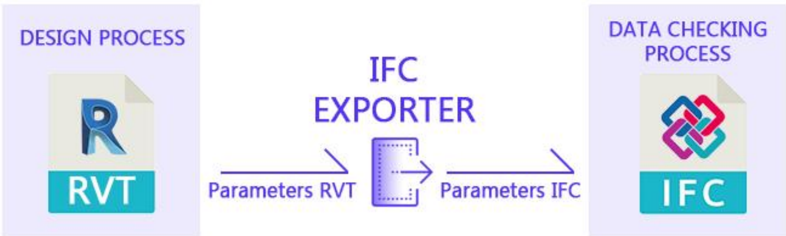

Figure 6: IFC Exporter position between design and data checking process (own illustration)

The exporting process to IFC is time consuming according to professionals at Hercuton. Thus, two ways of exporting models from Autodesk Revit have been identified:

- Revit Native IFC exporter: The wide range of possible settings in the native exporter was found a key obstacle when attempting to standardise IFC export processes at Hercuton. Designers may miss one or several settings out of the process and, as a consequence, geometries or data went missing in the IFC model. This was also noted by other authors in literature such as Choi et al., 2020 or Sobhkhiz et al., 2021.
- Custom solutions: At Hercuton, a custom software to export Revit models to IFC was developed for two reasons; first, as the process is usually time consuming, the focus was on scheduling the export to happen out of working hours, and secondly, to simplify and facilitate a standard process that can reliably export models across the company. With this solution custom mapping of parameters can be established and IFC parameters can be assigned based on their associated parameters in Revit.

Furthermore, according to Autodesk, 2018 and BIM Loket, 2020, there are mainly two different ways of working and preparing parameters in Revit to export to IFC and comply with standards:

- Using Revit built-in parameters and Revit native IFC exporter: Autodesk establishes relations between built-in parameters and IFC standard parameters. Therefore, when a model is exported with the Revit native IFC exporter, the built-in parameters can be mapped into the appropriate parameter in the IFC standard. However, only a few IFC parameters have a corresponding built-in parameter. Below Table 1 presents associated parameters from the wall category. Nonetheless, it is important to underline that the successful export depends on its extensive configuration which may prompt designers to errors. Furthermore, the mapping of built-in parameters is the last in the priority list for the Revit native IFC exporter meaning that if there is any other parameter with the exact name of the IFC parameter in an object the built-in parameter value may be overridden in the IFC model. This process can be misleading to designer as they can assign values to parameters that are later in the process overridden or not exported.

Table 1: Relation Revit built-in parameters and IFC parameters for a wall (Autodesk, 2018)

IFC Parameter for Pset_WallCommon	Revit Built-in parameter for Walls
IfcReference	Component type
IfcFireRating	Fire Rating
IfcThermalTransmittance	U-value
IfcIsExternal	Exterior component
IfcLoadBearing	Load-bearing
IfcExtendToStructure	Fixed on top

- Using user created parameters in the IFC Parameter group: Revit by default includes a built-in parameter group called IFC Parameter. All the user defined parameters in this group will be the first in the priority list when exporting to IFC. This methodology allows a consistent information exchange between the Revit model and IFC. Furthermore, it establishes a clear way for designers on where the information should be.

2.2.3.BIM data quality control tools

Most of the recent research is focused on the translation or implementation of rules, however it does not address how to engage stakeholders in the process (Sobhkhiz et al., 2021). The previous study stated that as consequence that this has led to an uncoordinated process and implementation. Professionals would prefer to have access to dedicated quality checkers that can minimise or replace manual tasks precisely and reliably. (Hjelseth et al. 2016). Fulfilling their needs and engage professionals is essential to have impact in the current operational processes. This is a cornerstone in the development of the new tool in this research.

From the literature review, preliminary interviews with professionals and manuals from software vendors, common key obstacles found in existing BIM data quality control tools are:

- The wide range of options and possible configurations makes existing software solutions complex and accessible only to skilled practitioners with a certain expertise. (Hjelseth, 2015) In the case of Hercuton, only very few BIM experts are trained to carry out quality checks with company standard rules. The expertise increases with the extensive rule definition process. BIM managers and modelers at Hercuton look for simple, effective, and ready-to-use checking systems they could rely on. Software complexity increases uncertainties and reduce end-users´ trust. (Hou & Jansen, 2022)
- Lack of integration with the design framework. BIM ARC tools have progressed as processes for post-design assessments. (Sobhkhiz et al., 2021). Furthermore, Sobhkhiz´s

study also noted that compliance with building codes and BIM standards is a step only exercised on the complete and detailed building model. They are static corrective processes. Tools that assess data quality at certain points in time in projects with interruptions and delays in designers´ and specialists´ workflows.

- Missing or wrong basic data structures could lead to incomplete or inaccurate data checking processes. For instance, rules could be created to check if door objects contain a certain parameter. However, if door objects are not defined as such, the check is not run on them. In contrast, if a wall object is defined as door, the previous rule would run a door check in the wall and it could raise a false issue.

2.2.3.1.Solibri Model Checker

Solibri Model Checker (SMC) is a BIM standalone application in which the data and geometry of a model is assessed against a preset of user selected rules. SMC is a thorough and powerful solution in terms of model checking capabilities. "The SMC can perform various functions such as space, accessibility, structure, constructability, and regulation checks" (Choi et al., 2020). Thus, there is a great variety of rules pre-created by the Solibri team from "Components Must Have a Unique Identifier" to "Required Property Sets" or "Comparison Between Property Value" which could be customized to run very specific data reviews in a BIM model. However, the fact that Solibri and most IFC-based checking tools are standalone solutions which require designers to leave their working environment to run data checks. At Hercuton, designers very rarely conduct data reviews with Solibri.

Given the wide range of possible rules in SMC, the classification of results is not explicit and their presentation does not facilitate their understanding. Possible results from rule checks are; critical issue, moderate issue or low severity issue. When is a result considered critical or moderate? This could indeed be customized by professionals with the required level of expertise, however it is important to underline that less experienced professionals could find difficulties understanding and working with SMC at first. Figure 7 shows how results are displayed in SMC.

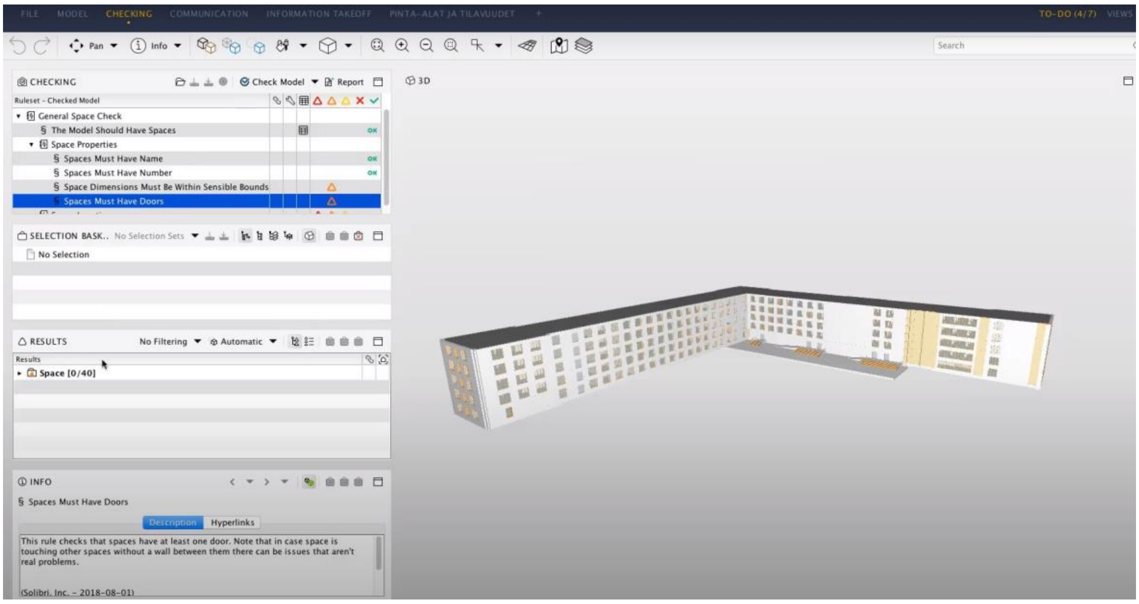

Figure 7: Results in Solibri Model Checker (Solibri Inc, 2019)

Additionally, SMC is compatible with IFC file format (.ifc), however it is not with Revit or Navisworks native files. Therefore, to run a check in a model, it first needs to be exported to IFC and then brought to SMC. After the checking, detected issues are shown in SMC standalone solution which could then be exported as BCF format to share them with designers. The entire process takes place in an external solution with different features and behavior than the design framework. As previously described, this is usually a time-consuming process and requires certain expertise that could end up disengaging professionals. How this affects organisational workflows is explained in detail in later sections of this document.

2.2.3.2.Autodesk Model Checker

Autodesk Revit Model Checker was released for recent versions of Revit as the package called BIM interoperability tools. Autodesk Model Checker is an Add-In or plugin for Autodesk Revit which enables professionals to check for instance model performance, project settings, duplicated elements or external files as defined in BIM standards. (Sacks et al., 2016) This solution is accessible directly through Revit. In that line, one benefit for designers is the certain level of integration in the design environment as they no longer need to export models to IFC. Additionally, this solution could often facilitate correction of objects in model, by referencing in the model the object that is violating a certain rule. (Sacks et al., 2016).

Nonetheless, from preliminary interviews (see *Appendix A: Information from industry professionals*), professionals find the rule definition and reporting processes highly complex. Moreover, Autodesk Model Checker does not allow to integrate the results fluidly in the designers´ workflows to dynamically detect and work on quality flaws as they model. Instead, Autodesk Model Checker could be run at certain points in projects and results are not properly integrated to efficiently work with them. Figure 8 shows how results in Autodesk Model Checker are displayed.

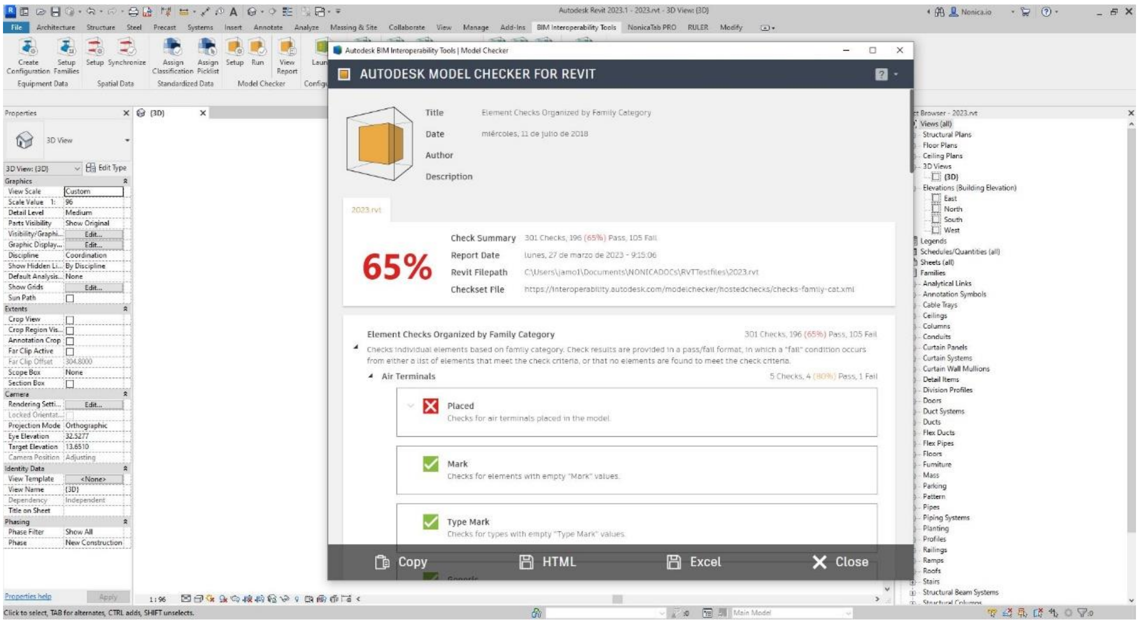

Figure 8: Results in Autodesk Model Checker (own illustration)

On the other hand, the default sets of rules in the solution check types or families that are not placed in the model. This adds a new layer of complexity and could be confusing when defining rules and understanding the result of rules as they are also included in the percentage-based result of the model. However, non-modelled types or families should not be considered as part of the quality of a model as they are only Revit configuration aspects not applicable to any object or included in standard exchangeable data formats such as IFC.

2.2.4.Data correction workflows

In practice, five possible results have been identified when applying a rule to an object in a model:

- Not containing parameter: The parameter does not exist in the specified object.
- Not properly setup parameter: The parameter is not properly setup. For instance, when a parameter has a text format, and it should have a number format.
- Empty parameter: The parameter exists in the specified object/s but it has no value assigned.
- Parameter not meeting rule: The parameter has a value assigned but the value is not meeting the specified rule. For instance, it could be that the value of the classification system based on NL/SfB is not following the code structure.
- Parameter properly filled: The parameter has a value assigned and it satisfies the specified rule.

In order to integrate effectively and efficiently the new data checking tool into data correction workflows, it is crucial to first break down current approaches by designers. After an issue is detected, three types of action are identified as the actions undertaken by designers in Revit:

- Create a parameter: This action is requested when a parameter is not contained in an object.
- Review a parameter: This action takes place when the settings or categories to be applied in a parameter are not properly setup.
- Fill/Review value in a parameter: This action is undertaken when the value of a parameter is empty or not meeting a rule.

The three types of action have different ways of being approached by designers based on the different grouping levels of objects. After an issue have been identified as non-compliant with a rule, how the new data checking tool should steer the professional should be based on forthcoming correction actions.

2.2.4.1.Model/Category level

There are not significant differences in the workflows between the model and category level. In both, workflows per action are:

- Create a parameter: According to Hercuton, designers very rarely create parameters from scratch but, instead, they attach predefined shared parameters created by BIM managers to categories. The assignment at this level is carried out from the project parameter panel.
- Review a parameter: This action takes place from the project parameter or shared parameter panel. Enabling or disabling the parameters in different categories is possible. However, there are limitations when the corrections must be made in the parameter settings and in almost all cases it requires to delete and recreate the parameter.
- Fill/Review value in a parameter: Values can be assigned per instance or type, and therefore, this workflow is explained at those levels.

2.2.4.2.Family level

At the family level, the workflows for the actions are:

- Create a parameter: The creation of a parameter starts from the selection of the object and edition with the family editor. After the family has been edited, it needs to be reloaded into the project to make the changes effective. Nonetheless, it is important to underline that families are usually managed at the company level by BIM managers. Therefore, the creation and management of family parameters is frequently carried out by BIM managers. It is a common and good practice that companies have their own libraries of families to work with. (Barbini et al., 2019) Therefore, all families in the company library should already have been set up properly before being included in a project. Thus, in this specific scenario, the designer would contact the BIM manager to create the new parameter in the library of families.
- Review a parameter: Similar to the previous action, the review of parameters takes place from the family editor after the selection of the object. In most cases, the removal and creation of a new parameter is required. Similarly, to the workflow of creating a parameter at this level, this sequence of actions are very often carry out at the company level by BIM managers.
- Fill/Review value in a parameter: Values can only be assigned per instance or type. Thus, this workflow is explained at those levels.

2.2.4.3.Type level

At the type level, the workflows are as follows:

- Create a parameter: Parameters for only a specific type cannot be created and they can only be created at the family level or higher.
- Review a parameter: Parameter settings cannot be changed at this level and must be made at the family level or higher.
- Fill/Review value in a parameter: The modification of a value in a type parameter first requires the selection of the object. Then, in the properties panel, the option Edit Type should be selected. Finally, the new value can be added.

2.2.4.4.Instance level

At the instance level, the workflows identified are:

- Create a parameter: Parameters for only an instance cannot be created and they must be created at the family level or higher.
- Review a parameter: Parameter settings are not modifiable at this level and changes must be made at the family level or higher.
- Fill/Review value in a parameter: The modification of a value in an instance parameter starts with the selection of the object. Then, the value can be modified directly from the properties panel.

2.2.5.Organisational workflows

"BIM gives higher design cost, but lower project cost." (Hjelseth et al. 2016). The research stated that business models steer how BIM is applied in the industry. The main paradigm here is who invests in the design and development during the conceptual phase and who gain the benefits in other lifecycle phases. However, companies aim at remaining competitive in the market and BIM quality control could bring them competitive advantage during the lifecycle of the end product.

At Hercuton, two different types of data checking reviews and durations have been identified:

- Regular: This review usually takes place every week or every two weeks. The review process is lighter and less strict as the work is in progress.
- End of phase: This review is carried out at the end of a phase usually before delivering the project to other parties. The review process is stricter as the work needs to be ready to be delivered to clients or other parties involves.

According to Sobhkhiz et al., 2021, the main challenge of ARC is not technological but rather in its governance and business management side. The study noted that, with current approaches, the final product does not fulfil the needs of designers. From the literature review, preliminary interviews with industry professionals and manuals of software vendor, an industry extended workflow for BIM data assessment is as follows: (Lipp et al., 2016)

- Prior the start of the project, several milestones are agreed upon stakeholders to validate data in the project.
- Based on design requirements, architects and modelers work on the BIM model.
- When a data validation milestone is reached, modellers export their work to IFC exchangeable format and share the files with the BIM manager.
- The BIM manager imports the IFC model in an automated data checking tool such as Solibri and carries out the necessary data checks against set of rules.
- After, the evaluation is completed, a BIM Collaboration Format (BCF) is uploaded or synchronise with the Common Data Environment including issues and geometry references by the BIM Manager enabling issue management.
- The modeler synchronises issues with their preferable design tool and work on them. Then, the file is exported as IFC again to be reviewed.

Figure 9 below decomposes tasks and responsibilities of the iterative process.

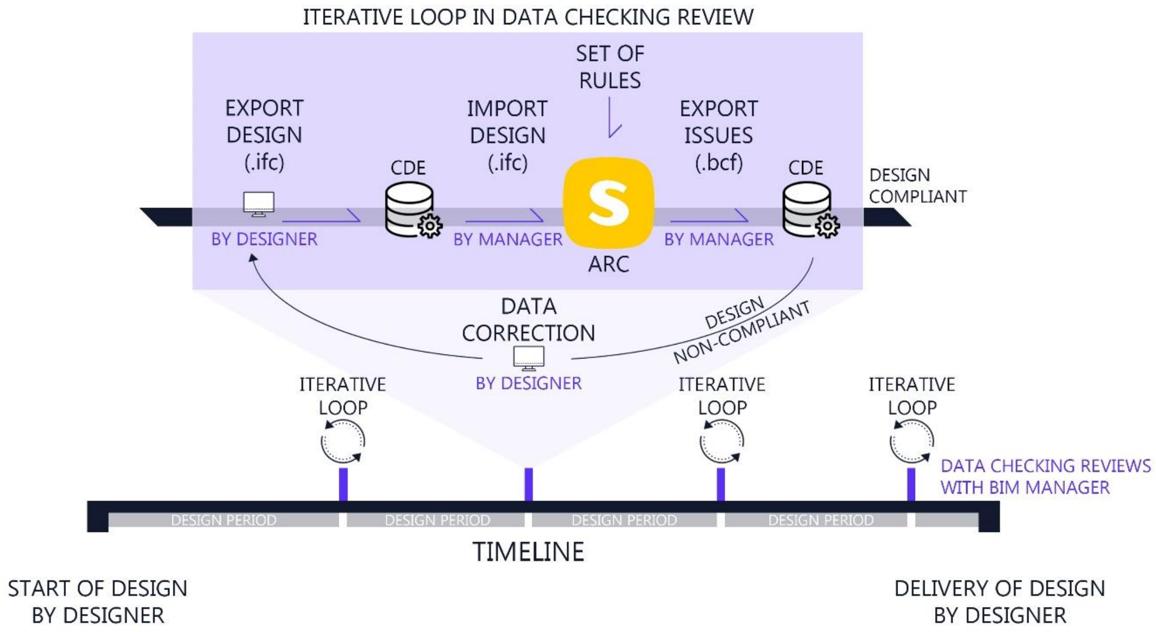

Figure 9: Organisational data correction workflow (own illustration)

The process is iterative until the necessary data quality in the model is achieved by the design team. The separated design-check workflow imposes a burden on designers as they must fix the fail-to-pass issues iteratively. (Sobhkhiz et al., 2021). The implementation of rule checking is expected to be employed by all parties in the BIM building lifecycle. (Sacks et al., 2018)

Furthermore, the exporting process to IFC is often not thorough and information can be lost. (Lilis et al.,2018) At Hercuton, they specifically developed their own custom software to export Revit models to IFC for two reasons; first, the process is usually time consuming, so the focus was on scheduling the export to happen out of working hours, and it was not feasible to standardise the process with the Revit native exporter given the wide range of different possible configurations.

Every iteration in the process brings interruptions and/or delays in designers´ workflows to review the data quality issues and export the IFC model to be rechecked. This has negative impact in the designer's productivity and the delivery time of projects.

Furthermore, as a project progresses, addition and modification of objects take place. Therefore, the same issues discussed for previous objects can be detected again for new or modified objects of the same nature. According to Prasanna et al. 2008, simple, repetitive, and limited in the handling of tools tasks can end up in a consequent feeling of discontent and draining interest and energy in the workplace. "Employee morale is determinant for productivity and retention" (Nur et al., 2021) This is an important challenge to tackle in the data evaluation process.

Traditionally, BIM-based data quality checking processes, such as ARC, have progressed to be tools for validation and post-design checking. (Sobhkhiz et al., 2021). The process is now executed correctively and focused on evaluating and communicating/reporting detected issues at certain points in time. However, several studies argue that design quality can improve if quality control requirements are actively controlled and that ARC systems need to be proactively providing feedback for specific issues during the design process. (Choi et al., 2020, Sobhkhiz et al., 2021)

Thus, the study from Sobhkhiz et al., 2021 noted that IFC tools push designers out of their design frameworks preventing simple intuitive checks. This has created difficulties in understanding the rules and its results which has inevitably led to a new area of specialisation usually undertaken by BIM managers or BIM experts. However, rule data checking should not be limited to specialists, and it should be easily applied by a wide range of users. (Sacks et al., 2018) For this research, this represents a challenge that limits the adoption of data evaluation processes in the industry.

Furthermore, issues detected or solved are communicated with the designer through the CDE. There are integrated solutions that connect common CDEs (e.g. Catenda Hub) with Revit to enable a more effective and efficient issue correction. However, two main issues were found by professionals at Hercuton in the solution by Catenda Hub; first, the integrated solution is not stable enough and it sometimes crashes Revit forcing designers to reopen projects which is usually time consuming. Second, the tool does not link well certain issues to object references and designer cannot retrieve where the issue happened in the model. Thus, Hercuton professionals opted for reviewing the issues directly in Catenda Hub and, in parallel, in another screen, search and work on each of the elements in Revit.

At Hercuton, the modelling team is found under time pressure. According to Eurostat 2019, up to 53% of the European workforce state to work often or always under time pressure. Additionally, several authors (Moore & Tenney, 2012, van Oorschot et al., 2018) found that time pressure can increase speed at the expense of quality. As a result, data quality in models could be compromised. Moreover, the research from Amabile et al., 2002 noted that time pressure likely has negative effects on creative processing even at moderate levels. The research indicates that the effects may be disproportionately worse at extreme levels. Therefore, reducing time pressure in modelling teams can be a critical challenge to improve not only data quality in models but also design quality of projects.

2.3.System requirements

In this chapter, first, the focus is on software engagement and perception to understand challenges and potential methods to engage users when developing and implementing the software solution. Then, software and theoretical background challenges combined with the needs and demands of professionals are translated into functional system requirements. The purpose is to summarise specific guidelines and requirements that will later shape the new tool. Given their distinctive level of interaction, functional requirements are distinguished based on two end-users: the designer and the rule definitor.

As previously introduced, the rule definition process in order to accommodate a wide range of possible quality checks has resulted in highly complex existing software solutions. To an extent, producing flexible solutions is important to enable systems to adapt to changing standards and future professionals' needs. However, a proper balance between a flexible and a simple and engaging system must be found to promote wide industry adoption.

2.3.1.Software engagement and perception

In construction projects, low stakeholder engagement is often found in research as the main cause of low automation. (Sobhkhiz et al., 2021). In this research, software perception and engagement are studied as a means to potentially achieve an impactful solution and a wide industry adoption.

Fitness for purpose is therefore essential. Something that is fit for purpose does what it is meant to do (Cambridge Dictionary, 2023). This concept may look rather simple, but inadequate understanding of the purpose leads to poor quality software. (University of Toronto, 2023) Fitness for purpose emerges therefore as the key feature of proficiency testing (Royal Society of Chemistry, 2015). According to Hjelseth et al. 2016 and preliminary interviews with industry practitioners regarding BIM model quality checking (see *Appendix A: Information from industry professionals*), professionals would prefer to have access to dedicated quality checkers that can minimise or replace manual tasks precisely and reliably rather than very advanced software solutions. In contrast, in the existing data checking tools, the information shown and the wide range of possible configurations are overwhelming as seen in Figure 10. This creates uncertainties and information overload which in turn, according to O'Brien & Toms, 2008, lead to user disengagement. Figure 10 shows the complexity and available options when defining rules in SMC.

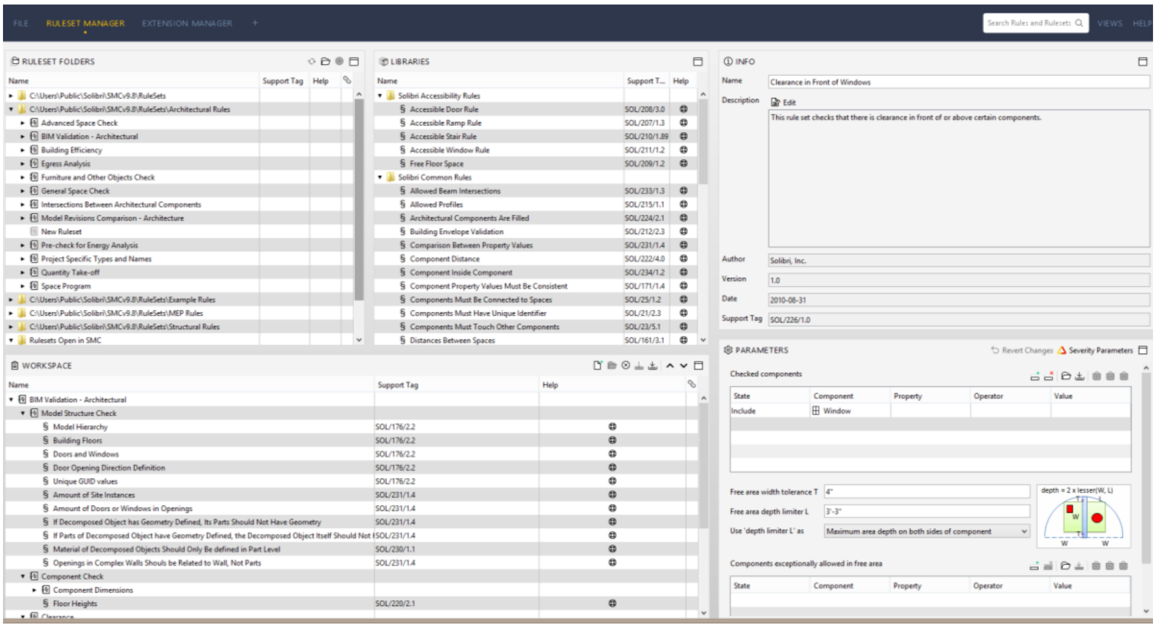

Figure 10: Set of rules in SMC (Lipp| et al., 2017)

User engagement is the state of mind that a user need to attain to take an action without meditation and distraction (Anawar et al., 2016). Evaluating user engagement with the new data checking tool developed in this research is crucial to assess its effectiveness. In the previous study two types of user engagement were distinguished:

- Topical engagement is developed through experience and emotions based on expectations. Thus, this is developed progressively as the tool is being used over time.
- Situational engagement is based on the novelty of a tool which trigger curiosity and the salience of content. This will be triggered at the beginning of the implementation phase when the software solution is first presented and available to end-users.

In this research, fitness for purpose and user engagement will be evaluated in the *4.Implementation and assessment* phase.

On the other hand, human perception is mainly visual. Around 90% of human-processed information comes from visual receptors. (Manic, 2015) In his study, Manic stated that visual content is easier to understand and remember as well as more eye-catching and with direct effect on human emotions. Furthermore, several authors (Sutton, 2011, Schoenfeld, 2012) concluded in their studies that dynamic visual content has higher user engagement rates.

How the tool interface is designed, and information is presented to the end-user is essential to achieve high user engagement rates. On the empirical analysis carried out by Asimakopoulos et al., 2017, it was found that user motivation is highly dependent on content design and appropriate feedback to the user. Additionally, in the previous study it was noted that there was a desired for app users to analyse relations between data and information. Thus, self-monitoring was considered an important intrinsic incentive to improve user participation (Anawar et al., 2016, Asimakopoulos et al., 2017). Moreover, progress-based tools can help perceived tasks as more achievable and increase job satisfaction. (Kim-Soon, 2015)

2.3.2.User needs and system requirements

2.3.2.1.Designer

Designers are referred to as architects and BIM modelers involved in the modelling of the project during the design phase. This cohort is the main target user as they are deeply involved in the development of the model from the very beginning. In Table 2, the identified needs of designers are summarised.

Table 2: Key user needs for designers

User needs
It should enable proactive design.
It should engage designers.
It should be fit for purpose

Based on the user needs and the previous analysis, system requirements for designers are extracted in Table 3.

Table 3: Key system requirements for designers

System requirements
The tool should be an automated rule checking tool.
The tool should be integrated fluidly in designers´ workflows and not be a standalone solution.
The tool should be dynamic and automatically report issues as the design evolves.
The tool should be concise and simple as well as avoid information overload.
The tool should be ready-to-use with the least possible amount of configuration.
The tool should have self-monitoring progress-based dynamic visual content.
The tool should avoid uncertainties and facilitate the understanding of inner processes.
The tool should avoid constant IFC and BCF file exchange workflows.
Results should be explicit and provide specific information about the nature of the issue.
The tool should be role-dedicated and focused on improving the quality of models on the designer side.
The tool should present concisely a list of non-compliant objects to work on.
The tool should link detected issues with object references in the model.
The tool should enable an effective and efficient data correction workflow.
The tool should simplify the implementation of BIM standards.
The tool should include objects satisfying the defined rules to understand the completeness of the check.
The tool should be developed in collaboration with designers.

2.3.2.2.Rule definitor

The definition of rules is usually undertaken by BIM managers who oversee the implementation of BIM standards in projects. Although the approach is to implement a ready-to-use system for designers, the rule definitor needs to be considered as they will be responsible of adding or changing predefined rules according to company specific requirements or updated BIM standards.

Table 4 includes the two high level user needs for rules definitors.

Table 4: Key user needs for rule definitors

User needs
It should engage rule definitors.
It should be fit for purpose.

According to the user needs´ and the previous analysis, Table 5 concludes with the system requirements identified for rule definitors.

Table 5: Key system requirements for rule definitors

System requirements
The tool should be flexible enough when defining rules to accommodate changes or updates in BIM standards.
The tool should simplify the current rule definition process and enable accurate checking.
The tool should avoid uncertainties and facilitate the understanding of processes.
The tool should simplify definition of set of rules based on BIM standards.
The tool should enable simple distribution of set of rules.
The tool should avoid hard coded systems to improve tool maintainability and flexibility.
The tool should enable the definition of rules for all objects in the model.
The tool should enable the definition of rules for specific categories, families, or types.

3.Synthesis and development

The synthesis and development phase is based on the challenges and system requirements found during the analysis phase. In this chapter, first the concept of the new data checking tool is defined. Then, the compliance method is described and its implications in designers´ workflows. To narrow down the scope of this research, a selection of rules to implement from the BIM Basis ILS is made. Next, the analysis is focused on designers and rule definitors and how they interact with the new tool. Finally, the tool is reviewed from an organisational perspective and how it is integrated at the project level.

The goal of this section is to reach an answer for the second sub-question:

How can new tools engage and be integrated fluidly in the designer´s and organisational workflows?

3.1.Concept data checking tool

The concept of the data checking tool is to create a design-integrated and dedicated tool that enables designers to fluidly detect and work on data quality issues while they are modelling in Autodesk Revit. The purpose of the new tool is not to replace existing data checking workflows but rather to support and make them more effective and efficient. The aim is at improving the data quality of models before entering the data checking reviews.

Based on the level of interaction of the different end-users, the system mainly consists of two layers:

- Designer layer: The designer layer is a ready-to-use design-integrated tool to reduce the level of expertise required to the minimum. This layer shows the issues detected from applying the set of rules to the model while designing. The results are updated dynamically in the background when new objects are created or modified in the model. This is essential to avoid continuous interruptions in the designer work. Additionally, an overview of all results in the model is provided to understand the completeness of the check and engage professionals to review data quality issues.
- Rule definitor layer: This layer consists of a system to create, edit, and remove rules applied in the model. The purpose is to include in the tool, by default, a predefined set of rules according to the BIM Basis ILS, therefore rule definitors don´t need to create all the rules from scratch at first but rather modify or adjust the preset of rules if required. The default setup will reduce implementation time in deployments but also reduce the expertise necessary to use the tool. Additionally, rule definitors can define custom rules applied in their organisations or change the predefined rules when a BIM standard is updated. As these changes in rules need to be shared with designers, set of rules can be exported and imported to enable interoperability between different professionals.

Figure 11 explains the inputs and outputs of the new tool and the different roles involved.

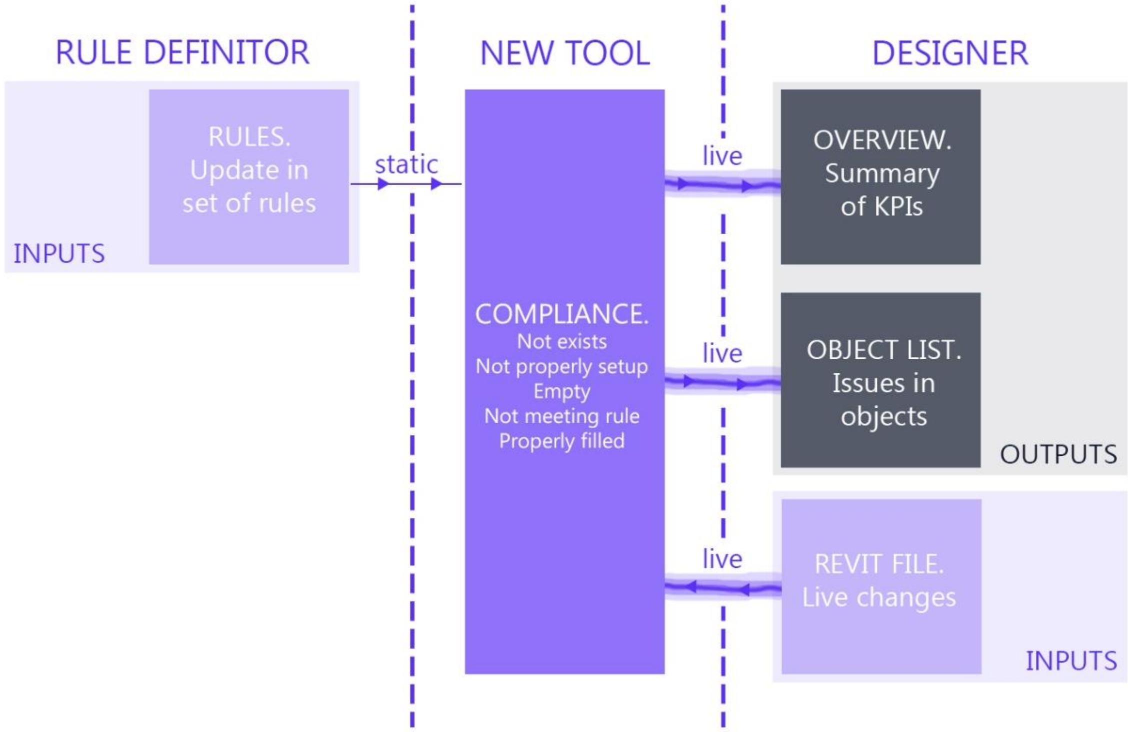

Figure 11: New workflow in data checking tool (own illustration)

3.2.Compliance method

This chapter first focuses on the internal workflows for the detection of issues and when to use each of them. Secondly, data quality metrics are established to bring results to end-users concisely. Finally, the new data correction workflows are presented to anticipate the designer forthcoming actions and make the process more efficient.

3.2.1.Detection of issues

How issues are detected is the cornerstone to enable a fluid interaction with the tool. Complete rule checks can be time consuming and present continuous interruptions in the professionals work. Therefore, two internal checking workflows are distinguished to optimise operations within the new tool when detecting new or solved data issues in models:

- Extended detection workflow. In this workflow, a complete check of all rules against the model takes place. The approach to this workflow is distinctive to existing tools because this process is run automatically within the design framework. Depending on the size and complexity of the rules and the model, this process can be computationally expensive and take a few seconds to execute. This process could have negative impact on designers' workflow, and it should only be executed when strictly necessary. The extended detection workflow is conducted for instance when a new project is loaded in Revit.
- Change detection workflow. Every time an object is added or modified in the model, that specific object is checked against the applicable rule/s to detect new or fixed issues. This process has no negative impact on designers´ workflows. This simplified workflow is novel and not existing in any of the current tools in the market. The change detection workflow is light and carried out in the background. If a new issue is detected, it is presented to the designer. On the other hand, if an issue is detected as solved, the issue

is deleted from the list of pending tasks. This progress-based dynamic approach could be engaging for designers as they become aware of their performance and the impact of their actions.

3.2.2.Data quality metrics

Results and metrics need to be as explicit as possible providing specific information about the nature of the issue at hand. Otherwise, their meaning may not be clear for professionals leading to disengagement. As described in the section *Data correction workflows,* there are five possible results, when applying a rule to an object in a model:

- Not containing parameter.
- Not properly setup parameter.
- Empty parameter.
- Parameter not meeting rule.
- Parameter properly filled.

Therefore, they have been chosen as key performance indicators (KPIs) to evaluate data quality in models during the detailed design phase. Additionally, KPIs are presented to designers to provide an overview of the quality of the model and completeness of the check. Furthermore, the results are specific and easy to link to the necessary actions.

3.2.3.Data correction

After an issue has been detected, in regard to the chapter *2.2.Application of BIM data quality control*, data correction workflows undertaken by designers can be summarised in:

- The creation of a parameter or the review of its settings in an object are in most cases carried out from the project parameter panel with an exception. As previously analysed in the section *2.2.4.Data correction workflows*, the creation of parameters at the family level requires a different sequence of actions than at other levels. Nonetheless, family parameters are often created and managed at the company level by BIM specialists and not by designers. In this specific scenario at Hercuton, the designer would communicate the BIM specialist the issue to review the parameter within the library of families.
- Review or fill value in a parameter for which, first, the object needs to be selected and then, either the value can be edited from the type panel or modified directly in the properties panel.

Anticipating and proposing the next action to professionals in the new workflow could result in higher efficiency when correcting data. Thus, based on the result of applying a rule to an object, the following links in Table 6 has been established to propose professionals the next suitable action:

Table 6: Relationship between possible results and forthcoming workflows

Result from rule	Forthcoming workflow	Action in new workflow
Not containing parameter.	Create parameter.	Open project parameter panel.
Not properly setup parameter.	Review parameter settings.	Open project parameter panel.
Empty parameter.	Fill value in parameter.	Zoom in and select object to modify.
Parameter not meeting rule.	Review value in parameter.	Zoom in and select object to modify.
Parameter properly filled.	No action.	No action proposed.

3.3.Selection of rules from the BIM Basis ILS

A selection of essential rules to implement from the BIM Basis ILS has been made together with Hercuton. Given the time available for this research, the goal is to implement strategic chapters for the new data checking layer. In order to approach the issue as a whole and avoid a biased development and implementation, standard data requirements were selected from the two main chapters of the BIM Basis ILS (BIM Loket, 2020); chapter three, as the specifications in this chapter apply to all objects in the model, and chapter four, as the specifications in this chapter apply or not depending on the object. Finally, data requirements have been simplified and translated into minimum necessary data checks to carry out in this research.

3.3.1.Construction level arrangement and naming

The reason to select this chapter is that this information is critical to use, filter and work unambiguously with objects in IFC models.

Thus, all objects in the model should be assigned a parameter called IfcBuildingStorey-Name with the value of the storey they are in. The values assigned should use a consistent naming convention. The principle of consistent naming is that objects can be sorted numerically and supplemented with a description to ease their understanding.

Level names are assigned to most objects in different parameters in Revit. The most effective check is to review the name of all levels in the model and ensure that they follow the NLRS naming convention. This will make all parameter values also follow the NLRS. Thus, the values are checked to start at least with two numbers plus a space and followed by letters.

3.3.2.Structure and naming

The properties IfcName and IfcType are essential to interpret the information exchanged in IFC software solutions. Consistent information in these properties across objects creates a clear and comprehensible structure that make objects traceable in IFC.

Thus, all objects in the model should be assigned the properties called IfcType and IfcName. The property IfcType represents the collection of elements with the same shape and different set of instance properties (e.g. wooden swinging door of 2 meters by 1 meter). On the other hand, the property IfcName refers to a specific instance with a specific set of instance properties of the IfcType.

In this case, IfcName and IfcType parameters are checked to exists in all objects. Additionally, if the parameters contain a value and are defined as type parameters. Finally, the settings of the parameters are checked to confirm if the parameter is formatted as text.

3.3.3.Classification system

In the Netherlands, the recommended code by the BIM Basis ILS and the most used classification system for building components in the Netherlands is NL/SfB (BIMLoket, 2023). As previously explained, objects can be classified based on their function and type (e.g. 21.11 refers to external walls; non-structural, solid walls). This code brings the possibility to create meaningful links between objects for specifications, estimates or facility management. Thus, all objects in the model should have an assigned four-digit classification code according to the latest publication of the classification system in that country.

For this section, the data checks undertaken are, first the parameter NL-SfB is checked to exists in all objects of the model. Then, that the parameter is defined as type parameter and contains a value. Next, the value should be formatted as text and follow the structure 00.00 (two numbers followed by a dot plus two numbers).

3.3.4.Fire safety

The fire safety topic attracts a lot of attention, not only due to buildings need to be fire-safe but also because it has to comply with laws and regulations. Therefore, it is crucial that the information is carefully recorded, maintained and reviewed, so building components fulfil the requirements.

Therefore, all applicable objects should be assigned a property called FireRating. Based on buildingSmart properties, the parameter should be a number representing the number of minutes that the object would withstand fire without altering its core properties.

In this case, the parameter is object specific and assuming that all objects of a category or model should contain the parameter would not be appropriate. Therefore, the check would only be carried out if the parameter contains a value. Thus, the parameter value is checked to be one of the values specified in the Dutch Guide of Fire-Resistant requirements introduced in the BIM Basis ILS (20,30,60,120,240).

3.3.4.Material

The material of an object defines its aesthetical, physical and maintenance properties. Therefore, being able to identify materials is important for architectural visualizations, building material passports and purchasing.

Thus, all objects should be assigned a parameter called IfcMaterial. In compositions, the parameter should contain the information of the dominant material. Quality, performance requirements and element codes such as NL/SfB are preferably not included in IfcMaterial to avoid data duplication.

The parameter IfcMaterial is internally translated from different Revit parameters. Therefore, one main Revit parameter has been selected in the implementation phase. The goal is to check that material parameters follow the NLRS naming convention which starts with XXXX_X (four letters followed by an underscore plus a letter).

3.4.End-user frameworks

In this section, frameworks are distinguished by end-users and their level of interaction within the new workflow. First, inputs and outputs from the end-user are analysed and how they can impact workflow integration and user engagement. Finally, these concepts are brought into the design of the user interfaces.

3.4.1.Designer framework

Designers are the key end-user of the new tool. The approach is to provide a ready-to-use solution integrated into their workflows so they can detect, review and work on data quality issues.

3.4.1.1.Inputs

Inputs from designers for the new tool are integrated in the design workflow and do not require any specific interaction from the designer. This facilitates the checking process as designers can focus on their designs and don´t need to explicitly run data checks. Unless the designer side panel is explicitly closed, the window will be automatically open when a new session or project is initialized.

Furthermore, the purpose is to optimise the performance of the tool to avoid as much as possible interruptions in the work of designers. Thus, two main types of inputs from designers can be distinguished and linked to the detection workflows:

- Selection of a model regarding the initial loading or opening of a model. This type of input requires the *Extended detection workflow* explained in the section *3.2.1.Detection of issues*. This input can indeed have a negative impact on the designer workflow as it can extend a few seconds the loading time for professionals.
- Changes referring to live changes that occur in the model while the designer is working in Revit. These changes include but are not limited to the creation of new objects, the modification of existing objects and the entering of new data into object parameters. They are checked dynamically in the background using the *Change detection workflow* explained in the section *3.2.1.Detection of issues.* This process has no negative impact on the designers´ workflow.

3.4.1.2.Outputs

Outputs in the new tool are designed to engage designers, facilitate their understanding of the issues and enable a more efficient and effective data correction workflow. After the model has been evaluated, detected issues are brought to designers in two ways:

- Overview of results: the purpose is to facilitate the understanding of the results in the model as a whole. Furthermore, without an overview of the results designers may not appreciate the completeness of the check which is essential to increase user trust in the solution. The information displayed is concise and explicitly based on the possible results explained in the section *3.2.2.Data quality metrics.*
- Object list: the object list, in most cases, is going to gather an extensive list of issues from applying all the rules to the entire model. Tasks that are large and complex can lead to action paralysis and feelings of being overwhelmed. Such tasks can benefit from being decomposed and organized in order to reduce the user cognitive load. (Zhang et al., 2021) Thus, issues detected are broken down into an organised and filterable list of objects. Results are treated and presented as pending tasks in the model. Issues with the result parameter properly filled are excluded from this list as those parameters already comply with the rules and don´t need any further action. To produce an effective workflow focusing on an object until all issues are resolved, a single object may group different results because of applying several rules. Therefore, another possible result, called several results, should be considered besides the KPIs in the *3.2.2.Data quality metrics* section.

3.4.1.3. Visual interface

Based on the functional and tool requirements, the user interface has been designed as a side panel integrated in Revit to enable the dynamic visualization of issues next to the designers´ modelling area. Figure 12 explains where the results are shown to the designer within their working environment.

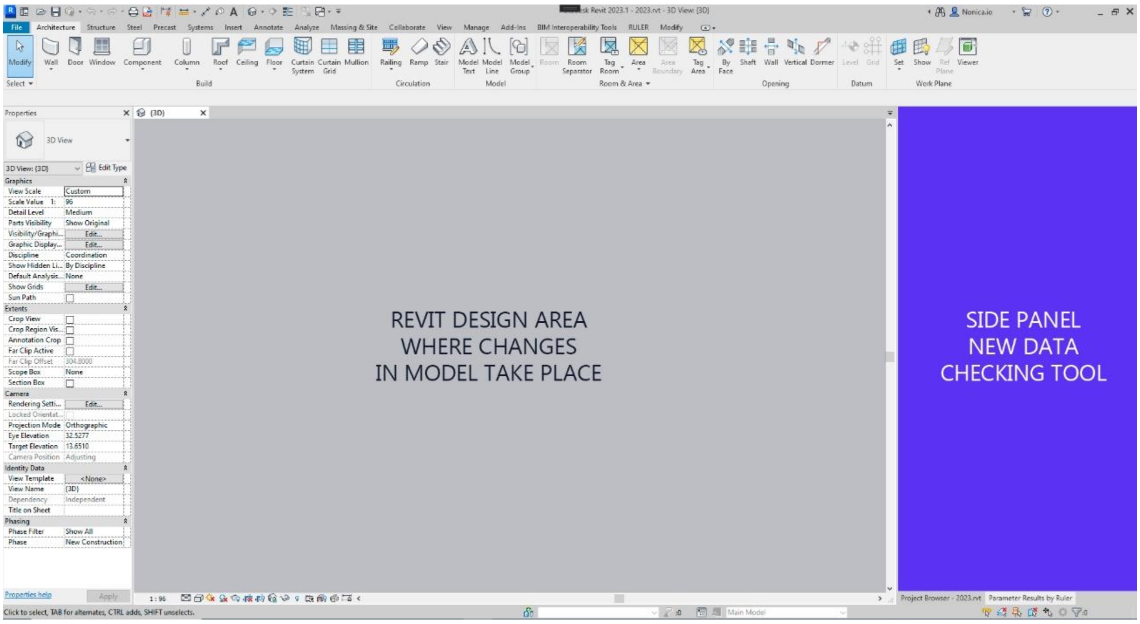

Figure 12: Design integration of new data checking tool (own illustration)

Additionally, the focus of the user interface is to engage designers in reviewing data quality issues with a fit for purpose tool. Therefore, the approach combines making the data checking process understandable in order to increase designers' trust in the new tool with avoiding information overload and uncertainties by showing strictly what it is necessary.

Thus, the new data checking tool consists of three main subcomponents shown in Figure 13.

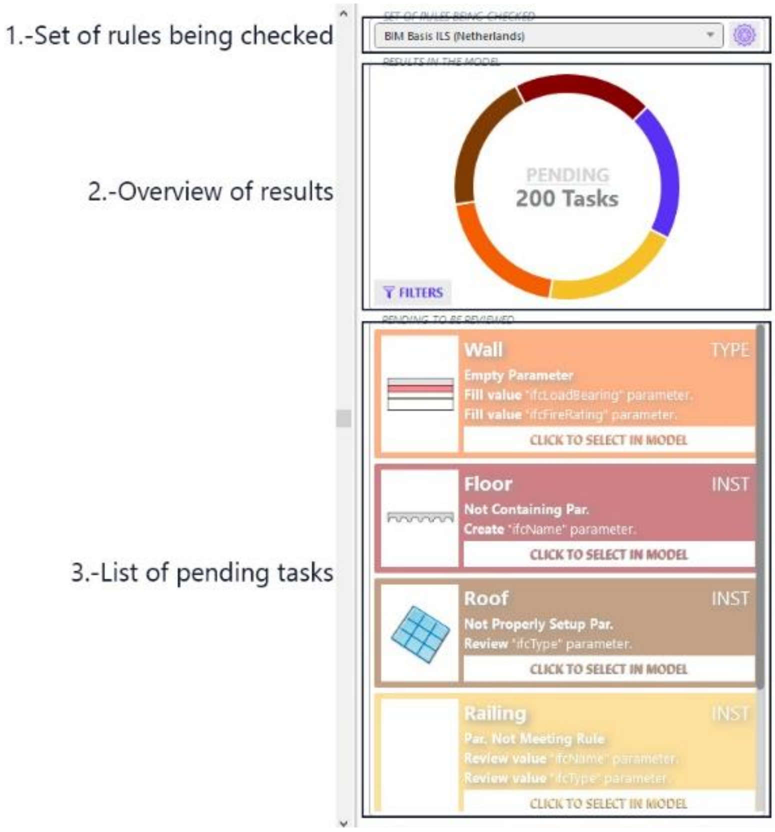

Figure 13: Components new data checking tool (own illustration)

- Set of rules being applied: The goal of this section is to concisely facilitate the understanding of the data checking process by making the process more transparent. By default, only the title is shown but if the designer is interested in having more information, the names of the rules are displayed when the control is clicked.
- Overview of results: The purpose of this content is to increase the designers' trust in the results by showing the designer the process completeness. This is achieved not only by summarising the results of detected issues but also by including objects that successfully passed the rule checking process. On the other hand, the progress-based pie chart is dynamic which enables designers to self-monitor their performance and engage them to work on pending data quality issues. Furthermore, the visualisation is interactive which enable the optimisation of screen space and can engage designers to explore their results by passing the mouse over the graph.
- List of pending tasks: The list gathers all the issues detected in the model. Issues are grouped by instance or type. The aim is to present a list of objects that is as concise as possible. On the other hand, the grouping per object promotes working on the data quality issues object after object which minimizes the amount of clicks and establish a more efficient process. Results can also be filtered and reordered to focus on issues of a certain result first. Additionally, the background of the issues depends on their results using the same palette of colors as the results in the overview graph. This visual relation intuitively help associate the issue in the list to a particular result. The information displays in each issues include:
  - Name of type and category presenting the issue.
  - Type or instance to introduce what kind of parameter is the issue related to.

- General result of the application of the rules. If it combines various results, the content is “Several Results” and the background of the issue is grey.
- Pending tasks indicating what is pending to do in the object.
- Proposing the forthcoming action to facilitate the imminent data correction workflow which could be “Select object in model” or “Open project parameter panel”.

3.4.2.Rule definitor framework

The rule definitor is the end-user responsible of adapting the set of rules to specific updates in BIM standards or company requirements. Given the approach of the new tool to deploy a ready-to-use system for designers, the responsibilities and tasks of this position, in regard to existing data checking workflows, substantially reduce.

3.4.2.1.Inputs

Inputs from rule definitors are the addition or modification in the deployed set of rules. These changes are conducted when BIM standards or company requirements are updated.

According to buildingSmart, 2023, updates in the IFC standard usually take place one time per year at maximum. Thus, the input of the rule definitor is not conducted very often. Nonetheless, rule addition, edition and exchange should still meet the requirements from the *Analysis phase,* to avoid hard coded systems and improve the tool maintainability and flexibility.

Given the frequency of the updates and the time available for this research, the workflow consists of two steps:

- Edition of set of rules: The addition or modification of rules takes place in the computer of rule definitor. After the necessary changes are made, the set of rules are exported to XML format and sent to the designers’ computer.
- Deployment of set of rules: The XML file can then be imported into the data checking tool.

3.4.2.2.Visual interface

In order to add or modify rules, the rule definitor needs to explicitly push the *Set Parameter Rules* button in the new tool. In order to avoid information overload, rules information is hidden when the window is first open.

Figure 14 shows how rules and set of rules are visualised within the rule definition panel.

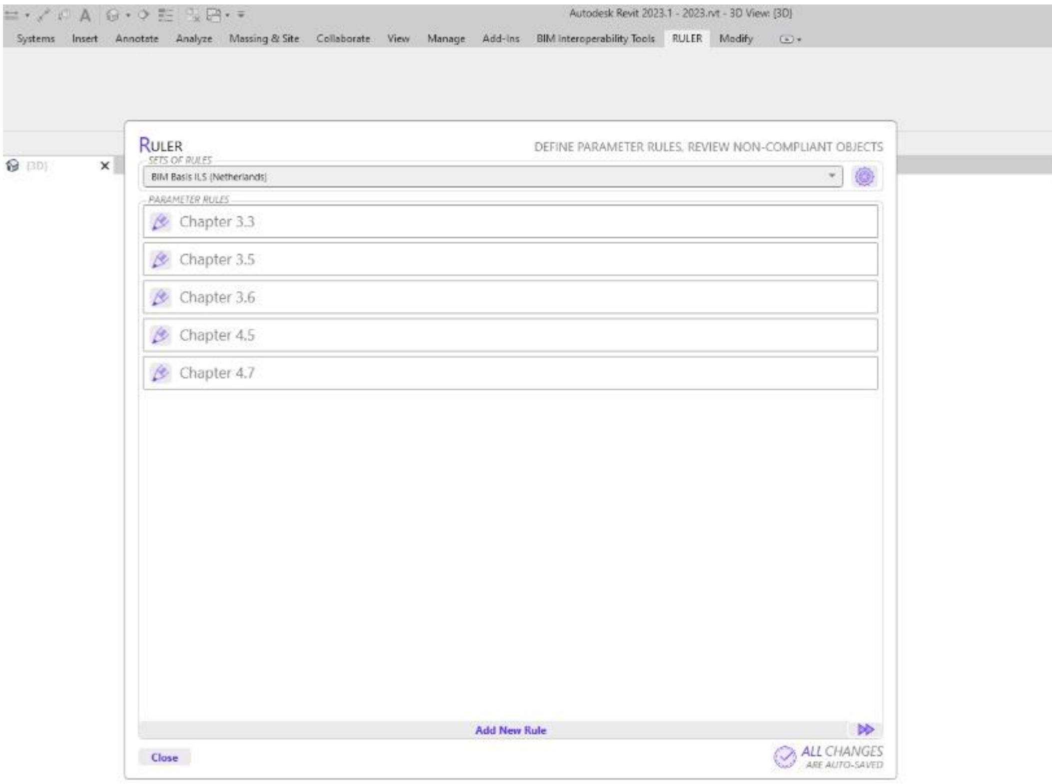

Figure 14: Rule definitor user interface (own illustration)

Thus, two main sections can be distinguished in the interface of the rule definitor:

Set of rules: In this section, different set of rules can be selected to apply a different BIM standard or specific company rules to the current model. Additionally, from the settings button, the rule definitor can, for instance, import and export a custom set of rules to share it with designers.

Parameter rules: This section depends on the set of rules. When a different set of rules is selected, the rules shown in this area change accordingly. Initially, the name of all the rules in the set are displayed. Nonetheless, rules can be edited by clicking on their edit button.

The possible configuration in rule creation and edition has been defined as the minimum based on the selection of rules made from the BIM Basis ILs in the section

3.3.Selection of rules from the BIM Basis ILS*.*

Figure 15 shows the different options available to define rules in the new data checking tool.

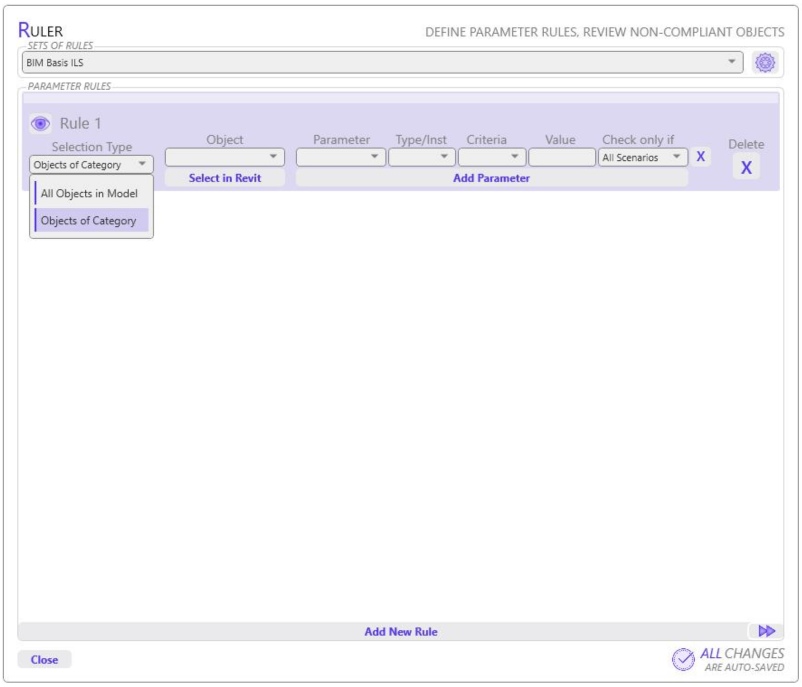

Figure 15: Definition of a rule (own illustration)

First, the selection type can be specified if the rule should apply to all physical objects in the model, as in chapter 3 of BIM Basis ILS, or to objects modelled of a specific category, as in some sub sections of chapter 4 of BIM Basis ILS. The second column allows to define the category (e.g. walls or columns). Then, the name of the parameter and its configuration as type or instance can be selected. User created parameters can be wrongly set up as type or instance leading to wrong values across the model. This setting can help identifying errors in that configuration in the objects. Then, the criteria column can have three possible values;

- Parameter is formatted as. Enabling to detect when a parameter is being formatted as text but instead it should be formatted as number or boolean.
- Value is structured as. Allowing to find which objects are not following the value structure defined in NL/SfB, two digits followed by a dot plus two digits.
- Parameter is one of the following. Allowing to find if the Fire Rating parameter contains a value according to Guide to Fire Safety Requirements in the Netherlands.

Finally, parameters and its values are in some cases context based. In Netherlands, the fire rating requirements vary for projects of different sizes and usage. Therefore, checking that the fire rating parameter is always filled would not always be appropriate. Therefore, the final column allows rule definitors to specify if a parameter should only be checked if the parameter contains a value or in all scenarios avoiding the detection of inadequate or duplicated issues.

3.5.Organisational workflow

During the existing organisational process, data quality mainly improves in models during the data checking reviews carried out in collaboration with BIM managers or specialists. The current process is not ideal. The purpose of the new tool is not to replace existing data checking tools but instead to support the organisational process in order to improve data quality in models during design periods before entering the reviews. Figure 16 visually explains the enhanced process in which data quality improvements also take place out of iterative loops.

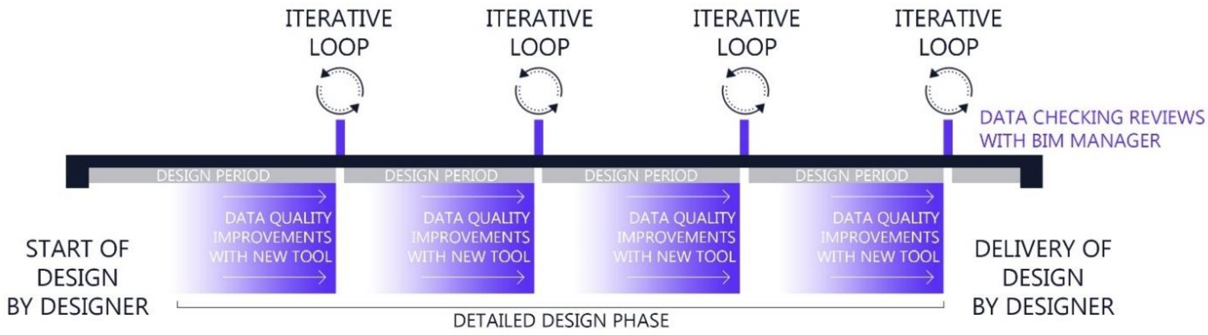

Figure 16: New organisational data checking process (own illustration)

Improving the data quality of models during design periods could reduce the duration and number of iterations in data checking loops with BIM managers and specialists. Consequently, the number of interruptions in designers´ workflow could also decrease. Additionally, designers, BIM managers and specialists work efficiency could increase given the reduction in time spent in the loops. Furthermore, there would be a decrease in multitasking which is less efficient, given that it takes extra time to switch mental gears every time a person changes tasks. (Gauthier, 2001) Figure 17 shows the different tasks and roles involved in iterative data checking reviews.

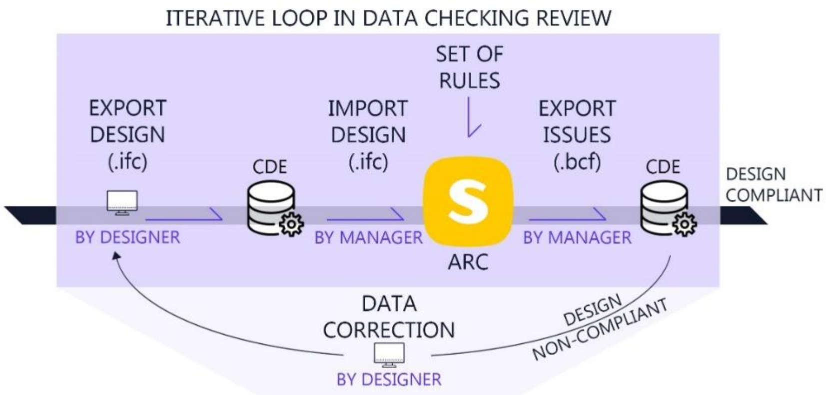

Figure 17: Workflow data checking review (own illustration)

As previously explained in the *Analysis* phase, basic data structures are often not properly defined or exported by designers. As a result, the data checking process by the BIM manager becomes ineffective and inefficient as it can lead to miss or raise false positive issues. Implementing the new design-integrated tool adds a new prechecking layer and tackles this obstacle before the IFC is transferred to the BIM manager.

In highly time constraint projects, data quality could be compromised. Increasing work efficiency and shorter iterative loops could lead to a reduction in time pressure in project teams. This could enable designers to spend more time on data quality or other aspects of the model in such projects.

Moreover, designers´ and BIM managers´ consequent feeling of discontent and frustration, as explained in *2.2.5.Organisational workflows* section, could reduce. This factor is key to achieve a data evaluation process that is engaging for all the professionals involved.

4.Implementation and assessment

The *Implementation and assessment* phase starts by approaching implementation details in this research. First, an introduction of a selection of three ongoing projects to conduct the assessment is made. Secondly, custom mapping of parameters at Hercuton are specified. Regarding the assessment, according to Peffers et al., 2007 a distinction should be made between demonstration and evaluation for assessments in design science research methodology.

Demonstration was referred as light-weight assessment to prove that the artifact feasibly works to solve one or more instances of the problem. This term is referred in this research as verification. The approach was to select strategic design processes and test them in two sample projects in order to ensure that the tool is functional and operational to fit its purpose.

Evaluation was defined by Peffers et al., 2007 as a more formal and extensive process in which the activity should assess how well the artifact supports a solution to the problem. This term is referred in this research as validation and it has been structured applying Venable et al., 2012 framework to design the evaluation. The four-step method is applied to validate the two sub research questions of this phase:

To what extent does the developed BIM model checking tool engage designers?

To what extent does the developed BIM model checking tool improve the data quality checking process?

Finally, the previous results are discussed and limitations in the research specified. All the professionals that have participated in this research agreed to share their responses and data anonymously.

4.1.Implementation at Hercuton

In this section, first, a selection of three ongoing projects is made to carry out the evaluation. Then, other important implementation details are explained such as the custom mapping of parameters at Hercuton. The goal is to introduce and define implementation details for later stages of the evaluation.

4.1.1.Selection of projects

The *Implementation and assessment* phase has been growing in complexity. Initially, tests were carried out for an isolated object to prototype the functionality. Two projects from Hercuton were used at this stage. Those projects are explained in *Appendix B: Initial projects for verification.* Then, three more ongoing projects at Hercuton were selected for this research for further verification and validation. Two projects are industrial and one commercial. The projects were in their detailed design phase. For instance, modellers were replacing conceptual elements such as general floors for more specific constructive elements such as prefabricated hollow slabs. Additionally, more parameters and values were included in the new elements. In all projects, the BIM Basis ILS was agreed as a BIM standard in their BIM execution plans. The projects are:

- DHL Parcel CityHub XL in Arnhem: The purpose of this project is to create a logistic centre for sending, receiving and storing parcels. The building has a total building area of 1.318 m^2. The majority of that is used as storage but there is also a 98 m^2 office. The building is surrounded by parking spaces to facilitate the access of loading vehicles. Figure 18 shows the scale and shape of the project in Revit.

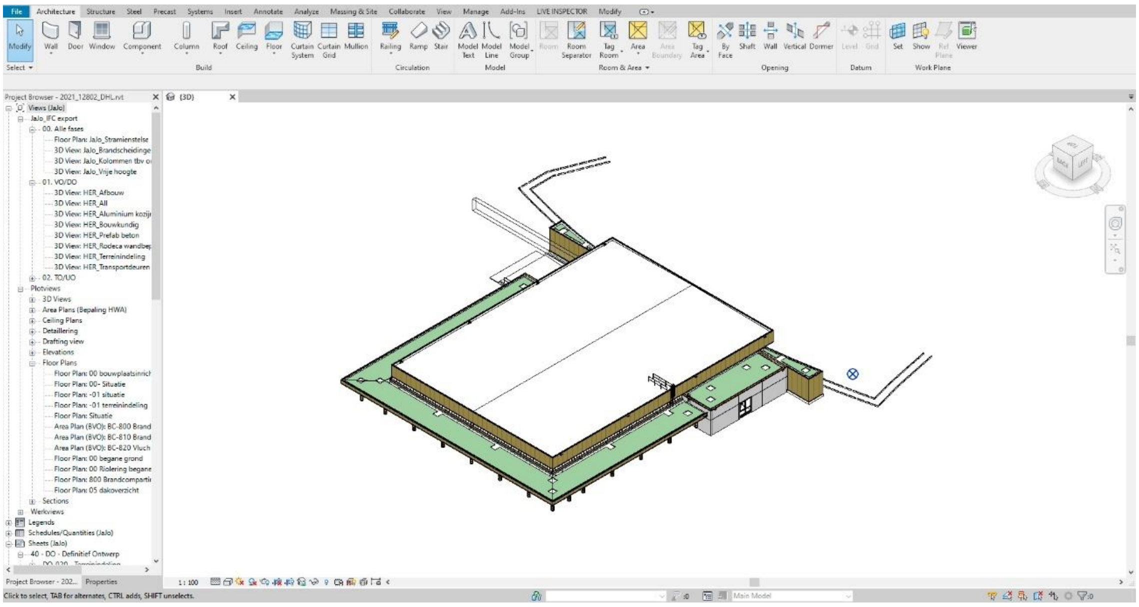

Figure 18: Revit project DHL Parcel CityHub (Hercuton, 2023)

- Mitari Hijstechniek in Eindhoven: The project consists of two parts; the main volume dedicated to store and distribute the goods into vehicles and the wooden volume designed to host three floors of office space. The total usable area of the project is 10.700 m^2. Figure 19 shows a general view of the project in Revit.

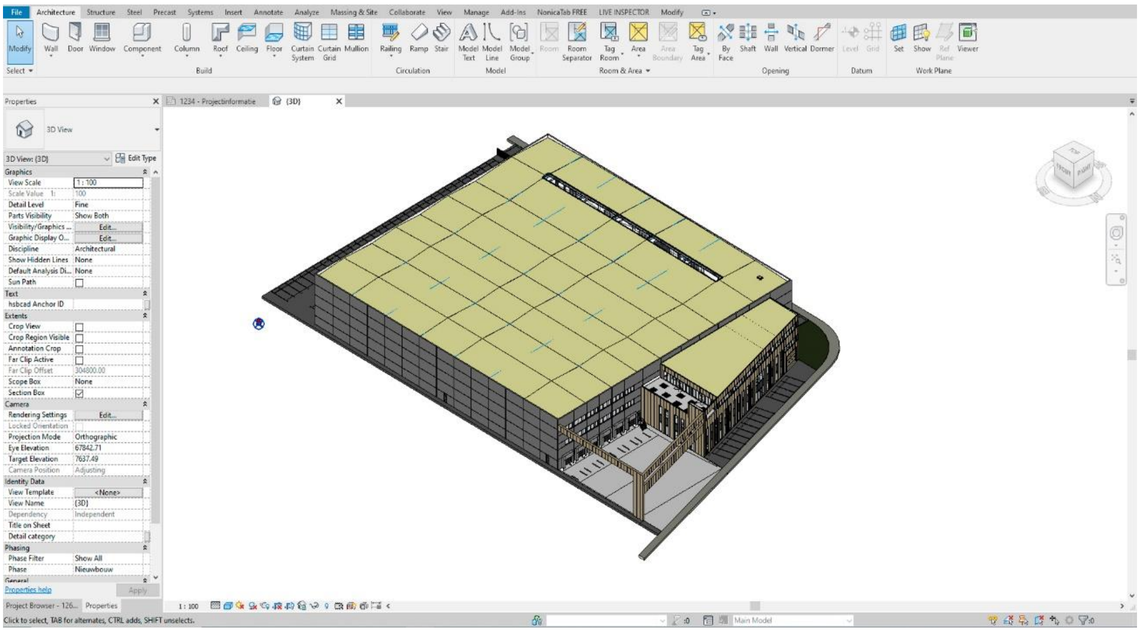

Figure 19: Revit project Mitari (Hercuton, 2023)

- Horeca Lindstedijk in Zwijndrecht: The building would be dedicated to a restaurant, bar zone and coffe area. The project is organised in three floors. The total built area of the building is approximately 676 m^2. Figure 20 below shows the current status and size of the project.

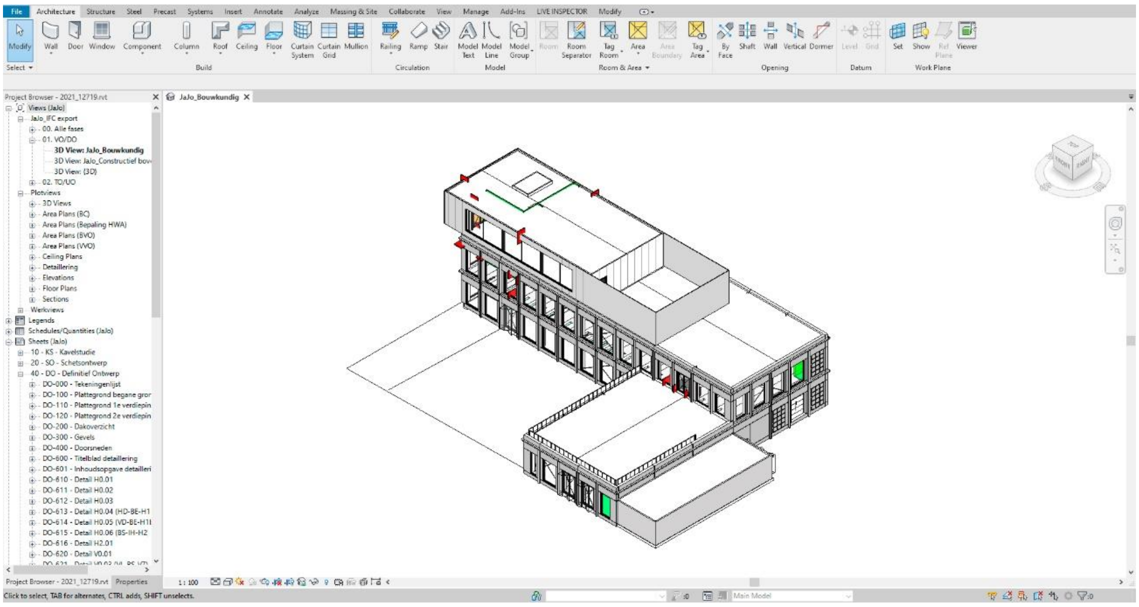

Figure 20: Revit project Horeca (Hercuton, 2023)

4.1.2.Custom mapping of parameters

As previously explained in the section *2.2.2.Data definition and export workflows*, Hercuton developed a custom IFC exporter to schedule and facilitate the standardisation of the process across the company. In this exporter, a custom data mapping was carried out. The goal was to facilitate the connection from existing Revit company standards at Hercuton with IFC standard parameters. Therefore, the correlation between parameters is shown in Table 7.

Table 7: Correlation of parameters at Hercuton and IFC standards

IFC Standard Parameter	Parameter Used at Hercuton
IfcBuildingStorey-Name	Name of level assigned to object
IfcName	JaJo_Name
IfcType	JaJo_TypeName
NL-SfB	Assembly Code
FireRating	NLRS_C_brandwerendheid_text
IfcMaterial	NLRS_C_materiaal

4.2.Verification

The verification of the tool takes place in two hardware environments (Hercuton virtual machine BIM environment and a standard HP Omen O15 laptop) for the four most recent versions of Revit (2021,2022,2023 and 2024). The goal is to achieve software stability and identify potential bugs that could limit or affect the usability of the tool during the implementation.

4.2.1.Criteria

A selection of strategic Revit processes has been made to ensure that the tool remains operational and fulfil its purpose in this research based on designers´ needs. Thus, the testing of the tool includes but it is not limited to the following processes:

1. Open and change project: The results need to be always up to date to proactively engage designers even when switching between projects.

2. Addition of new elements: As designers add new elements to the model, every added element should be checked against the set of rules.
3. Edition of existing elements: If an existing element or its type is edited, the results in the tool for that element and type should be identified and updated.
4. Deletion of existing elements: If an existing element is deleted, the results in the tool for that element should be deleted.
5. Addition and edition of project parameters: As project parameters may be added or edited in the categories of the model, the new tool should detect those actions and update the data quality flaws.
6. Rule definition and checking: As rules may change when updating a BIM standard, the tool should be responsive and recheck when attributes in rules change.

4.2.2.Results

The tool was successfully verified against the specified criteria. Thus, in relation to the selection of processes explained in the previous section, it can be concluded:

1. Open and change project: If a new project is open and the results window is active, all of them are recalculated automatically.
2. Addition of new elements: There is a dynamic detection and population of new issues as new elements are added to the model.
3. Edition of existing elements: The issues in the tool are updated when an element is modified.
4. Deletion of existing elements: The issues in the tool are deleted when an element is erased. Additionally, if the removed object is the last of its type, the result for its type is also deleted.
5. Addition and edition of project parameters: The issues are recalculated when project parameters are added or modified in the model.
6. Rule definition and checking: The tool updates the list of issues when there is a change in a rule or set of rules being applied.

4.3.Validation

The main purpose of this section is to find answers to the third and four sub research question. Validation has been structured applying Venable et al., 2012 framework to design evaluations in design science research. In his research, a four-step method is defined including evaluation requirements, criteria based on contextual factors, evaluation methods and design of the evaluation. This methodology is followed for the two research questions of this phase.

4.3.1. To what extent does the developed BIM model checking tool engage designers?

4.3.1.1.Evaluation requirements

The goal of this step is to analyse the context of the evaluation by identifying, analysing and prioritising the requirements and goals for the evaluation. It is important to underline that the key end-user is the designer given the design-integrated approach of the tool. Thereby, the purpose of this evaluation is to assess to what extent the tool engages designers. The evaluand, in this case, is the prototype of the data checking and reporting tool. The aspects or properties to evaluate are extracted from the designers´ needs and system requirements from the *Analysis* phase. The first part is focused on situational engagement while the second part on topical engagement, enabling proactive design and fitting its purpose.

Regarding constraints and features of the research environment, the implementation period is two weeks. Additionally, three modellers are involved in this process from a selection of three ongoing projects. The three projects were in their detailed design phase in which conceptual BIM elements like floors are switched into more specific construction elements like prefabricated hollow core slabs. It is understood that the sample selected is reduced which can lead to limited or biased results of this validation. Furthermore, there are also a significant number of other factors that can affect engagement such as modellers inner motivation, the complexity of projects or different levels of development in projects. Therefore, this sub question is approached qualitatively. This is aligned with the nature of the evaluand which is socio-technical.

The implementation takes place with no previous explanation or presentation to the BIM modellers. The goal is to simulate what other professionals could experience. This first part can serve as a preliminary evaluation of their engagement. However, in the second part after the tool has been used for two weeks, the evaluation is more extensive and rigorous to assess whether the artifact meets the goals.

4.3.1.2.Criteria based on contextual factors

Based on the previous contextual factors, a combination of two quadrants is chosen from the matrix introduced by Venable et al., 2012. The matrix for selection can be found in Figure 21.

DSR Evaluation Strategy Selection Framework		**Ex Ante**	**Ex Post**
		•Formative •Lower build cost •Faster •Evaluate design, partial prototype, or full prototype •Less risk to participants (during evaluation) •Higher risk of false positive	•Summative •Higher build cost •Slower •Evaluate instantiation •Higher risk to participants (during evaluation) •Lower risk of false positive
Naturalistic	•Many diverse stakeholders •Substantial conflict •Socio-technical artifacts •Higher cost •Longer time - slower •Organizational access needed •Artifact effectiveness evaluation •Desired Rigor: "Proof of the Pudding" •Higher risk to participants •Lower risk of false positive – safety critical systems	•Real users, real problem, and somewhat unreal system •Low-medium cost •Medium speed •Low risk to participants •Higher risk of false positive	•Real users, real problem, and real system •Highest Cost •Highest risk to participants •Best evaluation of effectiveness •Identification of side effects •Lowest risk of false positive – safety critical systems
Artificial	•Few similar stakeholders •Little or no conflict •Purely technical artifacts •Lower cost •Less time - faster •Desired Rigor: Control of Variables •Artifact efficacy evaluation •Less risk during evaluation •Higher risk of false positive	•Unreal Users, Problem, and/or System •Lowest Cost •Fastest •Lowest risk to participants •Highest risk of false positive re. effectiveness	•Real system, unreal problem and possibly unreal users •Medium-high cost •Medium speed •Low-medium risk to participants

Figure 21: Matrix DSR Evaluation Strategy Framework (Venable et al., 2012.)

Thus, the selected strategy is a combination of Ex Ante and Ex Post Naturalistic framework as the focus is on a summative evaluation with real users within a real system for a socio-technical artifact, the new data checking and reporting tool. Thus, the evaluated object is a prototype and judged only from practical experience ("Proof of the pudding").

4.3.1.3.Evaluation methods

Based on the previous quadrant selection, evaluation methods can be extracted from the matrix DSR Evaluation Methods Selection Framework (Venable et al., 2012). This matrix is shown in Figure 22.

DSR Evaluation Method Selection Framework	Ex Ante	Ex Post
Naturalistic	•Action Research •Focus Group	•Action Research •Case Study •Focus Group •Participant Observation •Ethnography •Phenomenology •Survey (qualitative or quantitative)
Artificial	•Mathematical or Logical Proof •Criteria-Based Evaluation •Lab Experiment •Computer Simulation	•Mathematical or Logical Proof •Lab Experiment •Role Playing Simulation •Computer Simulation •Field Experiment

Figure 22: Matrix DSR Evaluation Method Selection Framework (Venable et al., 2012.)

From the proposed list of methods for Ex Ante and Ex Post Naturalistic framework, qualitative surveys are selected to conduct the evaluation of this part. Using the results of the surveys, discussions in focus groups with the modellers take place to obtain broader insights of their engagement and experience.

4.3.1.4.Design of the evaluation

First part

The first session is focused on situational engagement, as previously introduced in the *2.3.1.Software engagement and perception* section. The purpose is to assess how engaging the tool initially is with no previous presentation. The only information given to the designer is "*The new tool is used to dynamically review project parameters in Revit*". Then, for 30 minutes, the designer works and explores the tool for the first time. After the session, a survey is filled by the designer and a discussion about the statements takes place.

To establish a solid foundation for the discussion, the modellers involved are asked to first fill a survey after the first session has concluded. The statements of the survey are defined in Table 8. The three modelers can score them from 1 (if they completely disagree) to 10 (if they completely agree). The selected modelers are of different age ranges (from 25 to 50 years old) and different level of expertise (from 1 to 10 years).

Table 8: Survey 1 asked to modellers after the first session.

User needs	Statements presented to modellers
It should engage designers.	I understood well the purpose of the tool.
	I found the tool intuitive and easy to use.
	I found the tool helpful to identify errors in parameters.
	I found the tool simple and concise but with enough information to fit its purpose.
	I found the tool helpful to work more effectively and efficiently with issues in parameters.

Second part

After two weeks using the tool, a second set of sessions with the modellers is carried out. These sessions are focused on topical engagement. After designers has had enough time to experience the tool and obtain a deeper understanding of its functionality, a survey is passed to the modellers and the results are discussed. The statements of the survey are defined in Table 9.

Table 9: Survey 2 asked to modellers after the second session.

User needs	Statements presented to modellers
It should enable proactive design.	The tool had no negative impact in my design job.
	The tool was well integrated in Revit and I was able to model in Revit effectively.
It should engage designers.	I kept the results side panel open most of the time.
	I found the pie graph helpful to monitor my progress in the model.
	Overall, I trusted the results detected by the tool.
	Overall, I found the tool helpful and I would use the tool again for other projects.
	Overall, I prefer to use this tool over Solibri which I do not fully know how to use.
It should be fit for purpose.	The tool helped me to identified errors in parameters that I probably did not notice while designing.
	The tool helped me to work with issues in parameters more effectively and efficiently.
	The tool helped me understand what the issues in the parameters were about.
	The tool helped me find reference to the objects that needed more attention.
	Overall, I believe the tool helped me to achieve a higher data quality model before delivering the IFC model.

4.3.1.5.Results

The three projects were first opened using the tool. The projects Horeca Lindstedijk and DHL Parcel CityHub XL in Arnhem displayed around 20 data issues mostly in types. On the other hand, in the project DHL Parcel CityHub XL in Arnhem, more than 70 data issues were detected. In the three cases, the majority of the issues detected were empty parameters and parameters not meeting the rule of the NL/SfB.

First part

The results for Survey 1 were extracted and the average rate was calculated for each of the statements asked to modellers. Statements were rated from 1, if they completely disagree, to 10, if they completely agree. The results are depicted in Table 10.

Table 10: Average ratings to statements in Survey 1

Statements presented to modellers	Average rating
I understood well the purpose of the tool.	9.0
I found the tool intuitive and easy to use.	8.6
I found the tool helpful to identify errors in parameters.	8.6
I found the tool simple and concise but with enough information to fit its purpose.	8.0
I found the tool helpful to work more effectively and efficiently with issues in parameters.	9.0

The results in Survey 1 represent a high situational engagement from the designers. They understood well the goal and the functionalities of the tool. Despite the short time to test the tool, they already found it fit for purpose and helpful to work more effectively and efficiently. Furthermore, before and after the installation, the modellers were enthusiastic with the new process. The results of the survey have been decomposed in *Appendix D: Results Survey 1.* Although it was not discussed or required, one of modellers even took the time to write a brief report of her thoughts about the new tool. The summary can be found in *Appendix C: Report of the tool by a designer.* This is a sign of interest and engagement from the modeller to improve the workflows and the organisational process. Two important points raised were:

- Several of the results were missing parameters, such as JaJo_TypeName, not included in a few objects. Modellers explained that adding or editing parameters to a family within the library is not within their scope of work and responsibilities. This also shows a slightly lower rating for the question of the survey "I found the tool simple and concise but with enough information to fit its purpose." One of them proposed to have a filter in the tool in order to filter in and out those family issues. However, they agreed that the tool can help them identify the issues and communicate them to the BIM specialist responsible of managing the library of families.
- In a few specific cases, one modeller explained that she didn´t know which value she should fill in for a parameter. Specifically, this happened with the classification system according to the NL/SfB standard.

Second part

Similarly, after the second session, the results from surveys were gathered and the average ratings for Survey 2 were calculated. The outcomes are presented in Table 11.

Table 11: Average ratings to statements in Survey 2

Statements presented to modellers	Average rating
The tool had no negative impact in my design job.	8.0
The tool was well integrated in Revit and I was able to model in Revit effectively.	8.6
I kept the results side panel open most of the time.	8.6
I found the pie graph helpful to monitor my progress in the model.	8.6
Overall, I trusted the results detected by the tool.	8.3
Overall, I found the tool helpful, and I would use the tool again for other projects.	8.3
Overall, I prefer to use this tool over Solibri which I do not fully know how to use.	8.6
The tool helped me to identified errors in parameters that I probably did not notice while designing.	9.0
The tool helped me to work with issues in parameters more effectively and efficiently.	8.6
The tool helped me understand what the issues in the parameters were about.	8.0
The tool helped me find reference to the objects that needed more attention.	9.0
Overall, I believe the tool helped me to achieve a higher data quality model before delivering the IFC model.	9.6

The outcomes from Survey 2 and discussions were very positive. They validate that the new checking and reporting process meet the designers´ needs from the *Analysis* phase. From this part of the validation, the new data checking and reporting tool:

- Enables proactive design.
- Fits its purpose.
- Generates high topical engagement from designers.

Most of the data quality issues in models were solved between session 1 and session 2. From these results and the discussions that followed, it can be extracted that:

- The new checking process was perceived by practitioners to make a difference or delta in the data quality of the model before the model is exported to IFC and it enters the data quality review. The tool was perceived to help identified errors that otherwise would have been missed.
- Modellers understood the BIM standards and naming conventions to follow as well as the necessary actions to solve the issues. The new data checking and reporting process enabled designers to identify and work on data quality issues more effectively and efficiently within the design process.
- Although the checks undertaken were not advanced, modellers preferred the design-integrated and the ready-to-use approach over more advanced and complex solutions like Solibri.

- Potential improvements in the tool were detected and proposed by the modelers. The tool served well as a prototype for the research, however it is understandable that more developments need to take place to make data correction workflows even more effective and efficient. These improvements are described in detail in the section *5.3.1.Recommendations for future research and development.*

These outcomes corroborate essential factors and establish a solid foundation to validate the ultimate goal of this research.

4.3.2.To what extent does the developed BIM model checking tool improve the data quality checking process?

4.3.2.1.Evaluation requirements

The main purpose of this evaluation is to evaluate the extent of the benefits in the organisational data checking process. This evaluation follows up the previous evaluation process about modellers engagement. However, in this case the evaluand is the organisational data checking process with the new IFC models created in the previous evaluation. The three main aspects or properties to evaluate are:

- Increase in effectiveness and efficiency in the identification and correction of data quality issues at the organisational level.
- Improvements in data quality before entering the data quality reviews and in the overall process.
- Reduction of total duration and the number iterations in the data quality reviews between modeler (correction) and specialist (detection).

In regard to the features and constraints of the research environment, this evaluation counts on the previous implementation period of two weeks with three modellers involved in three different projects. The three projects were in their detailed design phase in which conceptual elements like floors are specified further into more specific construction elements. Nonetheless, now the focus is on the BIM specialists. The reason to select the BIM specialist role is that they usually have a deeper understanding on how the data checking processes work at the organisational level. The sample selected is reduced and therefore it could lead to limited or biased results in this validation.

Similarly to the previous validation, there are a number of external factors, such as the inner motivation of the professionals involved or the complexity of the project which can have large impact on the data checking process at the organisational level. Therefore, this section is approached qualitatively. This is also in line with the nature of the evaluand which is socio-technical.

In this case, a presentation of the tool takes place before the data quality review is conducted. Thereby, BIM specialists are aware of which aspect of the model may present improvements, so they can judge on those. The evaluation is specific and based on the qualitative comparison to the organisational process without the tool implemented in previous reviews of each project.

4.3.2.2.Criteria based on contextual factors

Based on the previous contextual factors, now the evaluation is on an instantiation (an instance of a data quality review) instead of on a prototype. Nonetheless, the judgement would still be based on practical experience from the practitioners ("Proof of Pudding"). Therefore, using the matrix included in Figure 21 in the section *4.3.1.2.Criteria based on contextual factors*, the selected quadrant/strategy for this case is an Ex Post Naturalistic framework.

4.3.2.3.Evaluation methods

Using the Ex Post Naturalistic quadrant, potential evaluation methods can be explored in the matrix DSR Evaluation Methods Selection Framework (Venable et al., 2012). The matrix can be found in Figure 23 in the section *4.3.1.3.Evaluation methods.* Thereby, qualitative surveys are the method used to assess this validation. Additionally, discussions in focus groups with the BIM specialists followed after the results of the survey were explored. The goal was to get specific feedback about the different statements or other benefits that could have been missed.

4.3.2.4.Design of the evaluation

In this case, surveys and discussions take place just after the data checking review by the BIM specialist finishes. The goal is to obtain clear insights about the iterative process after the tool has been implemented. Thus,

Table 12 collects the statements of the survey presented to BIM specialists. Those statement can be scored from 1 (if they completely disagree) to 10 (if they completely agree). The selected BIM specialists are from a similar age group (from 35 to 45 years old) and similar level of expertise.

Table 12: Survey 3 asked to specialists after data checking review

Statements presented to BIM specialists
The tool helped us reduce the number of iterations with the modeller in the data checking review.
The tool helped us improved the data quality of the model before entering the data checking review.
The tool helped us achieve a more effective and efficient data checking review.
Overall, the tool helped us reduce the total duration of the data checking review.
Overall, the data quality of the model at the end of the data checking review was the same with or without the tool.
Overall, the data quality of the model at the end of the data checking review was higher with the tool.
In highly time constraint projects, I believe the tool could reduce time pressure.
In highly time constraint projects, I believe the tool could help us deliver a higher data quality model.

4.3.2.5.Results

The results from three BIM specialists were gathered and depicted in Table 13.

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Table 13: Average ratings to statements in Survey 3

Statements presented to BIM specialists	**Average rating**
The tool helped us reduce manual work when checking the model.	7.6
The tool helped us reduce the number of iterations with the modeller in the data checking review.	8.0
The tool helped us improved the data quality of the model before entering the data checking review.	8.0
The tool helped us achieve a more effective and efficient data checking review.	8.3
Overall, the tool helped us reduce the total duration of the data checking review.	9.0
Overall, the data quality of the model at the end of the data checking review was the same with or without the tool.	2.0
Overall, the data quality of the model at the end of the data checking review was higher with the tool.	8.6
In highly time constraint projects, I believe the tool could reduce time pressure.	5.6
In highly time constraint projects, I believe the tool could help us deliver a higher data quality model.	7.6

The results from Survey 3 and the discussions were positive. According to the specialists involved, the tool helped them reduced manual work specially on the designer´s side. Additionally, the number of iterations and duration to review data with the modeller was perceived as reduced. The organisational data reviews were also considered to be more effective and efficient with the tool implemented. Specialists explained that in comparison with previous data quality reviews in the same projects, the presence and data quality had significantly increased. They mentioned that, in previous reviews without the tool implemented, there were far more objects with missing data.

Regarding the data quality after the organisational reviews, specialists are confident that it would be higher with the tool implemented. One specialist explained that this is because, during the organisational data checking reviews, they found it difficult to communicate the modellers the different issues as well as to pass object references to them. As a result, specialists often give up in their explanations and end up the data reviews with certain aspects of the model with wrong or missing data. In contrast, regarding the final delivery of projects, specialists explained in the discussions that the final reviews are stricter and more extensive, and they believe that there would not be substantial improvements in the data quality with or without the tool after the final review of a project.

Given the limitations to check data completeness based on project contexts, the check in several of the parameters was only carried out if the parameter already had a value. However, it was found that specific families which were used for fire protection purposes could have been checked to contain that specific data. The rules could have been more refined and checks more accurate and complete.

Regarding the organisational data checking process, one of the specialists explicitly added to the discussion “This tool makes me very happy” as he often finds the repetitive process frustrating. This was also discussed with the other specialists who perceived that the improved process was also less annoying and frustrating as a result of the decrease in the number of issues to communicate.

Finally, in highly time constrained projects, two out of the three specialists argued that the tool would not significantly reduce the time pressure. A discussion about the results and their limitations is provided in the next section.

4.4. Discussion and limitations

From the previous results, it can be concluded that the new data checking and reporting tool was successfully validated in terms of fulfilling the designers´ needs specified in the *Analysis* phase and producing perceivable benefits in the organisational data checking process.

Several lessons are learned from the previous process:

- The context is as important as the solution to achieve successful implementations with new tools. Factors such as the company structure, as in our case for the responsibilities of creation and edition of families, can alter professionals' workflows, affect their engagement and/or the fitness for purpose of new tools.
- The field specific expertise and knowledge of professionals, as in our case for the modellers with the classification system, can play a determinant role in approaches that simplify an area of specialisation.
- Although discussions with BIM modellers and specialists took place to involve and get feedback from them during the entire research, it was noticed that a significant part of the feedback came during the implementation. Thereby, further development iterations during implementation phase would have probably improved the overall results and the benefits perceived in this research.

Additionally, it is important to acknowledge the potential bias of the results in this research. The sample of projects and professionals were very limited and only within one single company. Although the professionals selected had a similar level of expertise to other colleagues at Hercuton, other companies with less knowledgeable or less motivated-to-change professionals may find obstacles when implementing similar strategies.

On the other hand, specialists expressed that the organisational data checking reviews would produce higher data quality models with the tool implemented. One of the main obstacles they found in the existing data correction workflows was the communication and explanation of the issues and references to the objects to which they are related. One specialist argued that they often give up in their efforts to correct some of those issues during the organisational reviews and end up with certain aspects of the model with missing or wrongly filled data. Thereby, they explained that the implementation of the tool increases data quality also after the organisational reviews. Nonetheless, issue managers could be of significant help to overcome this difficulty. Therefore, the perceived benefit in the enhancement of the data quality after the reviews may be limited to companies which do not already implement issue managers in their workflows.

In highly time constrained projects, the benefits in the reduction of time pressure seems to be limited. However, if the process is more effective and efficient and the duration of the reviews shorter, it seems obvious that there should be a reduction in time pressure in such projects. Two out of the three specialists perceived that the tool could be beneficial in that sense but argued that the reduction of time pressure would not be substantial or perceivable.

Furthermore, the developed data checking and reporting tool presents several limitations important to underline:

- Limitations in terms of adaptability to different BIM standards. Although other BIM standards were reviewed and considered in the *Analysis* phase and during the development of the tool, the main focus was on implementing the rules included in the BIM Basis ILS. In contrast, in other more extensive and specific BIM standard such as ILS O&E, information requirements are defined by project phase. In those cases, the new tool may not adapt to the changing requirements and fulfil its purpose effectively.
- Limitations in terms of data completeness checks. Obstacles were identified when implementing several of the rules selected from the BIM Basis ILS such as Fire Safety or Material. As explained in the *Analysis* phase, varying information requirements made the checking of certain parameters relevant or irrelevant. In those cases, the approach was to only check the value of a parameter if it already had a value. On one hand, this strategy avoids flagging false positive issues with parameters that do not actually need to exist or be filled in. In contrast, parameters that should be filled in are skipped from the checking process if they don't exist or were left empty by the designer.
- Limitations in terms of data correctness checks. In most cases, values were checked to follow specific naming conventions. However, following a naming convention does not mean that the value of a parameter is correct. In that sense, issues in the tool can look as properly filled, as they follow the naming convention, but still have a wrong value.
- Limitations in terms of software compatibility: Although integrating the tool in Revit can be considered an opportunity to reach a large number of professionals using a common design framework, it may also be a limitation for professionals using other design solutions.

5.Conclusion

In this section, the goal is to summarise the results from the previous phases and find answers to each of the sub research questions. Then, the main research question, *How can novel design-integrated tools improve the data quality checking process in organisations?* is approached.

Finally, future research into the topic is suggested and a final reflection is undertaken.

5.1.Sub-research questions

5.1.1.What are the main challenges to improve data quality and compliance with BIM standards?

The conclusion to this question is extracted from the *Analysis* phase. A literature review is carried out to examine the state of the art in BIM data quality control and BIM standards. Next, the focus is on how those concepts are applied in practice and which challenges are found from the micro level (e.g. data schemas) to the macro level (e.g. organisational process).

Based on the categories of BIM data quality checking of Lilis et al., 2018, data consistency was found the least challenging category for automated rule checking systems. Formats, data structures or naming conventions bring limited technical challenges for automated data checking processes. However, data completeness was considered to be often project specific and based on varying information requirements. Similarly, data correctness was found dependent on meaning and context. Therefore, data completeness and correctness can bring significant challenges when converting information requirements from BIM standards to machine readable formats.

In literature (Siebelink et al., 2020, Jensen & Gade, 2022), there is a general agreement on the benefits of adopting BIM standards in the industry. BIM standards enable that professionals work with the same level of detail and consistency, reducing the risk of errors and conflicts.

Nonetheless, given the large number of available BIM standards combined with the possible conditional checks to be applied, defining rules is complex and demanding. As there is not an established way of creating BIM standards and codes, a new layer of difficulty is added to translate them effectively to specific rules in applications. Moreover, organisations usually agree on BIM standards on a project basis which makes the adoption even more challenging for professionals.

The BIM Basis ILS is an excellent first step to work with information that is exchangeable, structured, and reusable. Its simplified and flexible structure at the sector level represents an opportunity to establish a minimum threshold of information requirements in the industry. Thus, the BIM Basis ILS can be an impactful alternative to take the industry to the next step in the adoption of BIM standards.

In practice, several challenges were found in existing exporting processes and data checking tools. Firstly, the wide range of possible settings in native exporters are a key obstacle when attempting to standardise IFC exporting processes. The process is usually time-consuming interrupting designers´ workflows. Additionally, IFC tools are pushing designers out of the design framework preventing simple intuitive checks. Modellers often find technical difficulties in understanding data evaluation systems which is leading to a new area of specialisation usually undertaken by BIM managers or specialists. These technical obstacles limit the adoption of data evaluation processes further in the industry.

On the other hand, there is a lack of integration of existing data checking tools in the design framework. This has brought checking processes to be carried out after design periods. They have become iterative multiagent static processes that assess data quality at certain points in time. The separation of detection and data correction workflows in the iterative process leads to constant interruptions in the designers´ workflows. Furthermore, by the time the data reviews take place, it is already late to tackle missing or wrong basic data structures in models increasing the duration and iterations in the organisational process. As a result, the data checking process becomes ineffective leading to missing or false positive issues.

The existing organisational data checking process was found in the intersection of the time of project delivery and the data quality of models. Organisations establish implicitly or explicitly a balance when delivering a project. Depending on the situation, one factor may be compromised in favour of the other. For instance, in highly time constraint projects, the checking process could be shorten to meet the project schedule which can produce lower quality models. Therefore, the culture of organisations and how projects are managed can have significant influence in the final quality of models.

5.1.2.How can new tools engage and be integrated fluidly in the designer´s and organisational workflows?

This sub question was introduced in the *Analysis* phase with a summary of user needs and system requirements to approach the identified challenges. Those concepts were developed further in the *Synthesis and development* phase. Firstly, the functional concept of the tool and specific workflows were defined. Then, frameworks and interfaces for the end-users were analysed and designed.

Increasing the designers' understanding and trust in the data checking process is critical to gain and maintain engagement over time. Thus, the purpose was to present information in a simple and concise manner to avoid information overload and facilitate end user comprehension. Thereby, the completeness of the checking process was introduced to designers with visual and dynamic graphs that depicted overall results in the model. This may have helped to perceive tasks as more achievable and increase job satisfaction.

Fitness for purpose also plays an important role in engagement rates. If the tool does not fulfill its purpose, it is very likely that the end users will find it helpless and will not use it at all. In this case, the goal was to improve basic data structures during design periods by enabling designers to detect, review and work on data quality issues dynamically. This was approached by making the identification of data quality issues more accessible, effective and efficient as well as anticipating and proposing forthcoming actions based on the issue at hand.

Regarding the organisational workflow, the new tool was integrated into a design software solution already-in-use within an existing functional process. This facilitated and sped up the implementation process. Similarly, the novel approach to support existing tools instead of attempting to replace them could have reduced reluctance to organisational change.

Furthermore, another aspect influencing end-user engagement is the design dedicated approach of the tool. The fact that the tool has been designed with modelers and for their specific needs may have been determinant to achieve high engagement. Thereby, the development of more specialized and dedicated tools has significant potential to achieve high end-user engagement rates of specific target groups.

On the other hand, a side dockable panel allowed to display information from the tool while enabling designers to work with other design commands. This part was essential to enable proactive design and dynamic data checking in the tool. The MVP was designed as an intuitive and ready-to-use system with the least necessary configuration and previous knowledge expected from designers. Nonetheless, the developed system is still flexible by enabling edition of the default settings to potential changes in BIM standards and/or organisational changes.

The live reporting of objects may be the most engaging and distinctive part compared to existing data checking tools. This allows designers to fluidly carry out their work with no specific input or action in the tool while data quality issues are updated and displayed automatically. This was achieved by distinguishing and developing two different detection workflows:

- The light change detection workflow was called when objects were added or modified in the model.
- The extended detection workflow is a complete and heavy process which runs a check in all objects of the model for all the rules specified.

The two distinct processes and their integration in different design processes enabled to minimize work interruptions and engage designers in the identification and correction of data quality issues.

5.1.3.To what extent does the tool engage designers?

This sub question was approached during the validation process through the four-step method from Venable et al., 2012 to evaluate design science research. The assessment was divided into two parts. The first part was a preliminary study focused on situational engagement and the first encounter of the modellers with the tool. Secondly, after the modellers used the new tool for two weeks, a more comprehensive evaluation took place. In this part, the main goal was to assess whether the new tool fulfils the user needs and system requirements found in the *Analysis* phase as a determinant factor in the engagement of designers. Surveys and discussions were used to collect and evaluate the qualitative results.

The new data checking and reporting process promoted situational and topical engagement from designers in the organisational data checking process. The three modellers were enthusiastic with the new data detection and correction process. They found the tool intuitive and understood well its purpose and functionality since the beginning. Furthermore, they declared the tool was helpful and they would use it again in other projects. During the two-week implementation period, the tool was used 242 times by the three modellers to identify and review issues in parameters. A central data log was established to record every time a modeller made use of the tool. All detected issues by the tool were solved during the implementation period.

Additionally, the tool enabled proactive design. The three modellers agreed that the tool had no impact in their design job and that it was well integrated to model effectively in Revit. It is important to emphasize that, at Hercuton, the creation and edition of families is managed independently by other professionals. However, it was noticed that if the family edition takes place while modelling a project, as it may happen in other companies, the extended checking workflow can have a negative impact in the productivity of the designer as the tool loads all the new issues when switching back from the family to the project.

On the other hand, the participants found the tool fitted for purpose by helping them to work with issues in basic data structures more effectively and efficiently. Additionally, the new data checking and reporting process enabled them to identify issues in parameters that they would not have noticed. As a result, the tool is perceived to have helped them achieve a higher data quality in the model before entering the organisational data checking review.

The combination of the three previous factors leads to a positive response to this question. Nonetheless, one factor, that can affect to other implementations with a similar strategy, is the expertise of modellers with the adopted standards and classifications system. Thereby, specialised training programs could help companies to overcome this obstacle before the implementation takes place.

5.1.4.To what extent does the developed BIM model checking tool improve the data quality checking process?

This sub question can be answered with the results of the *Implementation and assessment* phase. Verification and validation were carried out through surveying and discussing with the modelers and specialists involved at different stages of the data quality checking reviews.

First, the approach was to evaluate the engagement of designers. The nature and focus of the tool required designers' engagement to achieve enhancements in the organisational checking process. After the first two sets of sessions, the modelers showed high situational and topical engagement as well as the tool was validated to enable proactive design and fit its purpose. Next, the perceived benefits in the organisational data checking review were surveyed and discussed in comparison to previous reviews in the same projects. From the evaluation, it can be concluded that the improved process was perceived to produce:

- <u>Enhancements in data quality before and after the organisational checking reviews.</u> The three modelers perceived that the new tool helped them achieve a higher data quality model before entering the organisational review. This was also noticed by the specialists who, in comparison with previous reviews on the same projects, found less missing and wrongly filled in data. Additionally, specialists argued that, not only did they agree that the data quality had increased before entering the data quality reviews, but they were also confident of the improvements in data quality after the data checking reviews. Their reasoning is that they find obstacles communicating and specifying issues to modelers. As a result, they often end up the regular data reviews with certain aspects of the model incomplete or wrongly filled. Nonetheless, issue managers could be of significant help to overcome this obstacle. Therefore, this benefit may be partially limited to companies that do not implement issue managers in their workflows. Regarding the data quality in the final delivery of projects, specialists argued in the discussions that the final reviews are much stricter, and they believe that there would not be significant improvements in the data quality with or without the tool after the final review of a project.
- <u>Reduction of duration and number of iterations between modelers and specialists in organisational reviews.</u> The perceived higher data quality of the model before entering the organisational process, led to shorter reviews by the specialists and modelers as there were less issues to identify, communicate and correct. Furthermore, it was perceived that less iterations in the organisational process took place to achieve the required result of the reviews.
- <u>Increase of effectiveness and efficiency in detection and correction of data quality issues.</u> Data quality issues in basic data structures were identified and reviewed directly by the modeler within the design environment. Otherwise, issues would have had to be detected and communicated by the specialist and identified and reviewed by the

modeler. The increase in effectiveness and efficiency was perceived by modelers and specialists who notice the enhancements in design workflows and the organisational process respectively.

- <u>Decrease of personnel frustration in the organisational process.</u> Although this factor was not included in the surveys, during the discussions, specialists communicated that the repetitive process and the obstacles to communicate and specify issues to modelers was sometimes frustrating. As a result of the previous benefits, specialists expressed their contentment with the new tool and the enhancements in the process. This benefit may be limited to companies that do not include issue managers in their workflows.

Finally, the organisational data checking process was found in the intersection between the time of project delivery and the data quality of models. In highly time constraint projects, specialists agreed that there would be less benefits in the reduction of time pressure. However, considering the results, it seems obvious that there should be a decrease in the duration of project delivery and, as a consequence, a reduction in time pressure in highly time constrained projects. Two out of the three specialists agreed that there would be a reduction but that the decrease in the duration of the reviews is not enough to make it substantial in such projects. However, other companies with a different balance between the time of project delivery and the data quality of models, may experiment different results. This topic is suggested for further research in the chapter *5.3.1.Recommendations for future research and development.*

5.2.Main research questions

5.2.1.How can novel design-integrated tools improve the data quality checking process in organisations?

A large amount of building information is defined in BIM models from and for different disciplines and lifecycle phases. Automated rule-based checking tools can minimize human errors in the identification of issues and reduce inefficiencies in the use of time and human resources. Although there were automated rule-based solutions available, none of them were focused on the needs and expertise of designers and met the business needs of most organisations.

In contrast, according to several authors (Volarik et al., 2022; Choi et al., 2020), model quality significantly relies on the modelling phases and design quality could be improved when quality control requirements are actively utilized. Design-integrated tools can facilitate continuous checks and speed up the implementation of new data quality checking processes, as designers are already familiar with the design framework, but most importantly they can actively engage and give responsibility to designers early in the process who play a key role in the development of models.

The new design-integrated tool enhanced the organisational checking process by adding a new checking layer during design periods. Improvements were achieved with constant checks which raised the data quality of the source models before entering the organisational reviews. In that line, mid-size or small organisations, which may lack of the expertise to check building data with existing advanced tools, may experience more extensive benefits in terms of data quality improvements and increase of effectiveness and efficiency with similar strategies.

Other authors encountered advantages in specialised data quality checks (Volarik et al., 2022; Leygonie et al., 2022) for specific building analysis and tasks (Lilis et al., 2018) during the modelling phases. However, the approach of their research was fundamentally different. They did not actively check the model while the design was actually being developed and instead, they opt for solutions out of the design framework. In contrast, this research creates new development opportunities and lines of research to enhance the data quality checking process for different disciplines (e.g. structural, mechanical and electrical engineering) by using design-integrated specialised data checkers.

Given the uncertainties in project information in conceptual design phases, BIM data may be incomplete or inaccurate at that stage. On the other hand, during the organisational reviews, it is too late to tackle basic data issues in models leading to an ineffective checking process. Thus, the detailed design phase seems to be the adequate stage to implement new design-integrated data checking tools.

The experimental and time constraint development of this research produced several dependent benefits at different levels. However, there is significant potential to enhance collaboration workflows and communication of issues across different roles in the process with further developments. In all cases, new design-integrated tools can raise awareness early in the process and promote designers' involvement of different disciplines in the organisational process who are in a dominant position to identify and correct issues.

5.3.Recommendations and reflection

5.3.1.Recommendations for future research and development

First, the implementation of the design-integrated solution at Hercuton was influenced by the custom IFC exporter. As the custom exporter mapped IFC files from company specific parameters, the review was conducted on those. However, the implemented information requirements are translatable and operational for other companies as well, by adapting parameter names and types.

The improved data checking and reporting process was verified and validated with a selection of chapters from the BIM Basis ILS. This research laid the foundations for more precise and extended data checks within designers´ workflows. Therefore, further research is suggested to expand the checks of the tool to other chapters of the BIM Basis ILS and other BIM standards.

Additionally, this research paves the way for targeted and dedicated approaches in BIM data quality control. The approach can be extrapolated to other disciplines involved in the development of BIM models, such as MEP or structural engineering. Thereby, engaging other strategic roles could bring benefits to the data quality of models and/or the organisational data checking process.

On the other hand, BIM specialists at Hercuton found that the developed solution could also be helpful to identify and review parameters in the creation and modification of BIM families in their company. This creates new opportunities for research to improve BIM content related activities and processes within companies.

Regarding the implementation of the tool in highly time constrained projects, the benefits in the reduction of time pressure were perceived by specialists as limited. Other companies with a different balance between time of project delivery and data quality may experiment different results. Therefore, further research is suggested across companies with different priorities and organisational culture.

Furthermore, apart from the proposed lines of research, improvements are also proposed to the developed data checking and reporting tool:

- Communication: As modelers found that the edition of BIM families is out of their scope of work, integrating the communication of those issues to the BIM content manager would make their work even more effective and efficient. Additionally, when the modeler lacks the knowledge to fill or review a parameter, the tool could be used to communicate the issue with other professionals with more expertise.
- Data correction: The developed data correction workflow enhances a more effective detection and review of parameters by designers. However, in discussions with modelers, it was noticed that the data correction process can be improved further. For instance, the filling and edition of parameters could be conducted directly within the tool or the selection of elements could additionally isolate the element to have a clearer view of them.
- Combination of rules: While implementing the selection of rules from the BIM Basis ILS, it was noticed that having the possibility to combine rules with "AND" or "OR" statements would have helped to conduct more accurate checks in the models.

5.3.2.Reflection

The literature review was essential to explore the state of the art and establish a solid foundation of theoretical concepts in this research. A considerable amount of research in the field of BIM data quality control and the use of existing tools was found. Nonetheless, dedicated data quality checking approaches and their integration in role specific and organisational workflows were found to receive little attention in the academic world.

In practice, new developments seem to be focused on communicating and synchronising detected issues to design solutions from external issue managers or CDEs such as BIMcollab, Revizto or Catenda Hub. Those solutions may have significant benefits but several processes are still manual such as the detection and creation of issues. This increases the resources and time spent on projects. On the other hand, external advanced tools were found too complex and advanced for designers raising the expertise for data quality checks and limiting its adoption.

BIM specialists, modelers, and managers at Hercuton were enthusiastic about this research since the beginning. The team was proactive to explore and give feedback about the structure and argumentation of this document as well as the developed tool. Their interest facilitated the development, implementation, and documentation process in this research.

On the other hand, the BIM Basis ILS presents an opportunity to facilitate the adoption of minimum information requirements with a clear and reduced scope. Thereby, it was of significant help in this research to narrow down the scope and focus on essential basic data structures in the checking process.

Finally, regarding the results of the research and development process, the higher goals of this research were met through the development and implementation of the new data checking and reporting tool. Furthermore, the results exceeded the initial expectations in some areas. For instance, improvements in the data quality of models before entering the reviews were expected but not enhancements in data quality after the reviews took place. Finally, it was rewarding to encounter such a high interest and willingness to research BIM data quality control and enhance organisational processes.

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Appendices

Appendix A: Information from industry professionals

Throughout this document, a significant number of references are made to preliminary discussion and interviews with professionals. As this graduation project has been carried out in collaboration with Hercuton, regular meetings and discussions with professionals within the company have been essential in the development of this research. Although discussions were unavoidably biased, the challenges and solutions found in this research have been analysed and found to be applicable to other AEC companies in the Netherlands. Thus, two types of meetings took place on a weekly basis with different roles in the company:

- Meetings with digital leader at Hercuton, Daan Arts. A deeper understanding of the current state of the art of the topic in practice was acquired. Additionally, the vision and challenges of where the company and industry are heading established a framework for this research. Moreover, insights on current organisational processes and the implementation of BIM standards were gathered and analysed.
- Meetings with BIM specialists at Hercuton, Robbert Ploegmakers, John Verhoeven, Milan Mastbergen and Xinzhi Jiang. Specific needs and solutions were discussed on a detailed technical level. Their participation in the development of BIM content and solutions as well as in the data correction process itself brought a unique hands-on perspective to this research.

The quotes included in this document have been explicitly reviewed and approved by the corresponding professional. Key information and statements extracted from the previous discussions and meetings are:

"There is a gap between roles in the current data checking process as BIM managers know data requirements and modelers should execute them. This gap often generates frustration and discontent."

"Available data checking tools are way too complex for our designers. We need simple and dedicated solutions to guide our designers during the modeling process."

"Solibri is very rarely used by our modellers. Partly, because they must make an IFC, run the check and then adjust everything in Revit again. The process is cumbersome and time consuming."

"Well defined basic data structures are essential for the checking process. For example, if objects are not correctly identified as types or names, rule checks can be missed for certain objects or applied to the wrong set of objects."

Appendix B: Initial projects for verification

The verification grew in complexity. Initially, tests were carried out for an isolated object to prototype de functionality. Next, two industrial projects from Hercuton were selected and tested, before other projects were selected for implementation of the tool. These two projects are:

- Sample project used previously by other BIM programmers at Hercuton. The project contains a selection families and objects developed and used across projects at Hercuton. This is helpful to initially approach the implementation and identify potential patterns in errors. Figure 23 shows the size and scale of the sample model.

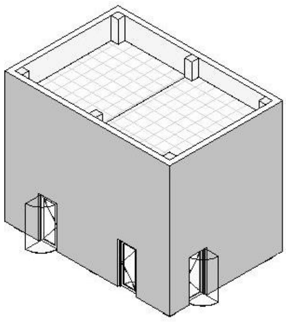

Figure 23: Sample project used for verification (Hercuton, 2022)

- A real project carried out at Hercuton in 2022 of two units developed in Rotterdam. This project enables us to verify the tool in a real working environment and with a significant number of different objects. Figure 24 shows the scope and scale of the model.

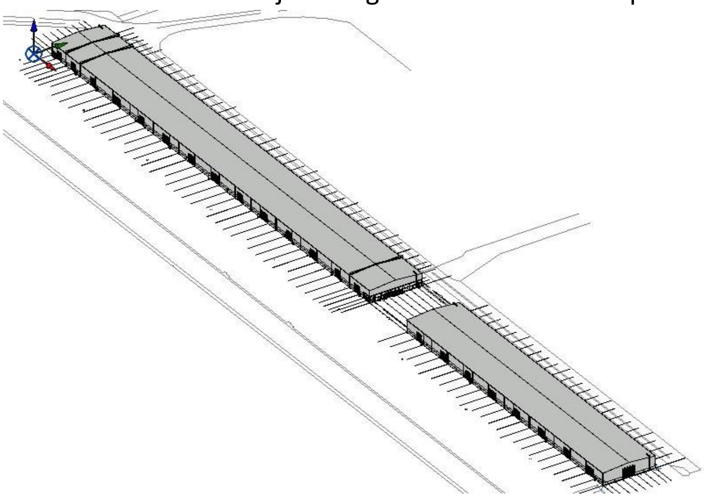

Figure 24: Industrial project in Rotterdam used for verification (Hercuton, 2022)

Appendix C: Report of the tool by a designer

Although it was not required during the implementation, one of the modellers voluntarily carried out a summary table with her thoughts about the tool. Table 14 shows the report by the modeller.

Table 14: Feedback summary created by a modeller at Hercuton

Tool	Pro's	Con's	Improvements
General	Very nice interface. Love the circle that shows how many things are wrong in the model. Immediately clear what the tool is being used for. I prefer the condensed view of the issues. How the results are shown is awesome. I like the filters and the options that are possible. Nice visual connection between issues and colours. That helps a lot.	Uses considerable space in Revit. I put the tab on another screen to have more modelling space. The plugin says that some parameters do not exists. Like the object 'Generic models - symbool 2'. But I am not the person that changes families. I could not solve some parameters because our Revit experts do that.	For me it would help if the name of the button on the main menu is the same and correspondents to understand it and make the connection in my head of what i am working with. Filtering by rule is awesome, maybe put by this button ILS so you know that the rules are coming from the BIM Basis ILS? We work a lot with the NLRS-B coding for the assembly codes. Maybe it is possible to also filter by assembly codes?
Results in the model	Very nice design! Like the legend that shows up if I am looking to the meaning of the tasks that appear.	If I click on filter, the tool makes a filter on the tab 'Pending to be reviewed'. For me it is more logical if the filter tab belongs to the tab 'pending to be reviewed'.	
Pending to be reviewed	Very helpful that I can select the building element in the plugin and that it can be displayed in the model by the tool. Makes it a lot more insightful.	The button 'Click to select in model' is available in the default list but not in the condensed view.	I don't know it is possible to make is to have the option to fill the missing or wrong parameters in the plugin itself.

Appendix D: Results Survey 1

In this appendix, the results gathered from designers in Survey 1 are broken down. From Figure 25 to Figure 29, those results are depicted per question.

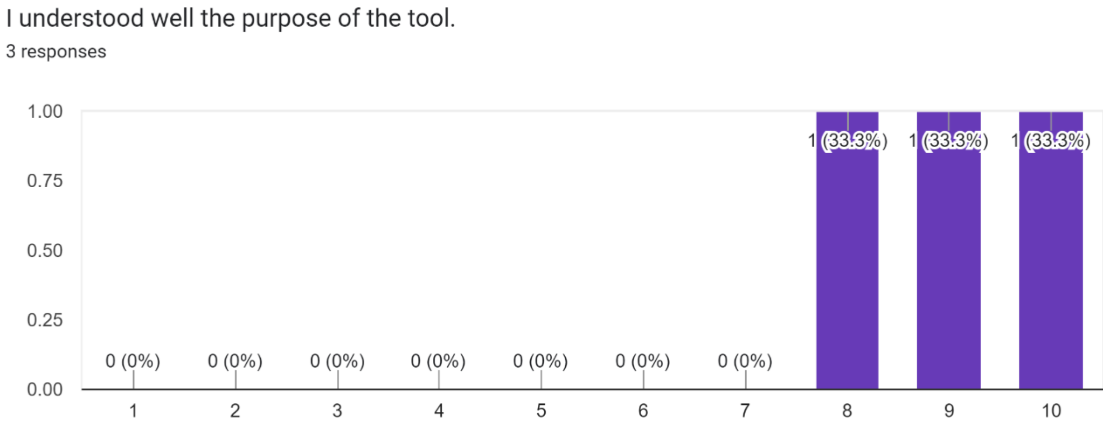

Figure 25: Graph Survey 1 Question 1 (own illustration)

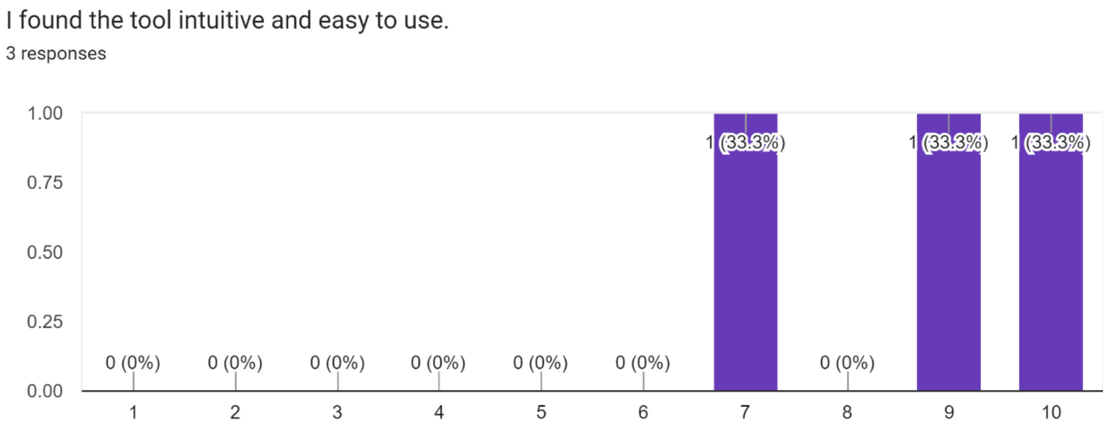

Figure 26: Graph Survey 1 Question 2 (own illustration)

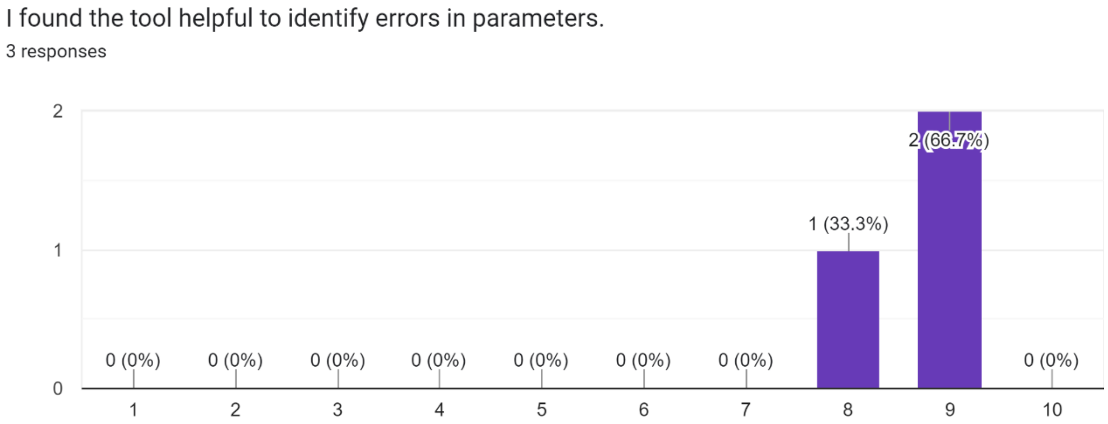

Figure 27: Graph Survey 1 Question 3 (own illustration)

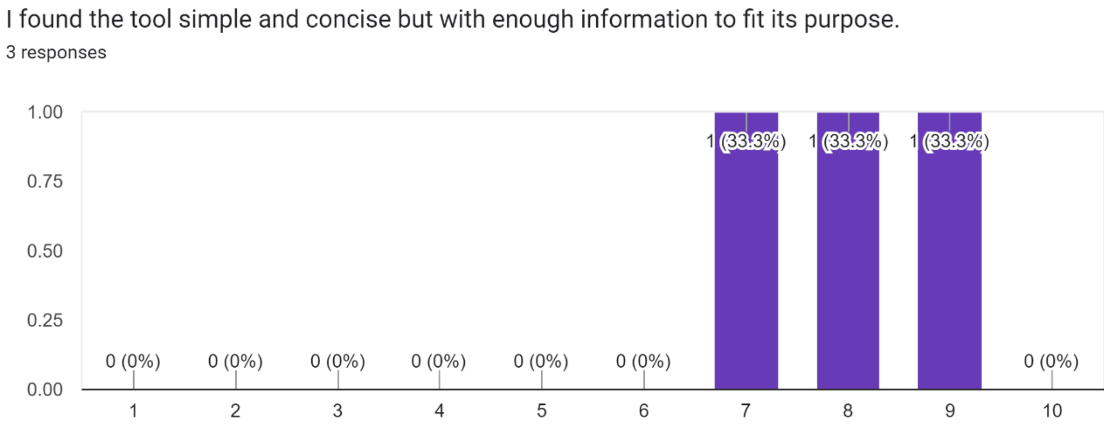

Figure 28: Graph Survey 1 Question 4 (own illustration)

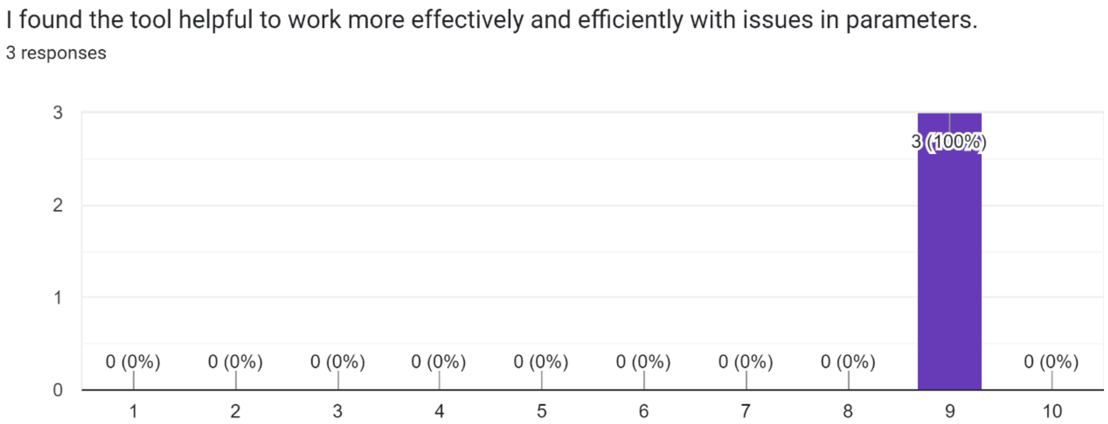

Figure 29: Graph Survey 1 Question 5 (own illustration)

Appendix E: Results Survey 2

The outcomes of Survey 2 to designers are collected and summarised in this section:

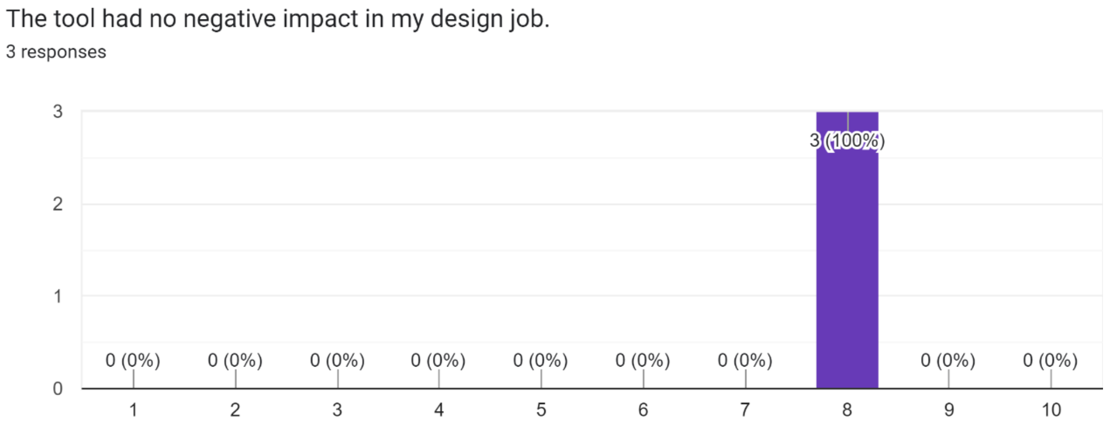

Figure 30: Graph Survey 2 Question 1 (own illustration)

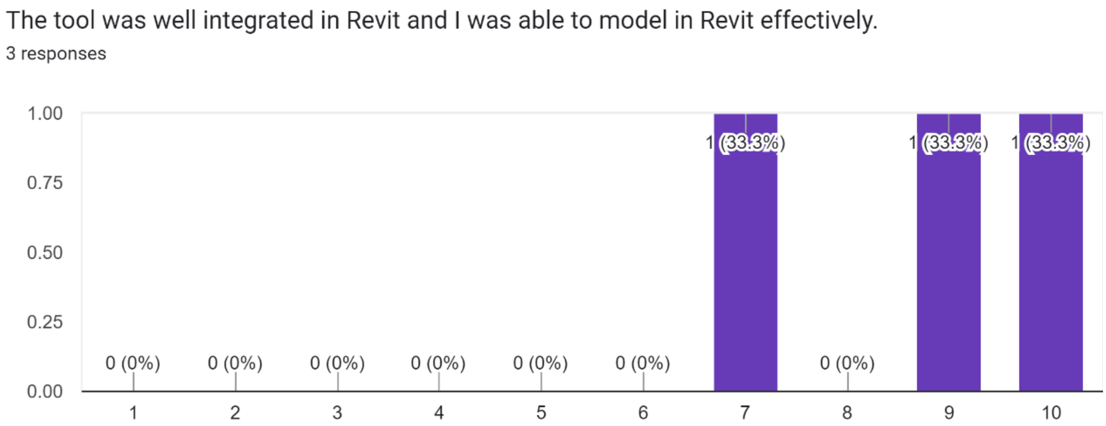

Figure 31: Graph Survey 2 Question 2 (own illustration)

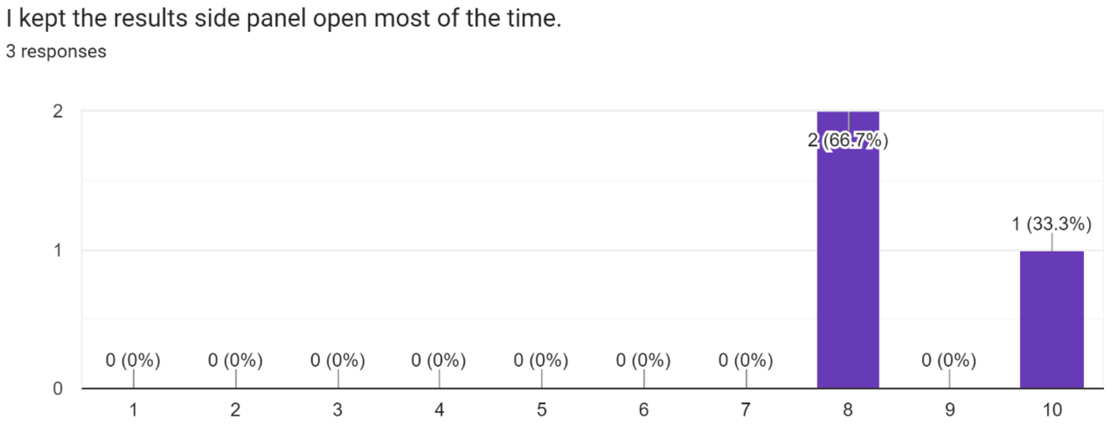

Figure 32: Graph Survey 2 Question 3 (own illustration)

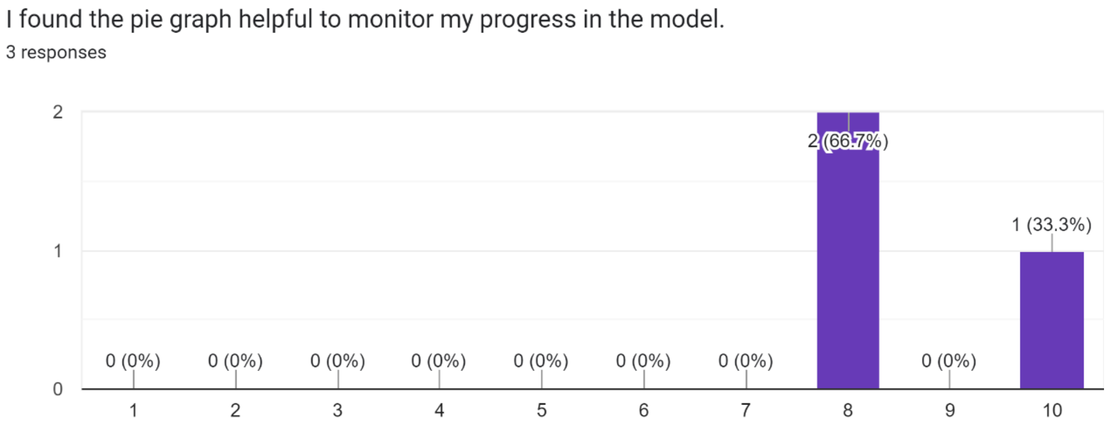

Figure 33: Graph Survey 2 Question 4 (own illustration)

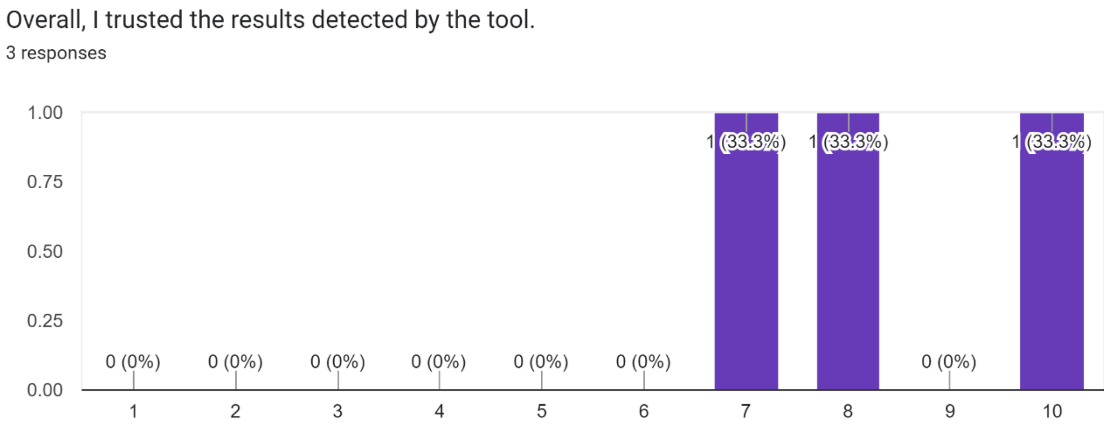

Figure 34: Graph Survey 2 Question 5 (own illustration)

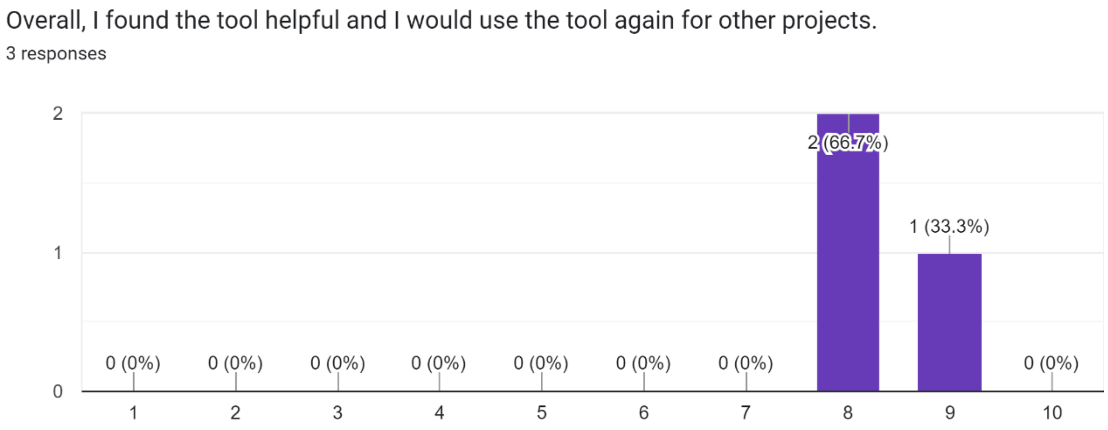

Figure 35: Graph Survey 2 Question 6 (own illustration)

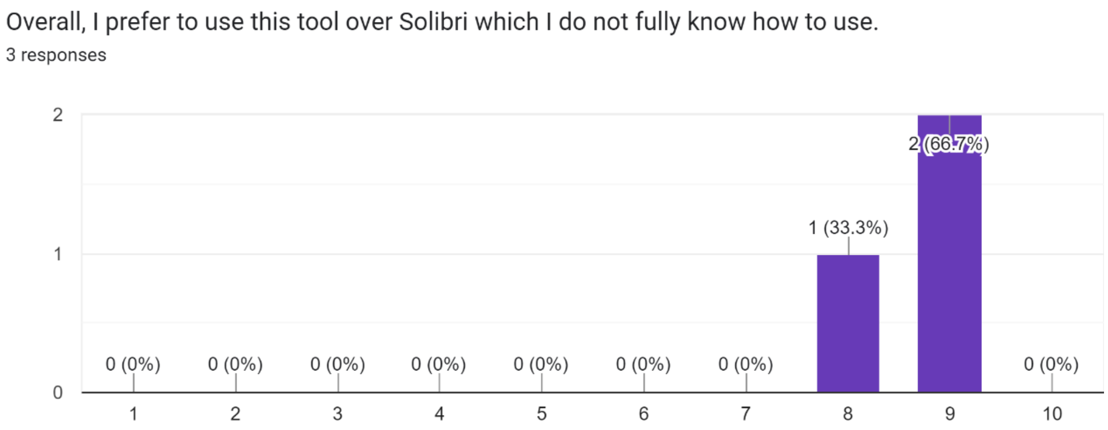

Figure 36: Graph Survey 2 Question 7 (own illustration)

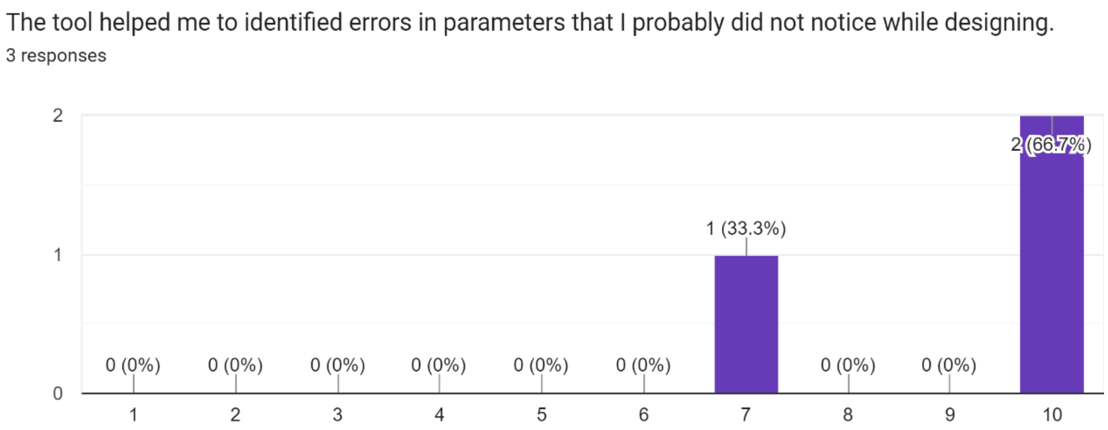

Figure 37: Graph Survey 2 Question 8 (own illustration)

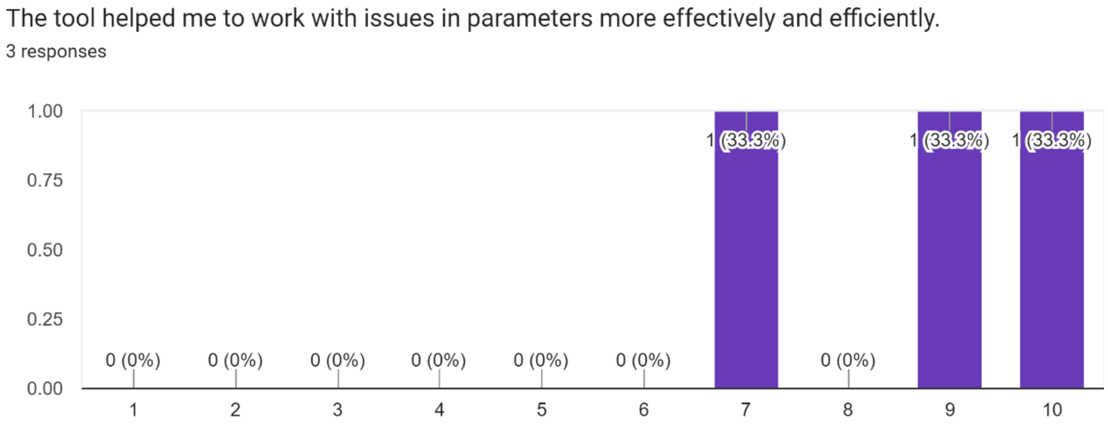

Figure 38: Graph Survey 2 Question 9 (own illustration)

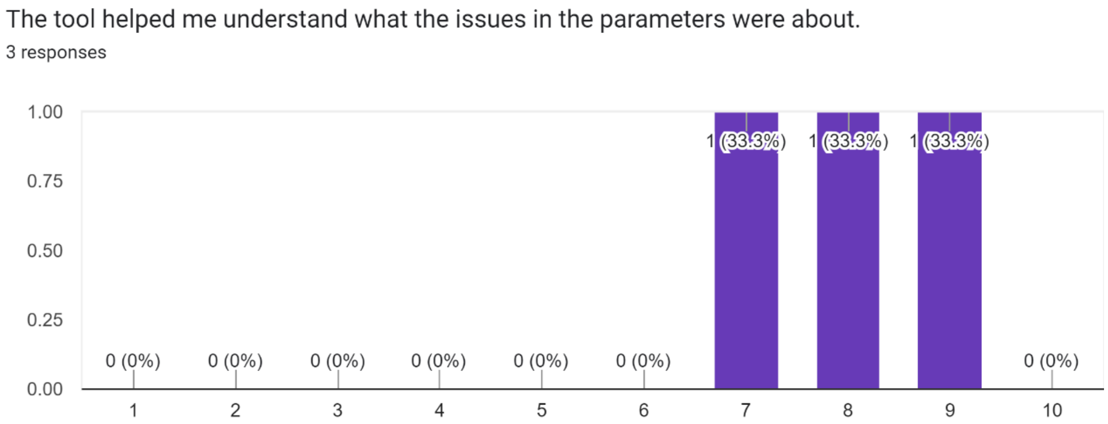

Figure 39: Graph Survey 2 Question 10 (own illustration)

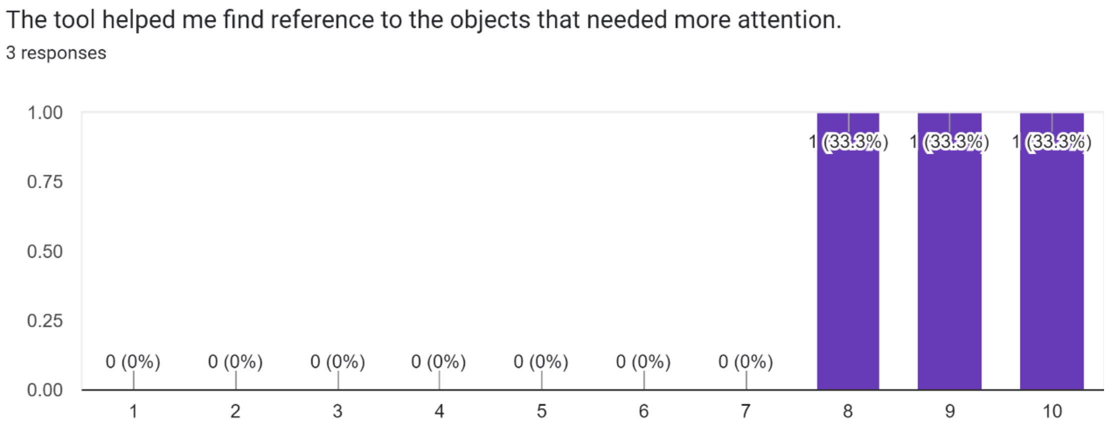

Figure 40: Graph Survey 2 Question 11 (own illustration)

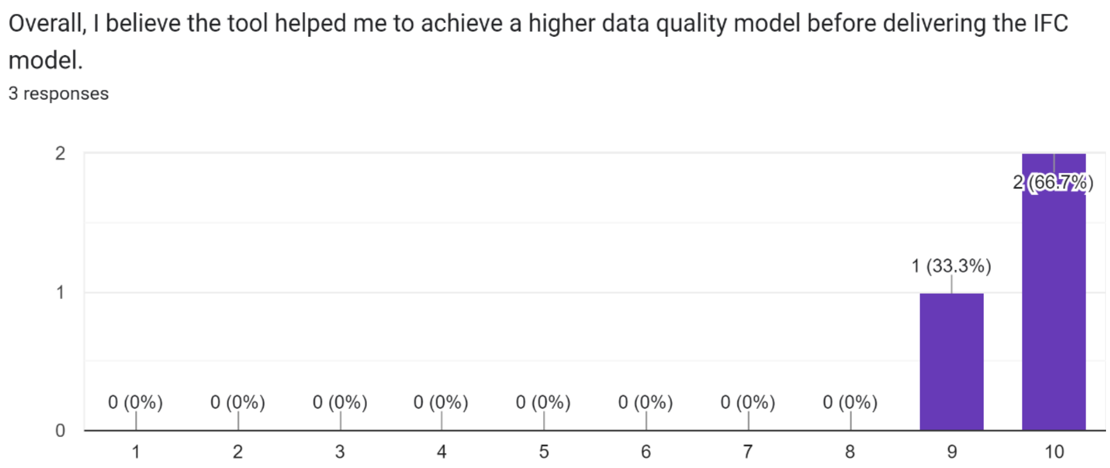

Figure 41: Graph Survey 2 Question 12 (own illustration)

Appendix F: Results Survey 3

The results of Survey 3 to BIM specialists are gathered and decompose in this appendix:

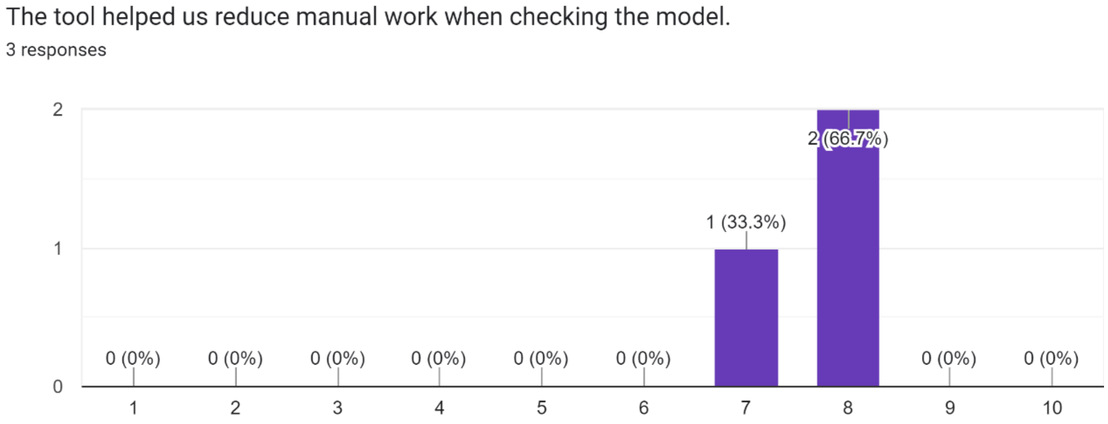

Figure 42: Graph Survey 3 Question 1 (own illustration)

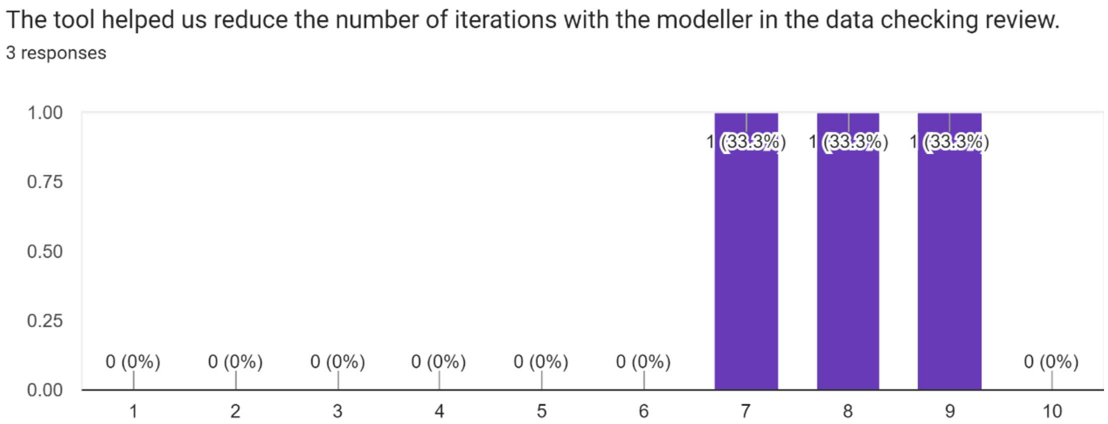

Figure 43: Graph Survey 3 Question 2 (own illustration)

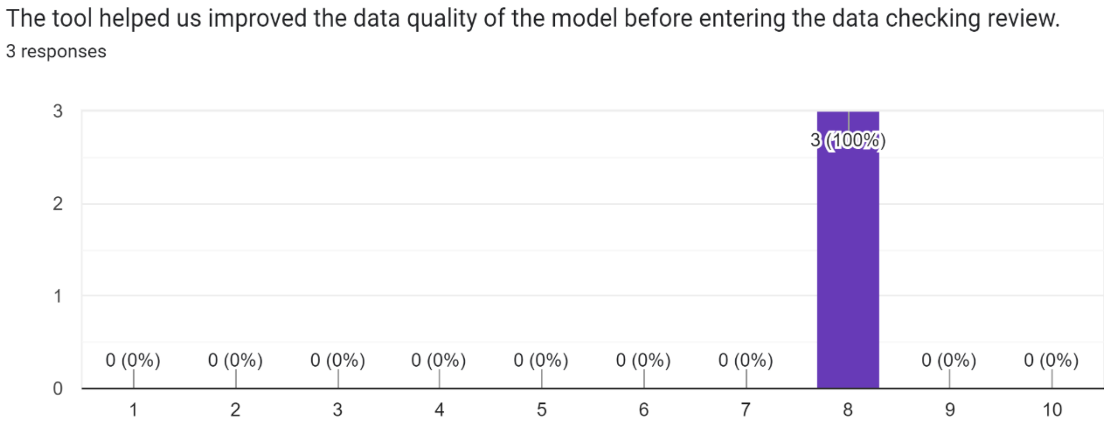

Figure 44: Graph Survey 3 Question 3 (own illustration)

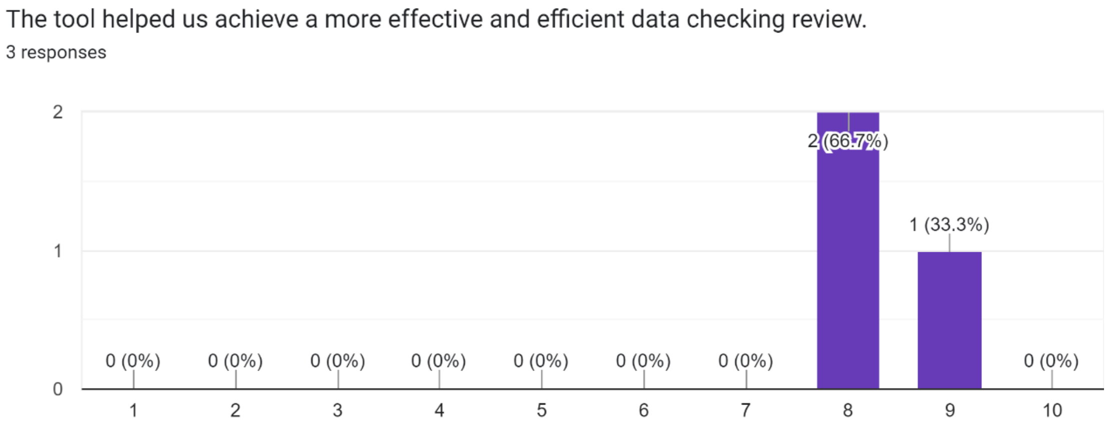

Figure 45: Graph Survey 3 Question 4 (own illustration)

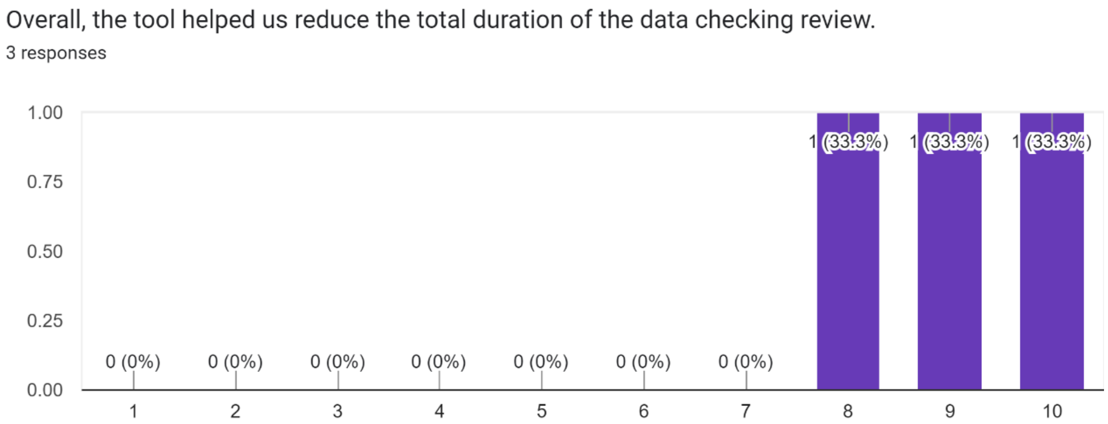

Figure 46: Graph Survey 3 Question 5 (own illustration)

Overall, the data quality of the model at the end of the data checking review was the same with or without the tool.
3 responses

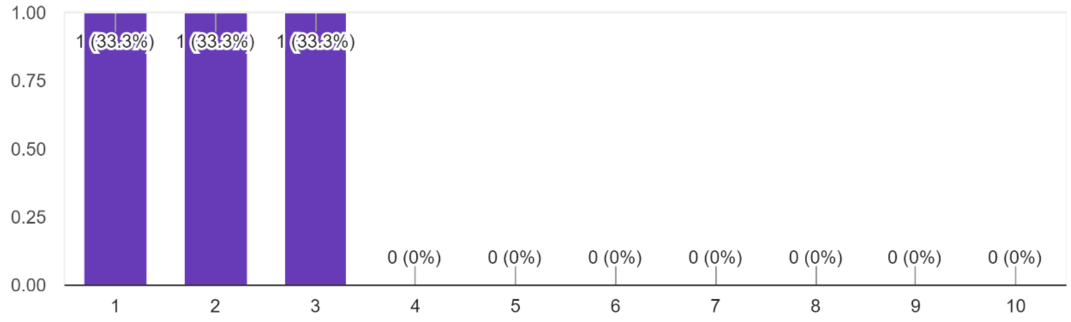

Figure 47: Graph Survey 3 Question 6 (own illustration)

Overall, the data quality of the model at the end of the data checking review was higher with the tool.
3 responses

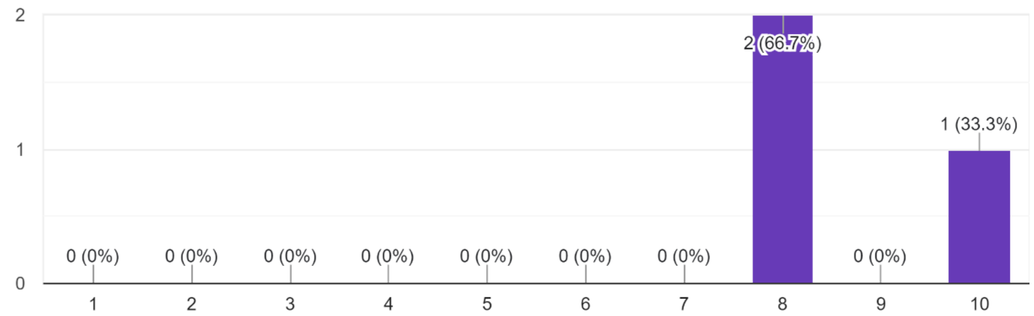

Figure 48: Graph Survey 3 Question 7 (own illustration)

In highly time constraint projects, I believe the tool could reduce time pressure.
3 responses

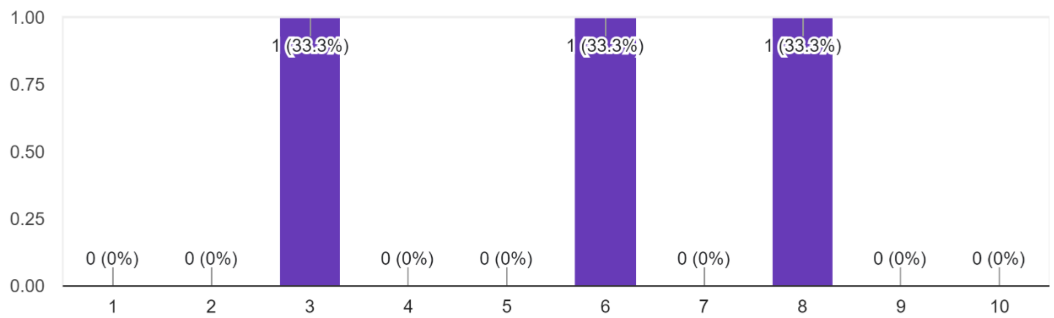

Figure 49: Graph Survey 3 Question 8 (own illustration)