IMPROVING FALL FROM HEIGHT RISK REDUCTION

CREATING A SAFER CONSTRUCTION SITE WITH THE USE OF BIM TECHNOLOGY

A.C. Ramsey
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CREATING A SAFER CONSTRUCTION SITE WITH THE USE OF BIM TECHNOLOGY

By Ashley Charleen Ramsey

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Student number:	4229282	
Institution:	Delft University of Technology Faculty of Civil Engineering and Geosciences	
Graduation company:	Royal BAM Group BAM Infraconsult, BIM services department	
Graduation committee:	Prof.dr.ir. A.R.M. Wolfert	TU Delft (Chair)
	Dr.ir. G.A. van Nederveen	TU Delft
	Ir. A.C.B. Schuurman	TU Delft
	Drs. Ing. D. van der Ploeg	BAM

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PREFACE

This master thesis is the product of my final graduation project at Delft University of Technology. With this graduation thesis, I conclude my Master of Science in Construction Management and Engineering at the faculty of Civil Engineering and Geosciences. The studies and graduation project have given me generous knowledge of civil engineering, the construction industry and all interconnected managerial aspects. I am very grateful to have gained these insights and to have grown tremendously both professionally and personally. Now I can complete my academic career and proceed to start my professional career in the industry that excites me every day.

I would like to thank my committee for guiding me through my graduation process. My professor Rogier Wolfert and supervisor Marco Schuurman, for improving the quality of my thesis. And especially my first supervisor Sander van Nederveen and company supervisor Dirk van der Ploeg, for supporting me with knowledge as well as personal guidance throughout my entire process. I want to express special gratitude to Gino Koolman, for helping me with programming and spending many online meeting hours with me to improve the quality of my script. I can only hope that our combined efforts will one day prevent construction site accidents and save people’s lives.

Finally, I want to thank my family and friends for all the support and love during my studies. It has been a rollercoaster, but you have always been there with comforting words and positive energy. I could not have done it with the countless coffee breaks, crazy conversations and diverting activities.

EXECUTIVE SUMMARY

Innovative solutions for safety and risk management on construction sites are required to reduce the amount of accidents that occur globally, as too many occupational accidents still happen in the Architecture, Engineering and Construction industry. A particular problem is the *fall from height (FFH)* accidents on construction sites, due to failing barriers with the underlying cause of insufficient planning. In previous research it has been suggested to develop dedicated BIM plug-ins to automate and visualise risk identification and evaluation of construction sites as a means to assist the safety management process.

To explore the impact of BIM on FFH accident reduction through automation and visualisation, a digital tool prototype is developed. This prototype focusses on *fall from height (FFH)* identification on construction sites during early project phases of civil engineering projects. It is programmed in Autodesk Dynamo for Revit, based on technical and functional requirements derived from literature and industry professionals. A simulation of the FFH tool prototype has been conducted through simulation on a pilot project. The simulation consists of a verification of the outcome of the operations and requirement satisfaction, followed by validation through a pilot project performed by two groups of industry professionals.

The result of this product development is a working *fall from height* detection prototype that is to be used as a supporting tool during the safety analysis of construction site design in Dutch civil engineering projects. The developed tool is added to the body of products that can be used for digitalisation and innovation within the construction process, where it digitalises part of the safety management process that is otherwise performed manually. The added value of the tool prototype is the addition of automated risk detection, creating support in the design and planning process and providing added information to group discussion on safety matters in risk identification and evaluation meetings.

Recommendation for future use of the tool consist of two parts, firstly the implementation of the FFH tool prototype and secondly further developments that can be performed. Implementation can be done by designers during the design phase, resulting in an FFH RI&E and warning signs overview that provide insights in potential situations that are created in the construction site design. These insights can be used in the iterative design process to improve the safety of the construction site during project execution. Additionally, the FFH tool prototype can be implemented by safety managers to use the results during safety meetings for better discussion and evaluation of the construction site. This allows for involving other departments and third parties in early project phases and including their perspectives in the safety management process. Through validation it has been determined that the FFH tool prototype provides added value by aiding in the communication between project representatives. For the implementation, improvement of the level of detail in the 3D models for the projects is essential. Modelling temporary site situations for one or more phases in the execution of the project are required for the results of the FFH tool prototype to provide the predicted added value. Greater model detail results in a more specific FFH analysis and better RI&E outcomes, and thus providing more useful information for design and planning of the construction site.

For further development it is recommended to focus on improving the import of linked models into the script and developing alternative operations to determine the height differences. With the alternative operations the probability of missing risks can be reduced and the warning signs can potentially be grouped for each risk instead of placed on each hazardous point on the surface edge. Grouping risks creates a more useful overview according to FFH tool prototype users, increasing the added value of the product. Furthermore, more developments and improvements can be made to the script to increase the applicability on more complex projects.

Concluding, the FFH tool prototype is considered to bring added value in digitalising an otherwise manual process regarding safety management. It is suggested to incorporate use of the FFH tool prototype in the design and planning process to proactively engage in digitalising and innovating engineering processes.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
FFH	Fall from height
FFL	Fall from ladder
FFS	Fall from scaffolding
GCVB	Governance Code Safety in Construction (NL: Governance Code Veiligheid in de Bouw)
HSE	Health, Safety and Environmental
LOD	Level of detail
ML	Machine Learning
NIOSH	The National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PPE	Personal protective equipment
PtD	Prevention through Design
RIE	Risk Identification and Evaluation
RIVM	National Institute for Public Health and Environment (NL: Rijksinstituut voor Volksgezondheid en Milieu
SCL	Safety Culture Ladder
SRS	Software Requirements Specifications
UI	User Interface
VPL	Visual Programming Language
VR	Virtual Reality

1 INTRODUCTION

This chapter gives an introduction to the current situation regarding construction site safety in the Netherlands, the type of injuries occurring on sites and the importance of new solutions for construction site safety.

Safety has one of the highest priorities within the construction industry in the Netherlands. Between the contractors, the government, national unions and other initiatives, there are many plans to improve the safety in construction. However, regardless of these plans, the construction industry is still in the top three most unsafe sectors within the Netherlands. One of the initiatives of these parties is the Governance Code Safety in Construction (GCVB) and the Safety Culture Ladder (SCL). The GCVB focusses on shared principles and core values for safety in four themes: standardisation, collaboration, training and knowledge sharing. The GCVB and SCL both intend to improve safety culture and awareness, and to shift the perspective from legal and regulatory obligation to collective and societal effort in creating a safer construction industry (Governance Code Veiligheid in de Bouw, 2014; Safety Culture Ladder, n.d.). Another organisation is Bouwend Nederland, the union for Dutch building and infrastructure companies. Bouwend Nederland has presented a Multi-Year Program Plan with the main goal of eliminating the risk of deadly or seriously injuring accidents (Bouwend Nederland, 2020). In 2019, the media reported the deaths of eighteen construction workers and in 2018 and 2017 each twenty construction workers lost their lives. While Maxime Verhagen, the chairman of Bouwend Nederland and former Dutch politician, and other directors of Dutch construction companies have expressed that the amount of construction fatalities should be zero (Cobouw, 2020).

In a statement, the Acting Assistant Secretary for the Occupational Safety and Health Administration (OSHA) Loren Sweatt said “the loss of even one worker is too many” (Occupational Safety and Health Administration, 2018). As stated in the Multi-Year Program Plan by Bouwend Nederland, the attention should shift towards the design phase and management aspects of the construction process in an effort to improve construction safety. Despite all these present initiatives, the ideal number of zero construction fatalities has not been reached yet. Innovative solutions and in depth analysis of specific accidents is stimulated to continuously improve safety in the Dutch construction industry. (Bouwend Nederland, 2020; Cobouw, 2020; Governance Code Veiligheid in de Bouw, 2014).

1.1 TYPES OF ACCIDENTS

The Netherlands National Institute for Public Health and the Environment (RIVM) performed an analysis of all the reported industry incidents between 1998 and 2009. The software tool used for this analysis is Storybuilder. The analysis concluded that the most common type of accidents is *fall from height (FFH)*, covering 20% of all accidents in the construction industry during that period. *Fall from ladder (FFL)* and *fall from scaffolding (FFS)* are the next most common type of accidents. In appendix A the most common types of accidents and their occurrence in the period between 1998 and 2009 in the Dutch construction industry are shown (Rijksinstituut voor Volksgezondheid en Milieu, 2009).

For the tool development, the type of accident *fall from height (FFH)* is used to analyse and reduce the construction site injuries. FFH incidents are mostly affected by design and material flaws. The main cause of FFH accidents is a failing barrier, indicating that the fall prevention system was not placed, defective or (temporarily) removed. In 21% of the cases regarding a missing or defective safety prevention system, the underlying cause was absent systems or insufficient planning and procedures for working on heights. FFL incidents mostly take place when using a mobile ladder (614 out of 814 incidents) instead of temporary works and are mainly caused by human factor as faulty placement (370 out of 814 incidents) and failing body control or balance (280 out of 814 incidents) instead of design flaws. FFS incidents are caused by both design flaws and human failure. The main cause of FFS accidents is failing body control or balance, a human factor associated with the use of the barrier. The second main cause of FFS accidents is a failing barrier, indicating that the fall prevention system was not placed, had too much distance between the wall and scaffold, or was defective or (temporarily) removed (Rijksinstituut voor Volksgezondheid en Milieu, 2009).

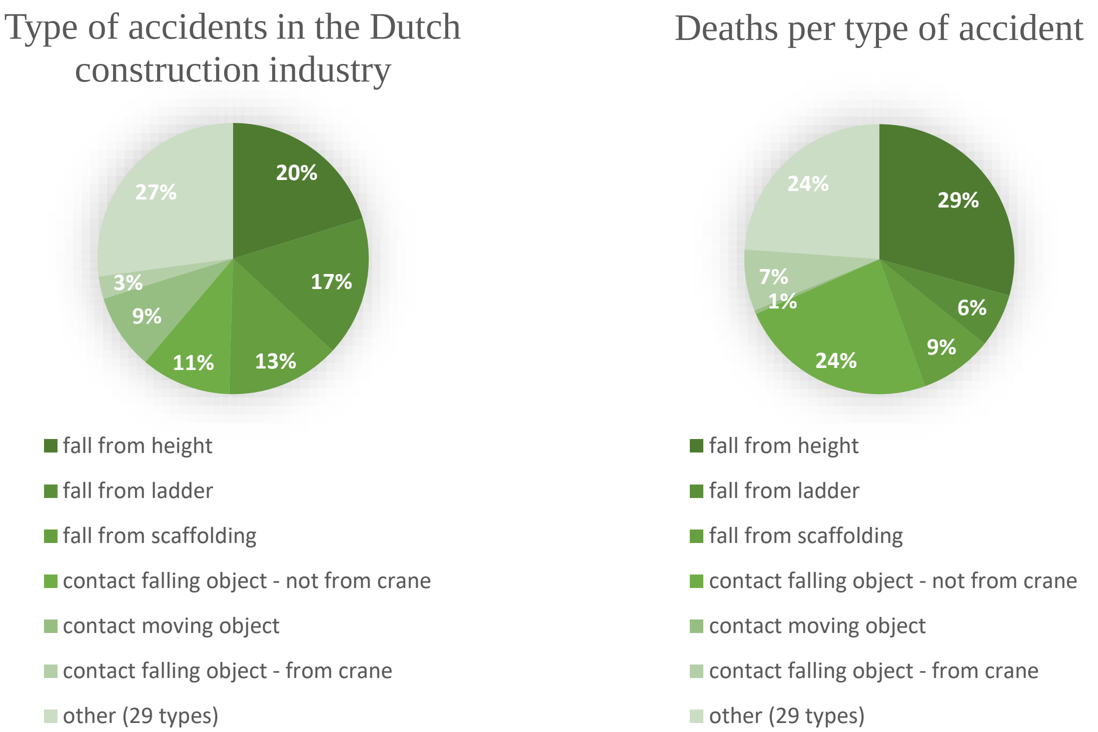


Figure 1 RIVM accident analysis data from 1998-2009 (Rijksinstituut voor Volksgezondheid en Milieu, 2009)

The FFH, FFL and FFS accidents make up 50% of all accidents from the RIVM analysis and 44,5% of the construction fatalities that occurred between 1998 and 2009. FFH is the deadliest type of incident, making up 29% of all fatal accidents. Besides the high fatality rate in the Dutch construction industry, data shows this type of accidents is a worldwide problem. Between 2011-2018, in the U.S. 7480 fatal occupational injuries occurred in the construction industry, 20% of the fatal injuries in all industries. Of these 7480 fatalities, 2593 (34,6%) were caused by falls to a lower level (U.S. Bureau of Labor Statistics, 2020). Between 2014-2019, in Great Britain 180 fatal occupational injuries occurred in the construction industry, 25% of the fatal injuries in all industries. Of these 180 fatalities, 89 (49,4%) were caused by falls from a height (Health and Safety Executive, 2019). Between 2014-2018, in Australia 156 fatal occupational injuries occurred in the construction industry, 17% of the fatal injuries in all industries. Of these 156 fatalities, 51 (32,7%) were caused by falls from a height (Safe Work Australia, 2019). Similarly, in Hong Kong alone, 49,3% of all fatal occupational injuries in the construction industry were caused by falls from height between 2011-2017 (Shafique & Rafiq, 2019).

Especially *fall from height* accidents have a great impact on the total number of injuries and fatalities in the construction industry. Combined with the fact that the main cause of these accidents is a failing barrier, with the underlying cause of improper placement and planning, makes FFH accidents the main scope for this prototype development. *Fall from ladder* and *fall from scaffolding* accidents are not included in the scope due to the underlying causes, this is more elaborated on in paragraph 3.4. Given this data, an innovative solution to prevent FFH accidents can have an extensive influence on the total fatal and nonfatal accidents in the construction industry. In this development process, BIM (Building Information Modelling) is used to determine if barrier placement and site planning can be improved through digitalisation in order to eliminate the FFH risk.

2 BACKGROUND STUDY

This chapter describes the current methods of construction site safety planning and elaborates on the perspective of different project representatives involved in civil engineering projects on reducing *fall from height* risk in early project phases. Furthermore, present innovations regarding to the implementation of Building Information Modelling (BIM) technologies for accident prevention in academic research are discussed.

2.1 CURRENT CONSTRUCTION SITE SAFETY MANAGEMENT

During the course of Dutch civil engineering projects, multiple construction safety risk identification and evaluation (RI&E) meetings are organised. In these meetings, managers and project representatives come together to discuss project safety and identify potential risks and hazardous situations in both the design and constructability. The participants of these RI&E meetings have different roles and thus different perspectives on the project. Additionally, the level of risk identification and evaluation is dependent on the project phase, ranging from very abstract in the concept design to detailed HSE (Health, Safety and Environmental) Plan in the construction documents. The HSE plan is required by the Dutch Working Conditions Legislation and should include risk identification, cause, design choices, work instructions, mitigation measures, decisions and supervision (Art 2.28 Wet Arbeidsomstandighedenbesluit, 1997).

The roles of the participants of the risk identification and evaluation meetings include but are not limited to: contractor, design manager, project controller, project manager, project planner and safety manager. These participants provide information from their perspective during the safety meetings and communicate the decisions and results from the RI&E meetings back to their respective teams. On each project an HSE coordinator is appointed, this coordinator can be personnel from the project or can be hired from a third party, and the function might be fulfilled by a different person in different project phases. The HSE coordinator is responsible for the risk identification and evaluation, the HSE plan and file, and communication regarding project risks. The coordinator checks whether the RI&E has been executed, that all risks and hazardous situations are analysed to the extent that the design can be constructed safely. Secondly, the HSE coordinator performs construction site checks during the project execution, to ensure all risks are assessed and measures are in place. When there are more than two companies involved in the construction during the execution phase, it is obligated by law to appoint one or more HSE coordinators for the design phase and one or more HSE coordinators for the execution phase (Art 2.28 Wet Arbeidsomstandighedenbesluit, 1997).

The goal of the RI&E meetings is to find design solutions for hazardous situations that are predicted to occur on the construction site. Currently, this is done by analysing the design, construction documents and, where available, a 3D model of the design. When risks are identified, they are mitigated by using the Hierarchy of Controls, developed by the United States federal agency The National Institute for Occupational Safety and Health (NIOSH). The Dutch equivalent is the Arbeidshygiënische Strategie in the Wet Arbeidsomstandighedenbesluit, 1997, based on the Code of Ethics of the International

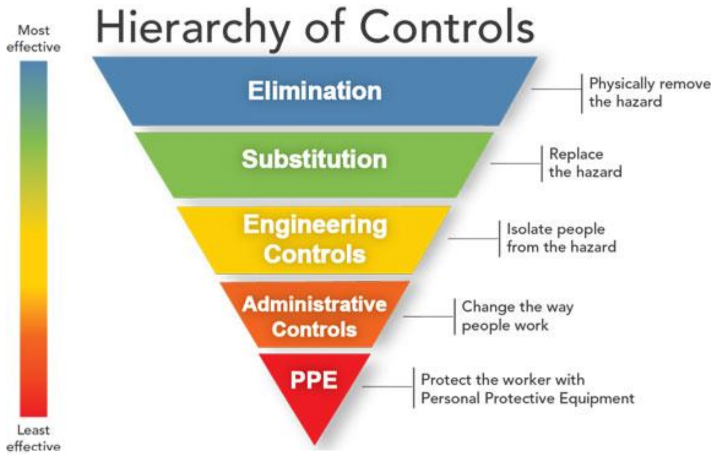


Figure 2 Hierarchy of Controls, Source: The National Institute for Occupational Safety and Health (NIOSH).

Occupational Hygiene Association. The Hierarchy of Controls (Figure 2) is frequently used as a method to determine effective and feasible solutions to risks and occupational hazards in a project. Control solutions at the top of the hierarchy, elimination or substitution of risk, are usually more difficult and expensive to implement in later stages of the project. However, these solutions tend to be more effective and have a bigger impact on the integral safety than solutions at the bottom of the hierarchy, provided they are implemented in early stages of the process. Elimination, substitution and engineering controls are proven to be more effective on the long term than administrative controls and personal protective equipment (PPE), while also requiring less effort from the construction workers on site (The National Institute for Occupational Safety and Health (NIOSH), 2015). These more effective solutions need to be thought-out and integrated into the project design, requiring a more extensive risk assessment process compared to administrative control and PPE solutions.

The RI&E meetings are organised to inform the project team of any hazardous situations and the goal is to change the design in order to eliminate or substitute the risk. If this is not possible, the residual risk is transferred to the contractor with suggestions for engineering or administrative controls (Figure 2). These residual risks and suggestions are documented in the HSE Plan. Currently, design managers have insufficient insight in the construction site logistics and design, making these project design decisions regarding site safety more difficult to integrate in early phases. The designers get little feedback from the constructability of the design and the level of safety of the construction site during execution, as this is not standard practice in the current process. A lack of visualisation of the construction site during the design phase contributes to this problem, besides the fact that designers are only urged to analyse the safety of the constructability during these RI&E meetings with the planners and contractors, instead of iteratively during the design process. It is the job of the HSE coordinator to encourage the team members to include safety of the constructability in the process, but the coordinator is not constantly involved in the design process. This results in infrequent safety checks of the design's constructability and construction site safety. The moment that the HSE coordinator, design manager and other project representatives come together in the RI&E meetings, the design is collectively analysed on the safety aspects. A discussion takes place to identify, evaluate and document as many risks as possible and find design solutions to eliminate or substitute the risks. Certain design agreements are made in order to prevent conflict at a later stage in the process, these agreements are documented in the HSE plan.

The ISO 45001 standard for occupational health and safety requires companies to have an occupational health and safety management system in place for risk identification, evaluation, mitigations, changes and documentation, yet it does not specify set requirements for this process (International Organization for Standardization, 2018). Companies are free to determine a process themselves, resulting in the fact that the procedures for documenting the risks and agreements are generally not unified for all projects, as is the case at Royal BAM Group. In the experience of several BAM experts, there are multiple software programs that have been used for RI&E documentation, including but not limited to Relatics, Microsoft Office and Autodesk Revit. The documents and HSE Plan are continually updated during the project by the HSE Coordinator. One of the problems in this static documentation is that information might not be correctly or clearly documented or information is lost in the handover from design to execution. The HSE plan and files need to conform to legal standards and are updated throughout the project development by the HSE Coordinator, who initiates the RI&E meetings and leads the discussion on the project safety. During these meetings, the HSE Coordinator will prompt the other participants, who have analysed the project in advance, to look at every aspect of the project and cover all possible hazardous situations on the construction site. In early project phases, the RI&E meetings are relatively abstract, but the effect of design changes and risk mitigation is large (The National Institute for Occupational Safety and Health (NIOSH), 2015). Involving many different participants from different roles has a large influence on the constructability and construction site safety in later stages. Especially contractors with ample site safety knowledge, as this means that their insights can be included from the start and less changes will have to be made when the design develops towards finalisation.

In later project phases towards the execution phase, concrete details regarding all project risks are evaluated and documented. Two types of risks are differentiated, firstly the permanent risk that are present in the definitive project design. The identified permanent risks are added to the scope of the project and require design changes before construction commences. Secondly, risks that occur due to temporary situations on the construction site during project execution. These risks are dependent on the temporary construction site design and if they cannot be eliminated or substituted, they are handed over to the contractor. The temporary construction site design is currently mainly projected onto 2D drawings or abstractly imported in the 3D model. Additionally, the discussions in the RI&E meetings are subject to the participants that are or are not present, leaving room for improvement for risk analysis and construction site safety management.

2.2 Room for improvement

There are several elements in the current RI&E process, according to industry professionals at Royal BAM Group, that are identified as successful and several elements that are insufficiently effective or form interesting fields for innovation. The elements are translated to needs that form the basis of the FFH tool prototype in this development process and have been identified from semi-structured interviews with BAM experts in the roles of design management, project control, HSE management, and construction planning. Further elaboration on the needs underlying the tool requirements can be found in chapter 4.

One of the biggest elements that is mentioned for improvement and innovation is the integrated information in the 3D models and its visualisation in earlier project phases, with the intent of improving safety management from the top of the Hierarchy of Controls (Figure 2). Designers often do not experience the construction process and the direct consequences of their design on the construction site. The expectation is that if the construction site is visualised during the design phase, any risk and conflicts can be taken into account and potentially eliminated or substituted in early phases. A visualisation of the construction site gives the opportunity for the project planner and contractor to be more involved during the design phase, so their insights can have a bigger influence on the design, preparation and planning. It would be preferred by the industry professionals that the outcome of the RI&E meetings is added to the visualisation of the construction site in the model, as the risk information can then be viewed in relation to other elements and information in the integral 3D model. The idea behind this is that it can potentially result in the removal of separate documentation software and become an easier and more efficient process. Ideally, all information regarding the project is stored in one integral model, including the design choices and motivation for certain project decisions. This can potentially make the handover from design to execution phase easier and more efficient. However, this does mean that the 3D model of the project needs to contain a high level of detail and include the temporary situations of the construction site. Currently, a significant part of the obstacle of implementing tools and BIM models on site is the type and detail level of models and documents that are available. Incorporating site detail in the 3D models is not standard practice and more development is needed for the models to be at a level that site safety can be added realistically. Besides the detail level of the model itself, the designers and other team members need to possess the spatial perception and ability to understand the abstract models in early phases before they reach the level of detail that depicts the realistic final situations. The interaction between model improvement and interpretation requires step by step improvement over time. Further model level of detail is discussed in chapter 4.

The predicted added value of including construction site safety to the BIM models is the visualisation and ability to actively include other team members or third parties in the RI&E meetings and safety management process. Eventually, markings on paper drawings and separate lists can be eliminated entirely and the overview of the risks and their measures can be collected in an integral model. Quantities and types of materials and equipment could be extracted from these models and used for the site preparation and execution. The residual risk can comprehensively be handed over to the contractor when it is included in the integral model, resulting in less information being lost and the contractor gaining insights from the accessible visualisation of the temporary situations and risks that might occur.

This tool development focusses on one of the possible steps that can be taken in the digitalisation process of the construction site safety. The aim, discussed in paragraph 3.2, is providing a tool that serves as one of the preliminary steps towards fully digital project design and management and is meant to improve the current process and discussions on the matter, without fully replacing present procedures of site safety planning.

2.3 BIM IN SAFETY MANAGEMENT

Building Information Modelling (BIM) is increasingly more useful in improving collaboration and information management, as well as reducing the accident rate when implemented in early stages of a project (Martínez-Aires et al., 2018). However, the exact role of BIM and digital design tools in the process of accident prevention is unclear. There is development in utilising BIM for training, forming a fundamental step towards improved construction safety (Akram et al., 2019). Building Information Modelling is very promising, as it provides a visual interpretation of a project and its site before commencement of the execution phase. The versatility of BIM has resulted in a wide variety of research key areas, so the potential of the technology is not yet fully covered (Martínez-Aires et al., 2018).

The use of digital tools has been proposed to enable site safety planning and knowledge management during the design phase for accident Prevention through Design (PtD). However, PtD has not been fully implemented due to the designer's lack of safety knowledge (Kamardeen, 2010). Similar situations occur with Virtual Reality (VR), as it is commonly used in education and training for safety, but limited to personal skill improvement and hazard response, instead of safety planning. It is recommended that further research towards using VR-MR (virtual reality and mixed reality) systems in safety interventions should be conducted with input from professionals in the industry (Frank Moore & Gheisari, 2019). As there is relatively lesser research on safety knowledge exchange and safety management through digital technologies, Akram et al. (2019) suggest that automation of accident identification and prevention on construction sites can be assisted by a dedicated BIM plug-in, creating a digital tool for decision support addressing information management and construction site design (Akram et al., 2019).

In 2013, Zhang et al. created a Tekla model that automated safety checks of 3D models using a rule-based algorithm. The safety checking system was designed for fall protection and successfully tested on a four-story architectural building, demonstrating Prevention through Design with the use of BIM technology can improve site safety management. The research concluded that a safety checking system requires a different approach than traditional BIM tooling. This particular model required manual interpretation, coding of rules for unsafe conditions and manual selection of the best corrective solution. The integration of the system with regard to best practices and acceptance by industry professionals is recommended to be researched further, as well as application on more complex construction projects (Zhang et al., 2013).

A 2021 research presented at the 18th International Conference on Computing in Civil and Building Engineering states that an improvement in practical applicability of BIM technologies requires combining traditional Risk Management with BIM-based methods. BIM supports Prevention through Design as it improves comprehension of hazards and risk assessment. When focussing on the execution phase, BIM-based Risk Management can be applied for assigning risk types to the model's objects, for visualisation of the environment and revision of the risk control proposal. In that research a proof of concept is created for a Dynamic Risk Map, using Mixed Reality on site during the construction and commissioning phase. Mixed reality is a visualisation of combined reality and Virtual Reality (VR). This determined that an adaptable and intelligent BIM technology which utilises visualisation is an important element in increasing awareness of the site safety, risk management and injury prevention (Moreira et al., 2021).

3 TOOL DEVELOPMENT PROCESS

This chapter gives an overview of the FFH tool development, including the objectives, scope and methodology. In paragraph 3.6 the outline of the report is presented.

3.1 PROBLEM DEFINITION

Too many fatal occupational accidents occur in the construction industry, with it being one of the top three most unsafe sectors within the Netherlands. The main causes of these fatalities are *fall from height* (*FFH*) accidents. Innovative solutions to improve construction safety should be created, where BIM and digital technologies could prove to be a useful addition once it is more extensively explored and applied in practice. More insights should be provided in the safety management process during early project phases to reduce fatal occupational accidents (Zhang et al., 2015). The hypothesis is that a dedicated plug-in or tool can support risk identification, decision making and information management in the design and planning phase of Dutch civil engineering projects.

3.2 OBJECTIVES AND DELIVERABLES

In this study a tool is developed that accommodates for optimising site safety planning, information management and risk identification & evaluation, specifically for FFH risk and construction site safety of temporary situations occurring during the execution phase. It aims to aid the process of allocating the temporary works more accurately and consistently during the construction site design and planning. The goal of the tool prototype is creating a completer and more realistic site plan during the project preparation and preventing accidents during the execution phase. The tool provides digital support during the planning phase and decision-making process by integrating currently available technical tools and automation. It gives insights on the temporary situations for the project execution phase and thus provides the planner and contractor with valuable information intended to reduce the safety management related time and costs as well as prevent accidents.

It should be noted that the tool is not designed for the safety of the constructed object itself, e.g. stability, loads or building code requirements, but focusses on the safety of the construction workers on site during construction.

The main deliverable of this development process is a tool prototype in Autodesk Dynamo for Revit that can be used by designers, planners and (safety) managers to evaluate the safety of the construction site relating to FFH risk in the coordination model of a project. The tool is to be used in the design and planning phase of infrastructure and construction projects to give a useful visualisation of *fall from height* risks in temporary site situations. The developed FFH tool prototype is intended to be added to the current safety management process to enrich communication and understanding of construction site safety, its goal is not to replace or entirely automate FFH risk identification and evaluation. Another part of the deliverables are the conclusions and recommendations in chapter 8, comprising the advice with regard to the implementation and further development of the FFH tool prototype.

3.3 Development statement

The result of this ameliorative development process is a software tool that is to be used for construction site safety analysis. Through digital design and development a prototype of this tool is created that focusses on automated identification of *fall from height* risks. The following development statement is used:

To design and develop a prototype of a digital tool that improves fall from height accident reduction on construction sites during the execution phase of civil engineering projects.

The steps of the development process are:

1. Analysis of the safety management context
    a. Identification of types of accidents in construction
    b. Description of current construction site safety process
    c. Description of the role of BIM in safety management
    d. Identification of requirements for an automation tool for FFH risk analysis
2. Synthesis of the prototype: design and visual programming of the script for the tool for FFH risk analysis
3. Simulation testing: verification and validation of the FFH tool prototype
4. Evaluation of the prototype: conclusions and recommendations for implementation and further development

The first step is a preparatory step to create an overview of needs and requirements for the tool. The design and simulation of the FFH tool prototype are the main focus of the development, closing off with the conclusions and recommendations for implementation and further development.

3.4 Scope and limitations

The product development focusses on accidents caused by *falls from height (FFH)*, relating to the incidents where the barrier is missing, placed incorrectly or defective. Since the underlying causes are insufficient planning and procedures, these incidents can be prevented through the use of the FFH tool by detecting missing barriers. Tripping due to smaller height differences is included in FFH risk. *Fall from ladder* and *fall from scaffolding* accidents are not included in the automated detection of the Dynamo tool prototype, as these accidents are mainly caused by human factors instead of design flaws, and mobile equipment instead of temporary works (Rijksinstituut voor Volksgezondheid en Milieu, 2009). The human impact in these underlying causes cannot be detected or changed by a digital tool for project preparation, but can potentially be influenced by implementation of VR technology, as mentioned in paragraph 2.3. The tool prototype is designed to detect dangerous situations related to height differences without barriers in the site design and temporary works, not related to human failure or mobile equipment.

The FFH tool prototype can be applied to civil engineering projects that have a coordination model available. The coordination model is a Revit or .IFC model that includes temporary works and site situations in different execution phases to a specified level of detail. The level of detail of the coordination models progresses as the project develops towards construction documents, however, sufficient detail regarding the construction site is essential for utilisation of the FFH tool prototype. The tool is programmed in Autodesk Dynamo for Revit, as it accommodates in the needs regarding the design and programming. The software is able to work with Revit coordination models, makes use of accessible visual programming language and is as an open source software available to global users and researchers (Autodesk Inc, 2016).

The tool aims to improve automation and visualisation of the construction site safety planning. It accommodates for the recognition of situations where temporary works should be placed in order to improve site safety. It does not create a new method for construction site planning or new safety management protocol. It is intended as a supporting tool for digitalisation and planning of the construction site safety. More information on the context in which the tool is intended to be used can be found in paragraph 5.1. For visualisation it has been considered to include Virtual Reality applications, however, due to the lack software availability this has not been included. There is currently no suitable software available that satisfies the requirements for tool programming and is compatible with VR technology to interactively detect and place safety signs. Software such as Enscape or Unity works with .IFC models and VR, however, this software does not accommodate automated placement of safety warning signs, which can be done in Dynamo. This means that an elaborate procedure would need to be in place in order to get a static VR visualisation of the automated risk overview after use of the tool. The limitations of these extra steps and thus more complexity outweigh the need for a Virtual Reality visualisation, as the added value of viewing the static visualisation through a VR headset is expected to be too little compared to viewing and adapting a 3D model on screen. For this reason, VR has not been included in the scope of this project.

The FFH tool development is performed in collaboration with the TU Delft and Royal BAM Group Infraconsult, meaning the projects, data, norms and regulations are based on Dutch practice. The projects are focussed on the Architecture, Engineering and Construction (AEC) industry, specifically infrastructure engineering in the Netherlands with the perspective of the contractor. For the analysis and validation of the FFH tool prototype expert opinions are used. These experts are BAM employees working in site preparation, execution, planning and BIM services. An elaborate explanation of the analysis is given in chapter 4 and of the tool prototype simulation is given in chapter 7.

3.5 Methodology

In this ameliorative development process a product is designed, created and tested. The product, in this case an automated *fall from height* risk identification tool, focusses on combining the safety management process and digital transformation to improve risk analyses and propose innovation for the future. The methods focus on the following phases of engineering development: analysis, synthesis, simulation and evaluation. For each phase a different method is applied, aligning with the methods of engineering for product design.

Phase	**Method**	**Purpose**
Analysis	Information gathering	A combination of literature study, tutorials, interviews and practical experience to align the requirements for the tool. Practical experience from industry professionals is important to determine the purpose and use of the tool.
Synthesis	(Visual) programming	Synthesis of the information and requirements result in a design of the tool and its intended functions. Followed by visual programming of the script in Dynamo.
Simulation	Verification and validation	Verifying the FFH tool by running the script, then assessing requirement satisfaction and operation outcomes. Validating by performing a safety analysis in a pilot project with industry professionals to determine the added value.
Evaluation	Formulating conclusions and recommendation	The tool prototype is evaluated based on the design, verification and validation. Satisfaction of the development statement and impact on the safety management process is determined. Recommendations for implementation and further development are given.

Table 1 Summary of used methods

3.5.1 Analysis

During the analysis phase, information is gathered to establish a background for the need of the tool. This is done through a combination of literature study, software tutorials and interviews with experts. The information is used to create the tool requirements. The input from industry professionals is relatively important, since the tool is intended to be used in practice and the experts are able to provide information on current methods and possibilities for implementation that might not be stated as such in the literature.

3.5.2 Synthesis

The tool is developed through visual programming in the chosen software; Autodesk Dynamo for Revit. The context in which the tool is intended to be used is assessed to determine the contribution of the integration in the safety management process. The requirements that are set up in the analysis phase form the basis for the design of the FFH tool prototype and its operations. These operations are then developed and programmed to such an extent that it satisfies the requirements and forms an operable prototype.

3.5.3 Simulation

A simulation is performed consisting of two parts, verification of the script against the requirements and validation of the added value of the FFH tool prototype.

The verification is performed by the tool developer through modelling. A real-life civil engineering Revit model is used to test the tool in an artificial environment and to determine its workability. This is done by running the script and assessing whether the nodes and node groups return the expected outcome. Then a reflection is made regarding the tool requirements and it is determined whether the tool meets its requirements. The verification process gives an answer to whether the script works and satisfies the tool requirements, rather than whether the tool has added value in practice or meets user requirements. This external validation is part of the second part of the simulation.

The synthesis and verification phase are combined in an iterative process. In situations where either running the script did not work or the requirements were not met, new design iterations were made in Autodesk Dynamo for Revit. When both running the script worked and the requirements were satisfied, the project proceeded to the validation phase.

The validation process consists of testing the FFH tool prototype by industry professionals, by means of a pilot project. These professionals are BAM experts working in different departments and project phases. The validation participants assess a prepared civil engineering Revit model on FFH risk in two groups. One group uses the developed tool prototype and the second group assesses the Revit model without use of the tool. The outcome of both groups is analysed on a set of criteria to determine the added value and acceptability of industry professionals. Based on this, an advice can be given on the implementations of the tool in future projects in the AEC industry.

For the pilot project, the criteria and test groups are determined before commencement of the simulation phase, in order to create a broad validation to determine the added value for a range of industry professionals and projects.

Criteria	
1. Accuracy of risk identification	a. Amount of risk, total
	b. Amount of risk, per category
	c. Correctness of risk
2. Speed of the risk assessment	
3. Usability	a. User experience
	b. Increased knowledge of project safety
	c. Tool potential rating for future integration

Table 2 Validation criteria

Criteria 1 and 2 are factual outcomes of the pilot project and can be precisely measured for each test. Criterion 3 is subjective and determined by interview questions. The validation participants are asked questions relating the experience of assessing the project safety with or without use of the tool prototype, and whether they feel that they have increased knowledge of the site safety of the particular project after the assessment. These subjective findings are compared and play a role in the final tool evaluation, however, the user experience and increased safety knowledge weigh less than the factual criteria. The criteria and their percentage of importance are elaborated on in paragraph 7.2

Validation participant roles
1. Execution
2. Planning and preparation
3. Project management
4. Process management
5. HSE management
6. Calculation and engineering
7. BIM services
8. Procurement

Table 3 Validation test and control group members

The groups are composed of a number of participants of comparable functions and departments. In the selection of validation participants, the seniority of each person has been taken into account, as a junior might not know as much about safety in practice yet compare to a senior in the same function. The groups are aimed to be as equal as possible, in order to minimise deviations in the outcome due to different perspectives of the validation participants.

3.5.4 Evaluation

After verification and validation, the safety tool is evaluated using the feedback from the tests. The outcome of the tests can be positive or negative when comparing the tool to the manual method. From the feedback it is determined whether the tool works as expected, better or worse than expected. Where possible, iterations to the Dynamo script are made based on the feedback. However, large alterations to the tool are not made, since that would require additional more elaborate testing, which is outside the scope of the prototype development.

The findings, including additional suggestions for adaptations to the tool prototype, are the basis of the conclusion and recommendations on whether a safety tool prototype such as this Dynamo script should or should not be used for further development and practice implementation. In the conclusions of this prototype development process, satisfaction of the development statement and impact on the safety management process is determined. Finally, recommendations are made for implementation in the AEC industry and for further development of future versions of the prototype or similar tools.

3.6 Thesis outline

In chapter 1 and 2 the context and background of this study is explained. The types of accidents in the construction industry are identified and the need for innovation is discussed. Based on literature and knowledge from industry professionals, a background on the current construction site safety process and role of BIM in safety management is given. Paragraph 2.1 gives an overview of how the safety management is currently incorporated in the entire project process, where paragraph 2.2 discusses elements in the current process that the industry professionals have identified as insufficient or interesting fields for innovation. Paragraph 2.3 shows the present developments of BIM in safety management in academic research.

Chapter 3 contains an in-depth overview of the problem, development statement, objectives and scope. The methodology of each phase in the study is explained in paragraph 3.5.

In chapter 4, an overview can be found of the tool requirements. The technical requirements for utilising and adapting the tool are given, such that a future user or developer can explore the tool without running into technical difficulties. User requirements for the tool are given, as a basis for the tool design. The user requirements are derived from the background study and analysis, these requirements influence the functions and concept design of the tool.

In chapter 5 the context and concept of the design are explained. The context needs to be understood before the functions and intended use of the tool can be understood. The tool has a place in the safety management process as a whole, and this place determines the functions, elements and outcomes in the tool. Concluding this chapter is paragraph 5.3, where the script operations are mapped out. For each element in the design of operations, it is explained what the desired function and outcome is, next to general design rules for the Dynamo script.

Chapter 6 contains the tool prototype, including the script for the tool. For several nodes or node groups, a more detailed description is given, to clarify the operations that are performed. Additionally, during the programming alternative solutions were explored for some node groups. These alternatives are explained, with the motive as to why the alternative has not been chosen. Finally, in paragraph 0 the design challenges are discussed. Recommendations are made for specific parts of the script that require more programming or a different approach in order to develop improved versions of the script.

In chapter 7, the simulation process is described. The tool is tested by means of verification by the developer and validation by industry professionals. The verification is done by modelling and programming iterations, the validation is performed through a pilot project. The outcomes of the simulation are discussed in paragraph 7.3.

Finally, chapter 8 concludes the study with a conclusion and recommendations regarding the FFH tool prototype. A reflection is made on the development statement from chapter 3 and the simulation results from chapter 7. Then the limitations are discussed for the FFH tool prototype as well as the development process. The thesis is concluded by paragraph 8.3 stating the recommendations for the implementation and further development of the FFH tool prototype.

4 TOOL REQUIREMENTS

The tool requirements chapter comprises a description of the preferred functionalities and the accompanying attributes. The FFH tool prototype is a supporting product to improve and innovate safety analyses, the requirements form the basis of the desired technical and functional properties (Wieringa & Heerkens, 2007). The requirements in this chapter are based on the IEEE Std 830-1998 Recommended Practice for Software Requirements Specifications (SRS), specifying the performance of the tool in the safety management context, which is defined in paragraph 5.1. The aspect of the requirements are functional requirements, external interfaces, performance, attributes and design constraints (The Institute of Electrical and Electronics Engineers, 1998).

In these requirements and the tool design the following definitions are used:

- **Fall from height risk** is defined as a situation in the design where a surface edge occurs without a barrier, such as a wall, fence or guardrail, with a height difference on the other side of the edge.
- **Safety warning sign** is defined as an indicator for a design solution, mitigating measure or warning. This is a visual icon that denotes the *fall from height (FFH)* risk in the 3D model.

4.1 FUNCTIONALITY

The functional requirements give a description of what functions the tool is expected and desired to fulfil. These requirements are defined by information retrieved from semi-structured interviews with industry professionals at Royal BAM Group, summarised in appendix B. It can be divided into six subjects where best practices, problems and needs are identified (Table 4), the needs subsequently form the basis of the functional requirements.

Subject	Tool needs
Design phase	Provide designers with more knowledge of the actual construction site
	Provide designers with feedback on the designed construction site
	Create a smart, innovative design process that includes site safety
	Provide planner and (sub)contractor with design choice motivation
HSE Plan (RI&E)	Prevent accidents by eliminating the source
	Identify risk source during the design phase using virtual models
Communication	Improve collaboration through virtual models, stimulating digital teamwork
	Improve discussions through visualisation, involving stakeholders/residents/developer and other parties
Documentation	Involve developer, planners and (sub)contractors in the decision-making process regarding risk during the design phase
	Have all information regarding buildability, design, safety and feedback in one place
Tool content	Have phases and temporary situations modelled for site visualisation
	Distinguish the type and location of the risks for better overview
	Placement of exact virtual replicas of real-life safety objects
Tool use	Starting simple/abstract, increase utilisation to increase acceptance, then expand the level of detail (LOD)
	Involve industry professionals in the development of the tool
	Create added value from experiencing visualisation and distinguish from clicking on a screen

Table 4 Tool needs according to industry professionals

The main requirements that can be derived from these needs are visualisation of the temporary situation and FFH risks, interdisciplinary collaboration in early project phases, information management and overall an addition to the current manual safety management process, in an effort to contribute to digital transformation.

Concrete tool functionality requirements that are used as a basis for the tool design in this development process are:

1. Include visual safety warning signs in the coordination model
2. Distinguish risk type and location by visual risk representation
3. Provide space for data allocation to specific risks and safety warning signs
4. Create a time specific 3D overview of the RI&E over multiple project phases

The tool is not aimed at creating a new method for construction site planning or new safety management protocol. Neither does it accommodate in preventing accidents caused by human failure or incorrect utilisation of the barriers. The tool is to be used in the design and planning phases, not on the actual construction site during execution. An example of that could be an aiding tool on a tablet that scans the existing barriers and alerts where barriers are missing on site compared to the coordination model. This is a different point of view than this prototype development and would require different software, requirements and properties, examples are given in paragraph 7.4.

4.2 External Interfaces

The tool is designed and programmed in Autodesk Dynamo for Revit, using the Visual Programming Language (VPL) in the software's open-source environment. Built-in nodes and user-created packages with custom nodes are available through the software and online libraries. In this FFH tool prototype no Python scripts are used for creating custom nodes, all nodes are used from the Dynamo library or installed packages stated in appendix C.

System requirements are as defined by Autodesk for Revit 2021 for large, complex models and Dynamo Studio. Since the FFH risk analysis is intended to be performed on large, civil models and the Dynamo script contains complex nodes, it is recommended to use the system requirements for higher performance. It is possible to run Autodesk Revit 2021 and Dynamo Studio with lower performance requirements, but good FFH tool performance cannot be guaranteed. The technical requirements can be found in appendix C.

The projects where the FFH tool prototype can be applied to are subject to requirements. The models that are to be imported should include temporary works on the construction site. Ideally, the models include works that are specific for a certain stage in the execution phase in order to analyse the safety at that particular time, instead of merely the stage of the final design. The 3D model of the design, topography and works of all disciplines should be integrated into one coordination model that can be opened in Revit 2021. It is important that the elements in the model are correctly placed, named and labelled in order for the Dynamo script to read and import them. The model requirements are as follows:

- 3D model compatibility with Revit 2021: an .RVT or .DWG file
- Include temporary construction site works
- Depict a temporary situation that occurs at a specific stage during the execution phase
- Include the topography as topography link
- Have all elements correctly placed, named and labelled

4.3 PERFORMANCE

In this paragraph the requirements regarding the performance of the Dynamo script are described. These requirements are base functions that need to be included in the script in order to contribute to the functional requirements and form a starting point for the tool design. Note that these performance requirements are intended to be automated operations in the FFH tool prototype, resulting in an automated *fall from height* risk overview for the project team to work with.

1. *Visual safety warning*
   a. Is able to import the projects' 3D model including geography and linked models
   b. Is able to place visual icons at allocated locations
   c. Is able to distinguish risk categories and place corresponding icons
   d. Is able to project the visual icons in a collaborative environment
2. *Distinguish risk type and location*
   a. Is able to detect missing barriers on horizontal surfaces that can be stood upon
   b. Is able to detect height differences between two horizontal surfaces that can be stood upon
   c. Is able to categorise the high risks with a minimum precision of 10cm
   d. Is able to place at least 1 safety warning on a surface edge where an FFH risk occurs
3. *Provide space for data allocation*
   a. Is able to allow for manual input of risk properties to each placed visual icon
      i. Risk owner
      ii. Design suggestion
      iii. Action required Y/N
      iv. Expected measures to be taken
   b. Is able to allow for manual alteration of the automatically placed visual icons
4. *Time specific 3D overview*
   a. Is able to allocate a time stamp to the safety warning signs placed during each FFH tool run
   b. Is able to filter views according to the FFH risk analysis at specific time stamps
   c. Is able to export the FFH risk data

4.4 ATTRIBUTES

This tool is a preliminary attempt of automated *fall from height* risk detection and digitalisation of the safety management process. The reliability and availability of the tool at the time of delivery are restricted to the verification and validation phase of this development process. Any further reliability and availability requirements can be defined in further development of the prototype and recommendations for implementation, discussed in paragraph 8.3. The Dynamo script of the tool prototype is version 1.0, in case of further development the current nodes should be reviewed and where necessary updated.

4.5 DESIGN CONSTRAINTS

The design constraints encompass restrictions imposed on the design and programming due to external software, hardware limitations and/or active standards (The Institute of Electrical and Electronics Engineers, 1998).

Due to the complex models and software used, the constraints of the external interfaces are important design constraints. Appropriate hardware with sufficient CPU speed and memory is required in order to run and alter the script. If the hardware is not capable of running and altering the script, the software will crash and programming the tool or performing the risk analysis is impossible.

Another design constraint is the model availability of the project construction site and temporary situations that occur on the construction site. Currently, these models containing the needed information are rarely fully available. In occasions, the temporary situations will be modelled during the definitive design phase, when design changes are hard to incorporate, as per the Hierarchy of Controls in paragraph 2.1. In earlier design phases, when the design can still be changed, the construction site with temporary situations might not be modelled yet. For projects using this safety check method, it is essential that the construction site design is present in early design stages. For programming of the Dynamo script, absence of a fully integrated construction site design imposes restrictions on the possibilities for detecting data that is needed for specific nodes and for testing the current script. In that case alternative nodes that work with generic models instead of specific nodes need to be used, resulting in a lower level of detail in the script.

5 TOOL DESIGN

The tool design is a combination of the beforementioned requirements and has incorporated elements of a Dynamo script concept that has been written by BAM experts L. Lippens, B. Theuns, D. van Kampen and A. Refoy for a Dynamo Hackathon. That concept focussed on the safety analysis of fall risk and confined spaces on a simple housing model. In this chapter, the context of the tool, including the Hackathon script concept and the position of the tool in the safety management process, as well as the FFH tool concept and design rules are described.

5.1 CONTEXT

The Dynamo script that came forth of the Royal BAM Group Dynamo Hackathon, appendix D, includes nodes detecting horizontal surfaces with missing barriers and placing warning signs according to the measured height difference from the horizontal surface downwards. This concept forms the basis of the script in this development and is developed further with a higher detail level and added functions. Additionally, the script is applied to infrastructure models in Revit 2021, expanding the type of projects that an automated FFH risk detection tool is developed for.

The tool is to be implemented in a particular moment of the safety management process, as its specific purpose is to detect FFH risk and automate placement of warning signs. The tool is an addition to the manual safety management process and can be applied in two different manners. The first being individual checks for the designers and planners during early project phases, to verify the safety of their design. The other manner is collaborative use of the visualisation proceeding from the tool in RI&E meetings and project team discussions regarding safety of the constructability and construction site. Ideally, the tool is used iteratively throughout the entire process, contributing to a better and safer overall project plan and construction site design. The process and incorporation of the tool, meaning the context in which it is intended to be used, are shown in appendix E.

5.2 CONCEPT

The tool concept describes the intended operations of node groups in the Dynamo script as a result of the performance requirements stated in paragraph 0. A general concept of the operations that are programmed using nodes from the Dynamo Library or installed packages is determined in advance, forming the foundation of the *fall from height (FFH)* tool.

Figure 3 depicts the foundation for the operations that need to be fulfilled by the FFH tool. These aspects are further developed in the design rules and programming of the script in Dynamo. However, the basis and underlying goal of these operations should be clear before commencing with the visual programming.

Firstly, the correct model needs to be opened in Revit 2021, including any linked models and topography. The nodes in the script need to fulfil the operations of importing and reading the model and its elements.

The next operations are to automate detection of any hazardous locations forming FFH risk, meaning horizontal surfaces that one can stand upon and are missing fall protection barriers. Subsequently, automated analysis of the height difference from these hazardous locations downward should categorise the type of risk. These operations are to occur automatically after running the Dynamo script, without manual assistance of the user of the tool, as the intention is to speed up and digitalise the risk identification and evaluation (RI&E). Automating these operations means that the user does not necessarily need to possess detailed FFH risk knowledge and can use the risk visualisation regardless of their level of expertise.

Following the automated detection is the immediate and automated placement of warning signs for each risk, taking into account their respective type and category.

Once the warning signs are placed, the tool allows for manual warning sign modification and placement of new signs, as certain hazardous situations might be perceived differently by the Dynamo script than it would be by industry professionals.

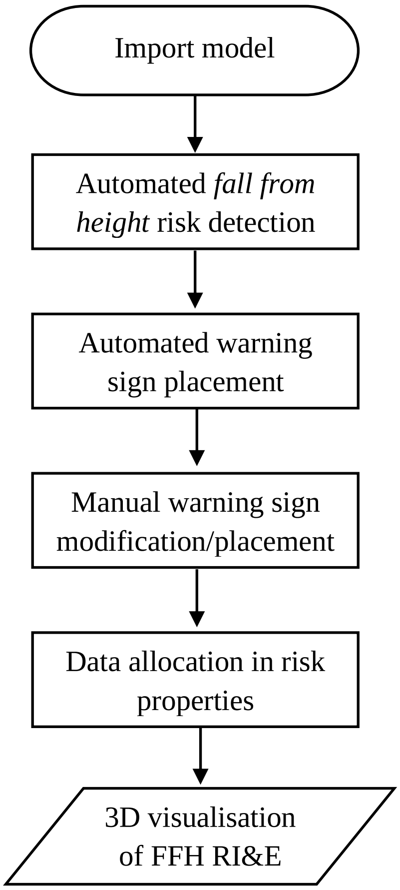


Figure 3 Tool concept functions

Finally, data is allocated to the specific risks either automatically or manually. This data, as described in paragraph 0, includes the risk type, category, standardised measures and time stamp of the moment that the Dynamo script is run and the risk analysis is performed.

As a result of these operations, a 3D visualisation of the *fall from height* RI&E is produced in the collaborative model. This visualisation can be used in the further safety management process by the individual team members or in group meetings for collaboration.

5.3 Design rules

Before programming in Dynamo, general design rules and specific node group operations are defined. The general design rules include colours and layout, adopted from the Royal BAM Group graphic template for working in Autodesk Dynamo. The visual scheme is intended to improve readability and uniformity within the Dynamo programs. Figure 4 shows the template graphics that are applied to the Dynamo script, specifically the colours used for the node groups and their purpose within the script.

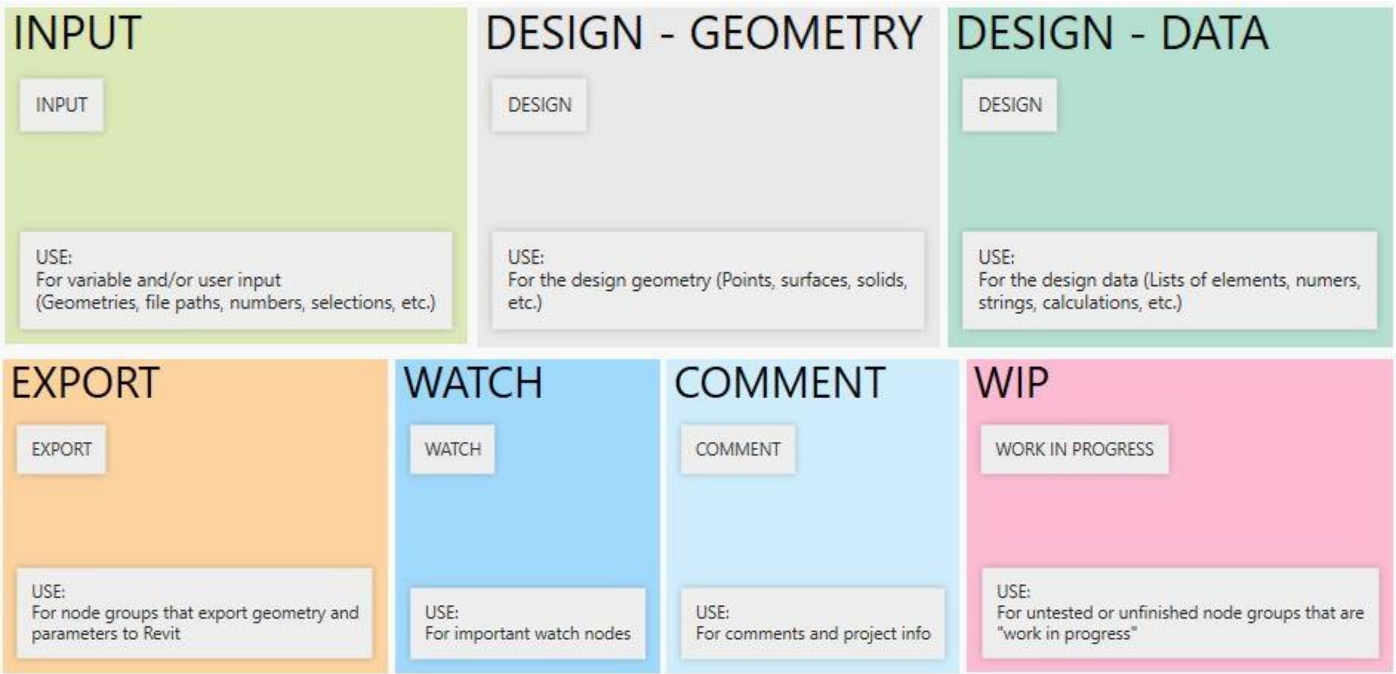


Figure 4 Applied Royal BAM Group graphic template colours for Dynamo programming (own image)

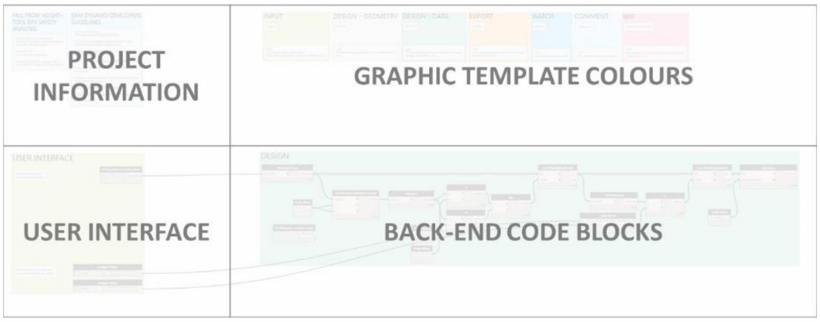


Figure 5 Applied Royal BAM Group graphic template layout for Dynamo programming (own image)

The script reads and works from left to right, see Figure 5. On the top the template and project information can be found. Any variable or user input is placed on the most left side of the workspace, forming the User Interface of the script. Any nodes and node groups to the right of the User Interface are back-end code blocks that should not be changed by the user of the FFH tool. The main flow of operations works from left (input) to right (export), simultaneous operations are placed underneath the main operation flow.

For workspace overview it is possible to use a Code Block with *InOut* as code to clean up connector lines. However, this adds extra operations to the script, taking up more workspace memory and causing the script to slow down. For this project it has been chosen not to use *InOut*-Code Blocks in order to preserve workspace memory.

The settings for render precision are set to *Large* and the number format is set to *0.000*. Only necessary nodes are previewed in the Dynamo background 3D preview in order to maintain a clear visualisation.

An overview and design of intended operations is made prior to the visual programming in Dynamo. This design of operations is a more detailed elaboration on the tool concept functions as described in paragraph 0 and defines the operations that need to be fulfilled in order to create a working tool for the intended purpose of analysing *fall from height (FFH)* risk in civil engineering projects.

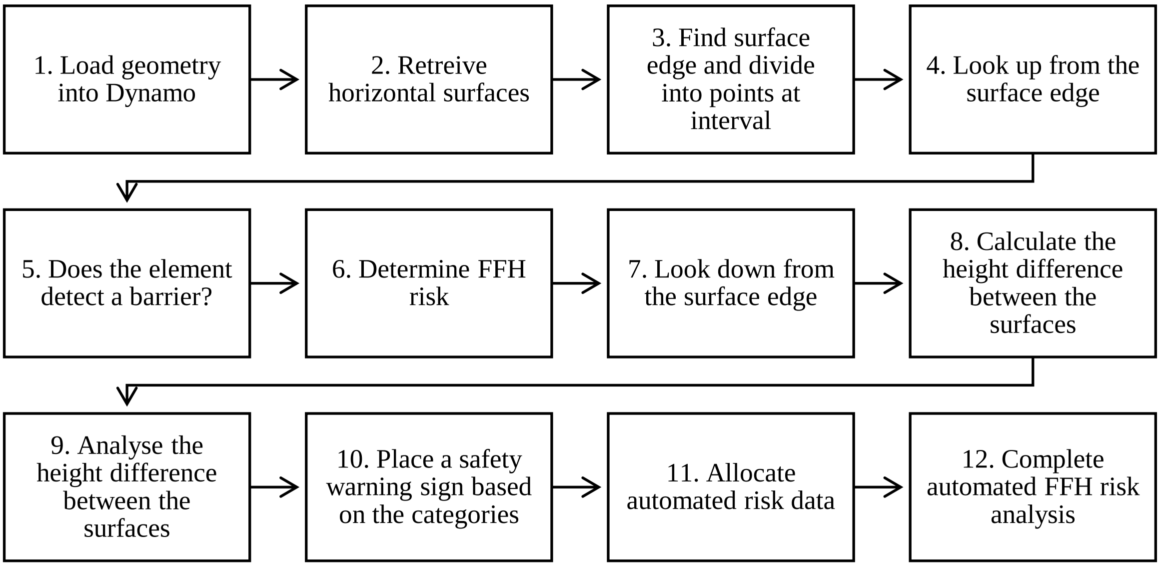


Figure 6 Fall from height tool concept; Design of operations (own image)

Design of operations:

1. **Load geometry into Dynamo**
   The project geometry is imported into Dynamo to run the FFH risk analysis.

2. **Retrieve horizontal surfaces**
   To find surface edges that form an FFH risk, the horizontal surfaces that can be stood upon are defined and listed for further analysis.
   Assumption: surface that can be stood upon is determined as a surface with an area of 1m^2.

3. **Find surface edges and divide into points at interval**
   FFH risk occurs at the horizontal surface edges, openings within the horizontal surface included, where no barrier exists. The surface edges are defined and points are placed at an interval to use for further analysis.

4. **Look up (vertical) from the surface edge**
   From the points a vertical element is created in the direction of the positive Z-axis to find whether a barrier is placed on or near the surface edge.

5. **Detect barrier geometries**
    a. **YES** – if the element from the point upwards clashes with a barrier element, the surface edge is protected by a barrier. This point does not form an FFH risk and can be ignored for further analysis.
    b. **NO** – if the element from the point upwards does not clash with a barrier element, the surface edge is missing fall protection and forms a starting point for further FFH risk analysis.

    Assumption: when the element looking upwards from the surface edge clashes, it encounters a barrier that prevents FFH risk, excluding this point for further safety analysis.

6. **Determine point causing FFH risk**
    If a barrier is missing the situation needs to be analysed, the script determines whether an FFH risk occurs and which category the risk fits into.

7. **Look down (vertical) from the surface edge**
    The points determined at operation 5b are the starting point of the analysis of the fall height. From these points a vertical projection is created in the direction of the negative Z-axis to find the nearest surface below that is fallen onto in case a hazardous situation occurs.

8. **Calculate the height difference between the surfaces**
    Calculate the height from the top point at the original surface to the bottom point on the fall surface.

9. **Analyse the height difference between the surfaces**
    The heights are divided into different severity groups based on the Wet Arbeidsomstandighedenbesluit, 1997 and practical heights for clear visual distinction. These groups form the categories for the RI&E.

10. **Place a safety warning sign based on the categories**
    Based on the height range and category a distinct warning sign is placed corresponding to the specific height of the FFH risk. The warning signs are distinguished by shape and colour.

11. **Allocate automated risk data**
    Where possible, automate data allocation to the identified risks and warning signs for later evaluation.

12. **Complete automated FFH risk analysis**

6 FFH TOOL PROTOTYPE

Following the requirements, concept and design rules stated in chapters 4 and 5, the *fall from height (FFH)* tool script is programmed in Dynamo for Revit 2021. The script for the tool prototype can be found in appendix F. In this chapter the operations within the Dynamo script are illustrated and explained, as well as specific programming choices and design challenges that are present in the current version of the script.

6.1 DYNAMO SCRIPT

This paragraph explains the node groups that make up the FFH tool script. These node groups and numbers correspond to the design of operations as presented in paragraph 5.3. The operations of the FFH tool script are illustrated in appendix G.

0. The User Interface (UI)

This section contains all variable input, i.e. number sliders, offset size, view selection and strings that can or have to be specified for each particular project. These code blocks are the only nodes that are subject to change within the script. The operation of each node is specified with a note within the UI group. The node *'All Elements in Active View'* is responsible for importing the project geometry into the Dynamo workspace. This node imports all the elements in the safety management view, meaning the user should make sure the correct active view is selected within Revit before running the script.

1. Load geometry into Dynamo

a. Import all elements operation through *'All Elements in Active View'* node.

b. Import linked topography geometry into Dynamo, transform into a PolySurface and place into Revit using ImportInstance.ByGeometry. This is required for the RayBounce node, which does not detect the linked topography as a surface it can bounce on. The linked topography is placed in Dynamo, the mesh count is reduced to make it readable and workable in Dynamo, as a more detailed mesh is too heavy for the program to work with. The mesh is then transformed into a polysurface, which is placed in the Revit model. This new instance in Revit can be used by the RayBounce node to bounce upon and return a point for analysis.

c. Delete the newly placed topography geometry from Revit. This is done after the script has generated the points for height analysis (in node group 8a), requiring a *'Passthrough'* node to ensure the geometry is not deleted before the RayBounce node has utilised the surface. It is important that the placed topography geometry is removed to preserve the integrity of the project design and model.

2. Find surfaces that can be stood upon

All faces of the imported elements are read and then filtered on surfaces where the Z component of the normal vector lies between 0.95 and 1.05. Surfaces where the normal vector has a Z-value ≈ 1 are assumed to be horizontal surfaces. A margin of 5% is taken to make sure all horizontal surfaces are analysed, including slightly tilted surfaces and surfaces sloped for water runoff, generally designed at 2% for infrastructure projects at Royal BAM Group. Subsequently, these horizontal surfaces are filtered by area, where an area of less than $1m^2$ is assumed to be too small to stand upon and does not form an FFH risk.

3. Find surface edge and divide into points at interval

a. The *Surface Perimeter Curve* is taken as the surface edge. These curves are offset by an amount of 10 millimetres to set them up correctly for the RayBounce offset points in node group 7; the lines are translated to both directions (onto and off the surface) and then the line closest to, and thus on, the surface is used as the line for reference further on. The line is shortened so that the detection of the intended line operates correctly in case of a surface opening. If the line is not shortened, there are situations, e.g. an opening in the floor, where a line is translated off the surface but where the line ends still hit the surface, thus the distance to the surface equals zero. This would be incorrect and disturb the detection of the required line.

b. The identified curve from node group 3a is divided into segments of 4m. Points are places on each segment of 4m and any duplicates are removed. The segment length is adjustable for smaller or larger projects, the slider is located in the User Interface.

4. **Look up (vertical) from the surface edge**

Inverted cones with a height of 1500mm are created to detect any barrier on or close to the surface edge points. The shape of the element, an inverted cone with a radius of 100mm at the bottom and 400mm at the top, allows for finding barriers that are placed up to 400mm inside the surface edge.

5. **Detect barrier geometries**

Walls and railings are considered to be barrier geometries, as well as any families that are specific to the project. These can be included in the analysis by entering the family name in the *String* in the UI. These barrier elements are filtered from all project elements and combined in a list to be used for further analysis.

6. **Determine points causing FFH risk**

The inverted cones created in node group 4 and the barrier elements defined in node group 5 are the input for the *Geomery.DoesIntersect* node, which determines which cones should be included for further analysis. If there is an intersection with a cone and a barrier geometry (Boolean is True), it means that there is no FFH risk and this point can be ignored. Where there is no intersection (Boolean is False), there is no barrier to protect from falls and thus there is a risk. From these cones, the StartPoint is determined and used for further operations. Note that for the *Geomery.DoesIntersect* node, the lacing has to be set to *cross product* to ensure all edge points are checked with all barrier geometries and determine whether they intersect.

7. **Look down (vertical) from the surface edge**

a. The relevant points that form FFH risk are offset with the Line Offset + 150mm, in 4 directions corresponding to the normal of the line (Figure 7). This results in 3 points that lie on the surface and 1 point that hovers off the edge of the surface by 150mm. The 4 points are combined in a list with the origin point to make sure the reference point is not lost.

b. The points are offset 1mm on the Z-axis to create room such that the *RayBounce* points bounce on the original surface. The 3 points that lie on the surface return the original surface, while the hovering point returns a unique surface. If the vertical offset is not included, the 3 points on the surface might return a non-original surface and disturb the analysis.

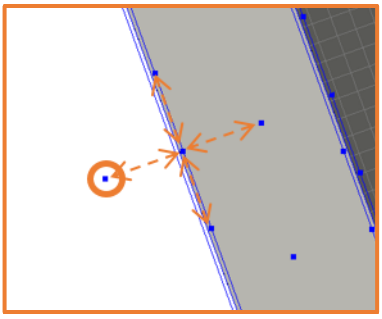


Figure 7 Point Offset (own image)

c. Once the points are offset in the X, Y and Z direction, the *Raybounce.ByOriginDirection* creates corresponding points below, in the reverse Z-axis direction, on the first surface it encounters. These points are used as a reference to calculate the fall height.

8. **Calculate the height differences between the surfaces**

a. The *Raybounce.ByOriginDirection* node returns the original and bounce point, as well as the element that is bounced upon. The Element IDs are used to determine at which point an FFH risk occurs by finding the *uniqueElements* within the list of 4 surfaces corresponding to the 4 offset points, for each origin point. Using the *uniqueElements* and lists of points, the offset point and corresponding bounce point at the FFH risk are determined. These points are used for further operation. Note that for the *List.IndexOf* nodes, the lacing must be set to *longest* to ensure all items in the list are analysed for finding the correct element index.

b. The list of points is used to find the Z-value of the upper and lower point, by subtraction the height in mm is found. Note that an error occurs in the subtraction node, this error does not affect the script, as it indicates the presence of *Null*-values that cannot be subtracted. These *Null*-values are the result of the *Raybounce.ByOriginDirection* node not being able to produce a bounce point, e.g. at the boundary of the project or when a linked model is missing, the latter being the case in this script as described in paragraph 0. The presence of these *Null*-values does not impact the script, as the operations are performed with the other values that are produced. The *Null*-values are replaced in node group 10.

9. Analyse the height differences between the surfaces

The heights defined in node group 8 are categorised according to severity into 6 categories ranging from light tripping to extra high fall risk.

Category	Minimum height (mm)	Maximum height (mm)	Warning sign
Light tripping	0	200	
High tripping	201	500	
Light fall risk	501	1500	
Medium fall risk	1501	2500	
High fall risk	2501	13000	
Extra high fall risk	13000	-	

Table 5 Risk categories

10. Place a safety warning sign based on the categories

Firstly, the previous mentioned *Null*-values are replaced by a *False*-value, cleaning up the list of relevant points and preventing further errors relating to *Nulls*. The entire list of points where FFH risk occurs, being the StartPoint of the cones in node group 6, is used for warning sign placement. The list of origin points is the *list* input for the *List.FilterByBoolMask* node, which is filtered by the *mask* list. The *mask* input is a list of Booleans (true and false values) containing true values for the items within the corresponding category and false values for any other items in the list. The *in*-output of the *List.FilterByBoolMask* node contains all the origin points on the surface edge where FFH risk in the particular category occurs. On these points a family instance is placed, corresponding to each respective category.

11. **Allocate automated risk data**
    a. Certain measures can be allocated automatically in accordance with the Wet Arbeidsomstandighedenbesluit, 1997. This law states that when working at heights up to 2.5m, the situation should be assessed individually and barriers should be placed where needed. In situations where working at heights concerns heights from 2.5 to 13 meters, a barrier of 1.0m high should be placed. Any situations with a height of over 13 meters, a barrier of at least 1.2m high should be placed. This information is automatically added to the properties of the placed warning signs and can be adjusted in the script when decided by the safety manager.
    b. Date and time parameters are added to the properties of the placed warning signs, to allow for view filters in Revit and create an overview of the safety analysis at a specific time stamp. Repeated safety analyses can be compared when the project progresses.

12. **Complete automated FFH risk analysis**
    The operations in the script are completed and the automated FFH risk overview can be used by project members for visualisation and risk identification & evaluation.

6.2 Programming choices

Within this FFH tool prototype, decisions are made regarding the visual programming, operations design and choice for specific nodes. These decisions are made based on the available nodes and node outcomes in relation to the design of operations and desires results. In this FFH tool prototype no Python scripts are used to create custom nodes, all nodes are used from the Dynamo library or installed packages (see paragraph 4.2).

0. **The User Interface (UI)**
    No alternative nodes are explored.

1. **Load geometry into Dynamo**
    a. In this prototype, all elements in the active view are imported into the Dynamo tool for analysis. The correct safety analysis view should be open in Revit. An alternative is to use the *Select Model Elements* node, in case the geometry in the view displays a large amount of elements that do not need to be taken into account for the analysis. It is recommended to (temporary) hide the redundant elements in the view and using the *All Elements In Active View* node, as this requires less user interaction than using the *Select Model Elements* node. Additionally, the *All Elements In Active View* node uses less workspace memory and CPU speed as it does not import the elements separately, but as a whole view.
    b. In the tool prototype the topography is imported by translating to mesh and then polysurface, subsequently requiring nodes for correct Workset selection and Level placement. Alternatives for importing the topography are explored with the use of additional packages, however, no working node has been found. For improving the script memory and processor usage, it is recommended to explore alternative nodes that allow for the *RayBounce* node to project onto the linked topography directly, instead of having to import, place and delete the topography geometry.

2. **Find surfaces that can be stood upon**
    An alternative for importing the horizontal surfaces can be using *Surface.FilterByOrientation*, a node from the package *Clockwork for Dynamo 2.x*. This node sorts surfaces based on their orientation (vertical, horizontal up, horizontal down). This does not account for slightly sloped surfaces and requires installation of the package and thus has not been chosen.

3. **Find surface edge and divide into points at interval**
    No alternative nodes are explored.

4. **Look up (vertical) from the surface edge**

   Alternatively, a line was placed in the direction of the Z Axis with the points on the edge as origin. The node *Line.ByStartPointDirectionLenght* was used. The operation is similar to the node group using cones in the current FFH tool prototype, however, using a line to vertically detect barriers does not allow for detection of barriers that are placed within the surface edge. Since barriers are not specifically always placed directly on the surface edge, the node group using cones has been chosen in order to detect barriers that are placed up to 400mm away from the surface edge.

5. **Detect barrier geometries**

   No alternative nodes are explored.

6. **Determine points causing FFH risk**

   No alternative nodes are explored.

7. **Look down (vertical) from the surface edge**

   An alternative method of offsetting the points is by creating a circle around the origin point with *Circle.ByCenterPointRadius*, subsequently creating a polygon with 4 sides within that circle and finally creating points on the corners of the polygon. Since the direction of the offset in relation to the direction of the edge is important in further operations, the *Geometry.Translate* nodes have been chosen, that offset the points in the direction of and perpendicular to the edge. This can also be possible with the use of the creation of the circle when the *NormalAtParameter* is taken into account. Since the outcomes of the alternative nodes do not differ significantly, the current node group has been chosen definitively in the FFH tool prototype.

   Alternative methods for looking down from the edge can be explored for further development, especially in relation to the linked models and the unique bounces posing challenges, as described in paragraph 0. The *RayBounce* node does not work as needed on linked geometry and does not detect all FFH risks due to the unique bounce method. It is recommended to explore alternatives to the *RayBounce* node that possibly resolve these issues.

8. **Calculate the height differences between the surfaces**

   No alternative options are explored.

9. **Analyse the height differences between the surfaces**

   No alternative options are explored.

10. **Place a safety warning sign based on the categories**

    No alternative options are explored.

11. **Allocate automated risk data**

    Alternatively, the allocation of the date and time parameters can be omitted and instead a node group at the front of the script can be added that deletes all existing warning signs. This deleting node group clears the model geometry of the previously performed FFH risk analyses and their respective warning signs. This allows for new risk analysis but deletes all data from earlier analyses. Hence, it has been chosen to add the date and time parameters to the warning signs and to filter the view on selected date and time properties in order to compare the FFH risk analyses at different points of time during the design and planning process.

12. **Complete automates FFH risk analysis**

    The operations in the script are completed.

Design challenges

Challenges were encountered in the development of the *fall from height (FFH)* tool prototype. These challenges are either partially solved by programming simplified operations or are open subjects for further development of the tool. This paragraph explains the encountered challenges and where possible the suggested concept of solutions.

- **Importing linked models into Dynamo**
  In many projects, the topography and terrain, road & hydraulic engineering is designed and modelled in separate software, and then loaded into the main model by linked models in Revit. Errors are experienced when loading the linked road model, which is a common problem in the industry. The linked models are not read correctly by the Dynamo script. Explored nodes require Python programming and did not produce the required outcome. In the prototype script, the topography is imported as geometry to be used for the analysis and then deleted from the model again. This method does not work for other linked models besides topography.
  Solution: It is recommended to request a simplified model from the designers with a single surface that can be placed as geometry into the coordination model for analysis purposes, preferably of the topography and road design combined. As the surface is solely used for the *RayBounce* to detect the heights, placing the geometry as a singular surface is sufficient in this prototype. Furthermore, custom nodes can be programmed using Python to import the linked models similarly as the linked topography. This requires programming and Dynamo expertise from the developer.

- **Find the correct surface**
  In the current script for the FFH tool prototype, surfaces with a normal that lies between a Z-value of 0.95 and 1.05 are considered to be horizontal surfaces that can be stood upon and thus fallen off of. However, surfaces with a steeper slope can potentially be the cause of an FFH risk, similarly sheet pile walls with soil on one side and a drop on the other side can form hazardous situations. These instances are not accounted for in the FFH risk analysis of this prototype.
  Solution: It is recommended to add more surface types to the analysis in future versions of the prototype, as these situations are likely to occur on civil engineering construction sites.

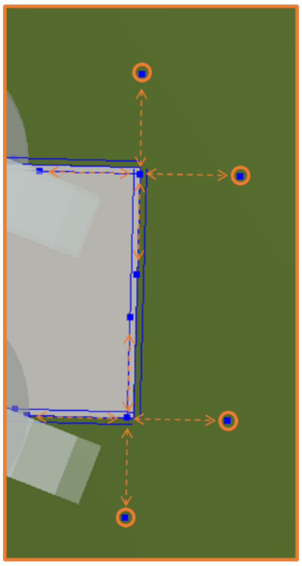
- **Point interval on surface edges**
  The spacing of the points on the surface edges is set at 2m. In the event that an opening or missing barrier spans a width of less than 2m and coincidentally occurs entirely in between 2 points, the opening or missing barrier is not picked up by the automated risk detection. The same might occur on surfaces where one or more edges are shorter than 2m. However, in the second situation, one or more other edges of the same surface might be longer than 2m and still be detected by the tool. The occurrence of these situations is estimated to be very low within the size and scale of the civil engineering models, so they are accepted in this prototype script.
  Solution: If a model is used where it is known that there are situations where risks occur on edges with a length shorter than 2m, a solution is to adjust the input in the tool from 2000mm to for instance 1000mm or 500mm in the User Interface.

- **Project specific barriers**
  Node group 5 specifies the barriers that are then used in node group 6 to determine whether each point causes FFH risk or not. General wall and railing geometries are included in the analysis, as well as a project specific family that is modelled as a barrier within the 3D model of the project. This FFH tool

prototype allows for one project specific barrier, the name of this family type can be input in the User Interface. The challenge here occurs when the 3D model of the project contains more than one project specific barrier. It is possible to include all these barriers in the analysis, however, this requires programming by an expert to add these nodes to the node group. It is not recommended to add many more options for project specific barriers, as this varies for each model.
Solution: It is recommended to either model the barriers as *Wall* or *Railing* geometry, or to involve a Dynamo expert in the *fall from height (FFH)* safety analysis process to make sure that all project specific barriers are accounted for.

- **Detecting height difference with point offset and RayBounce**

  In node group 7 the point on the edge is offset in 4 directions horizontally and then 1mm up on the Z-axis. These offset points are used for the RayBounce to look down and detect if and where the origin point causes FFH risk. The intention is that 3 points bounce on the original surface and 1 point bounces off of another lower surface, indicating a height difference and fall risk (Figure 7). This method poses some challenges in specific situations. Firstly, on the corners of the surface two of the points fall off the surface (Figure 8). As node group 8 detects the unique bounces of origin points with precisely 1 offset point bouncing back a different *ElementId*, these corner points are not seen as FFH risks. For this prototype, it has been determined that the likelihood of a point nearby indicating the FFH risk of the edge is sufficient enough such that no warning sign needs to be placed on the corner. Secondly, as node group 8 detects the unique bounces of the origin points with precisely 1 offset point bouncing back a different *ElementId*, no FFH risk is identified when all 4 points bounce on the original element with the same *ElementId*. This situation occurs when height differences are present within a singular surface. An example of this is the raised edge between the walkway and railway track on the superstructure, as can be seen in appendix H. The method with detecting the unique bounce has been chosen such that the warning signs can be placed on the origin point on the edge, as the structures of the lists are not lost, and it fulfils the operations and requirements as intended for the FFH tool prototype.

  
  Figure 8 Point offset - corners (own image)

  Solution: It is recommended to explore different methods of detecting the height differences such that the corners and heigh differences within one element are also included in the analysis.

- **Grouping warning signs**

  With the height detection method (node groups 7 and 8) as described in the previous bullet point, the warning signs can be placed on the origin point and maintain a reference to the surface that they are placed on. However, the reference to the specific edge that they are placed on is lost, resulting in multiple separate risk indicators of the same FFH risk. Ideally, each FFH risk is indicated with one warning sign in order to prevent a chaotic overview of too many warning sings in one place.
  Solution: It is recommended to explore nodes and operations where the height detection remains a reference to the specific point and edge that it occurs on, such that subsequently the warning signs at each point can be linked to all warning signs indicating the same FFH risk at that edge. From the validation result in chapter 7 it can be concluded that this challenge is recommended to be one of the main subjects of focus for further development of the FFH tool.

- **Preparation of the 3D model for analysis**
  The preparation of the 3D model is not part of the Dynamo script but essential to the FFH risk analysis. In order for the script to read the correct elements and simultaneously not import too many redundant elements, the intended view should be modified such that the relevant elements are visible in the view. The correct elements are needed for adequate safety analysis, where too many redundant elements can delay the run of the script by using more PC memory than necessary. Additionally, specific temporary structures can be added to the model if these are not present in the construction site design. This preparation requires manual adjustment of the filters and objects in Revit by designers, planners and coordinators.

The further developments with the highest priority are importing the linked models and finding an alternative for the *RayBounce* method to eliminate missing risks and including grouping the warning signs for each risk. As these influence the applicability on additional, more complex project and ease the implementation process.

7 SIMULATION

The simulation is performed in two parts; the verification to ensure fulfilment of the requirements and the validation to determine the added value of the tool in collaboration with industry professionals. Prior to the verification and the validation phase, the warning signs consisted of 4 categories: tripping (0-0.2m), medium risk (0.2-2.5m), high risk (2.5-13 m) and extra high risk (13m and up). The categories have been modified to the 6 categories mentioned in paragraph 6.1 as a result of the validation sessions.

7.1 Verification

The verification consists of four verification questions, related to modelling and testing to determine that the script performs the desired operations as intended. To answer these verification questions the script is tested in the artificial environment of Revit and Dynamo, on real-life engineering Revit models (Wieringa & Heerkens, 2007). This is done by running the script and assessing whether the nodes and node groups return the expected outcome. Then a reflection is made regarding the tool requirements defined in chapter 4 and it is determined whether the tool meets these requirements. The verification process gives an answer to whether the script works and satisfies the tool requirements and does not consider the external validation or added value in practice as this is done in the validation phase in collaboration with industry professionals. The external validation is performed in the second part of the simulation. In the verification phase, the following four verification questions are answered:

1. Does the script run as intended on an existing Revit 2021 model?
2. Does the tool satisfy the requirements?
3. Does the node group operation produce the desired outcome?
4. Does the script run as intended on different Revit 2021 models?

7.1.1 Script runs

The script runs are performed on the railway overpass model of the project Bedum. The model, with file name TABE_CO-ODG-Bedum_2020_1.rvt, is provided by Royal BAM Group. During design and programming, script runs are performed to identify any errors and ensure that the intended operations are successful. In the case of errors or incorrect operation outcome, new design iterations are made in Autodesk Dynamo for Revit. After running the script with successful operation outcomes, the FFH tool prototype was completed and used for further verification and validation. These iterations and programming runs resulted in the current tool prototype version and programming choices as described in chapter 6.

7.1.2 Requirement satisfaction

The satisfaction of the functional requirements is determined in the validation phase, as this encompasses user requirements where feedback for added value is needed in order to assess the requirement fulfilment.

The external interface requirements mainly focus on software needs to be able to run the script and thus do not require verification or requirement satisfaction. However, the model requirements defined in paragraph 4.2 pose challenges to the verification process. Availability of 3D models containing all specified elements is scarce in practice currently. The requirements and level of detail demanded in the models for ideal tool usage are higher than currently available in the construction industry. Improvements can take place in the digitalisation of the construction process, however, the models needed for usage as intended of the FFH tool prototype do not satisfy the set requirements of this development process. Commonly, the 3D models do not include the temporary construction site works at all or at sufficient level of detail, restricting the outcome of the use of the tool. As temporary situations that occur at a specific stage during the execution phase are not depicted and designed in the models completely, the script cannot import and read them and thus these situations are not included in the FFH risk analysis. This poses a large challenge on the verification of the tool, as these situations can only be tested once the detail level of the model is developed to a higher standard. The assumption is that over time, the detail level of the 3D models will improve and the FFH tool can be developed further simultaneously in this digital transformation process.

The performance requirements are the focal elements used for the FFH tool verification. The 4 requirements and their sub-requirements as stated in paragraph 0 are verified in the Dynamo script of the FFH tool. Requirement satisfaction is assessed with a score of 1-3 with definitions: (1) does not satisfy, (2) partially satisfies and (3) fully satisfies.

Requirement	**Satisfaction**
1. *Visual safety warning*	
a. Is able to import the projects' 3D model including geography and linked models	**2**
b. Is able to place visual icons at allocated locations	**3**
c. Is able to distinguish risk categories and place corresponding icons	**3**
d. Is able to project the visual icons in a collaborative environment	**3**
2. *Distinguish risk type and location*	
a. Is able to detect missing barriers on horizontal surfaces that can be stood upon	**3**
b. Is able to detect height differences between two horizontal surfaces that can be stood upon	**2**
c. Is able to categorise the high risks with a minimum precision of 10cm	**3**
d. Is able to place at least 1 safety warning on a surface edge where FFH risk occurs	**3**
3. *Provide space for data allocation*	
a. Is able to allow for manual input of risk properties to each placed visual icon	**3**
b. Is able to allow for manual alteration of the automatically placed visual icons	**3**
4. *Time specific 3D overview*	
a. Is able to allocate a time stamp to the safety warning signs placed during each FFH tool run	**3**
b. Is able to filter views according to the FFH risk analyses at specific time stamps	**1**
c. Is able to export the FFH risk data	**1**

Table 6 Verification of the requirements

1. Visual safety warning

a. Partially: linked models are not imported and used for analysis in this version of the FFH tool. At the moment of design and programming, no nodes were capable of importing the linked models in such a way that the surface could be read as geometry and used for the RayBounce operation. For further development, it is recommended to research different nodes and operations or to program a Code Block using Python that results in the needed import of the linked model geometry.

b. Yes: the safety warning signs are placed at the identified risk locations.
c. Yes: different heights in the FFH risk analysis are distinguished and corresponding signs are placed.
d. Yes: the FFH risks can be evaluated in the central or local Revit model, in individual or collaborative environment

2. **Distinguish risk type and location**
   a. Yes: surfaces are detected and used for the operations searching for the surface edges. From these edges, general and project specific barriers that are placed within 400mm of the surface edge are detected.
   b. Partially: due to the operations in node group 8, only unique bounces are seen as FFH risk. This means that on surface corners and if there is a height difference on the surfaces of one element, it does not detect this height as an FFH risk. For further development, it is recommended to research different nodes and operations or to program a Code Block using Python that is able to maintain the information in relation to the analysis, but does not require the *uniqueElements* nodes to find calculate the height differences.
   c. Yes: the calculation and analysis of the height difference occurs as intended and is able to distinguish severity categories with a precision of 1mm.
   d. Yes: the identified risk locations are indicated with a corresponding warning sign. However, one FFH risk might occur along a certain distance of the same edge. Currently, the FFH tool places signs at all instances at an interval of 4m. For further development, it is recommended to research different nodes and operations or to program a Code Block using Python that manages to place one singular warning sign for one FFH risk for better overview of the FFH RI&E.
3. **Provide space for data allocation**
   a. Yes: to each family type corresponding to the FFH risk categories, properties for the required data are added. Some properties, such as the measures and time stamp of analysis performance, are added automatically. Other properties, such as whether an action is required or who the risk owner is, can be added manually when selecting the specific safety warning sign in Revit.
   b. Yes: the placed warning signs can be changed to a different category sign, the location can be altered and data can be input or changed.
4. **Time specific 3D overview**
   a. Yes: date and time are automatically added to the properties of the individual instances when each safety warning sign is placed.
   b. No: automated filters are not added through the Dynamo script but can be done manually in Revit.
   c. No: automated exports are not created in the Dynamo script but can be done manually in Revit.

7.1.3 Operation outcomes

In the current version of the tool, the operations performed by the node groups do produce the intended results, as verified in the previous paragraph. However, the design challenges posed in paragraph 0 require further development for the tool to implemented to a better degree.

7.1.4 Model testing

The tool has been tested on other models to verify the operations with a different geometry input. As geometries can differ over a variety of projects, it is important to verify that the node groups produce the intended results when different elements are analysed. The results on different models are not as expected, as several errors occur due to the geometry and elements. Due to development of the FFH tool prototype on the Bedum project model, project specific operations work on the model that potentially do not work on different models. It is recommended to improve the operations in the script to increase the applicability on different and more complex projects.

The models and FFH tool prototype User Interface need to be prepared before the Dynamo script can be used. The following steps are required to be performed for model preparation:

- Import fall risk warning signs as generic models
- Insert required parameter fields corresponding to node group 11
- Select correct views and User Interface data
- Prepare Revit model view, hiding redundant elements and adding temporary structures

It is important to note that the restricted availability of models that satisfy the FFH tool model requirements limit the possibilities for testing the FFH tool in different environments. As the level of detail of the 3D models develops further, new models can be tested and included in the FFH tool verification, resulting in new feedback for further FFH tool development.

7.2 VALIDATION

The validation is performed through a pilot project. In this pilot project, a civil engineering model is assessed on *fall from height (FFH)* risk by industry professionals. In this pilot project, variables related to the FFH RI&E are measured and evaluated. The outcome of this validation is used to determine the added value of the FFH risk tool and whether or not the tool is recommended for implementation and further development (Wieringa & Heerkens, 2007).

For this pilot project, the same civil model that is used during programming and verification is used, to ensure the viability of the FFH tool performance. Two groups of experts are asked to perform an FFH specific RI&E, one with the use of the tool and one without. The results from these RI&E sessions are compared on a set of criteria and then used to determine the added value of the use of the tool, versus the current method of fall risk analysis. This method results in high external validation from industry professionals in a real-life environment, in contrast to the verification which has been performed in an artificial setting without any external input (Wieringa & Heerkens, 2007).

Note that at the time of this development process, COVID-19 measures were in place, restricting physical meetings. The validation sessions are performed online, through meetings in Microsoft Teams and with shared screens. This procedure might influence the validation results, as the amount and type of risks that can be identified may differ from a physical meeting where a risk analysis is performed. It is uncertain if the effect of the online meeting has a negative or positive influence on the validation sessions. The negative consequences can include being restricted to what is visible on the screen, being dependent on the person responsible for operating the model and restricted communication due to video and sound issues. The positive consequences can include good screen overview, limited distractions due to small digital environment and collective focus on the elements visible on the screen.

7.2.1 VALIDATION DESCRIPTION

The validation sessions are performed through Microsoft Teams due to the COVID-19 measures in place at the time of this development process. Two sessions are organised, one with a group performing an FFH RI&E without the use of the tool and one with a group performing an FFH RI&E with the use of the FFH tool analysis.

The groups consist of industry professionals of different roles, some members are part of a safety council (*veiligheidsraad)* that concerns themselves over safety issues and improvements company wide.

Group 1 – without tool	Group 2 – with tool
HSE department	Project controller
Project manager	BIM specialist
Project controller	Project planner
BIM specialist	

Table 7 Roles of the validation group members

The setup of the validation session without the tool is as follows:

- Collective assessment of the 3D model
- Performance of the FFH RI&E through discussion and documentation
- Indication of FFH risk and data
- Concluding the safety analysis

The setup of the validation session with the tool is as follows:

- Run of the FFH tool Dynamo script
- Collective assessment of the 3D model including placed warning signs
- Modifying and adding safety warning signs and the data
- Concluding the safety analysis

7.2.2 Validation criteria

The validation session results are assessed based on a set of criteria. The criteria determine the added value of the use of the tool, compared to the assessment without the use of the tool.

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	1-10	20%	1-10
Amount of risk, category	Amount	1-10	10%	1-10
Correctness of risk	Amount	1-10	15%	1-10
Speed of assessment	Minutes	1-10	20%	1-10
User experience	1-10	1-10	10%	1-10
Increased safety knowledge	1-10	1-10	5%	1-10
Tool potential rating	1-10	1-10	20%	1-10

Table 8 Validation criteria matrix

These criteria are a combination of objective and subjective criteria. The amount and correctness of the identified and evaluated risks are objective, these are determined by the data resulting from the validation sessions. The user experience, increased knowledge on project safety and the tool potential rating are based on the opinions of the industry professionals participating in the validation sessions. The opinions of the industry professionals are included as their experience and expertise form a central element for future implementation of the tool, as the FFH tool should connect with the current safety analysis process and bring useful added value for it to be integrated in future project processes.

The objective and subjective criteria results are scored a grade of 1-10 and are then distributed according to a percentage of importance, forming the final score per criterium. The scale for percentage of importance is determined on a division from most to least important aspects for validation of this version of the tool prototype. The industry professionals have been consulted to determine the distribution, in order to verify that the percentage of importance corresponds to the important aspects of such tool prototype in practice. The amount of total risk, speed of assessment and tool potential rating are the 3 most important aspects of the validation, and thus each take 20% in the distribution. Followed by the correctness of the risk, then the amount of risk per category and the user experience, which are seen as important aspects of the tool that grow to be more important as the prototype is developed further and integrated in the safety management process. Finally, the lowest level of importance is for the subjective increased safety knowledge. As the tool is expected to aid the safety management process and not entirely replace the manual process, the increased safety knowledge is least important for this tool prototype.

7.2.3 Validation results

The full results can be found in appendices I & J. The validation matrix has been filled out for both validation sessions, giving a final score on the FFH risk analysis without and with use of the Dynamo script for the FFH tool.

Session 1 - Without use of the tool:

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	8	20%	1.6
Amount of risk, category	Amount	5	10%	0.5
Correctness of risk	Amount	7	15%	1.125
Speed of assessment	Minutes	7	20%	1.4
User experience	1-10	7	10%	0.7
Increased safety knowledge	1-10	7	5%	0.35
Tool potential rating	1-10	7	20%	1.5
Total rating				**7.2**

The amount of risk total has been scored an 8 out of 10. All 6 major risks have been identified to an extent and the identified risks cover a range of subjects throughout the entire project.

The amount of risk per category has been scored a 5 out of 10. The severity of the identified risks is important, as a singular high risk outweighs several tripping risks. Since 10 risks were identified and a scale of 1-5 applies to this category, a total of 50 points can be scored. The category score was 24 out of 50, which translates to 5 out of 10. A similar method applies to the score for correctness of the risk. Where the score was 37 out of 50, translating to 7.5 out of 10.

The score for speed of assessment is calculated with the following formula: 10 – (time in minutes / 90 * 10). The time in minutes is 26, so the final score is 7 out of 10.

Session 2 - With use of the tool:

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	6	20%	1.2
Amount of risk, category	Amount	6	10%	0.6
Correctness of risk	Amount	8	15%	1.2
Speed of assessment	Minutes	8	20%	1.6
User experience	1-10	7	10%	0.7
Increased safety knowledge	1-10	6	5%	0.3
Tool potential rating	1-10	8.5	20%	1.7
Total rating				**7.3**

The amount of risk total has been scored a 6 out of 10. Only 4 out of 6 major risks stated in appendix H have been identified. No risks regarding the missing approach slabs or the abutment are mentioned, but several other risks covering a range of subjects throughout the entire project are identified, making this an adequate score.

The amount of risk per category has been scored a 6 out of 10. The severity of the identified risks is important, as a singular high risk outweighs several tripping risks. Since 8 risks were identified and a scale of 1-5 applies to this category, a total of 40 points can be scored. The category score was 23 out of 50, which translates to 6 out of 10. A similar method applies to the score for correctness of the risk. Where the score was 32 out of 40, translating to 8 out of 10.

The score for speed of assessment is calculated with the following formula: 10 – (time in minutes / 90 * 10). The time in minutes is 18, so the final score is 8 out of 10. And the final three scores are the subjective scores given by the validation session participants (appendix J).

Functional requirements validation

With these validation results, the tool prototype is validated against the functional needs as described in paragraph 4.1. Functional requirement satisfaction is assessed with a score of 1-3 with definitions: (1) does not satisfy, (2) partially satisfies and (3) fully satisfies.

Subject	Tool needs	Satisfaction
Design phase	Provide designers with more knowledge of the actual construction site	**2**
	Provide designers with feedback on the designed construction site	**2**
	Create a smart, innovative design process that includes site safety	**2**
	Provide planner and (sub)contractor with design choice motivation	**2**
HSE Plan (RI&E)	Prevent accidents by eliminating the source	**2**
	Identify risk source during the design phase using virtual models	**3**
Communication	Improve collaboration through virtual models, stimulating digital teamwork	**3**
	Improve discussions through visualisation, involving stakeholders/residents/ developer and other parties	**3**
Documentation	Involve developer, planners and (sub)contractors in the decision-making process regarding risk during the design phase	**3**
	Have all information regarding buildability, design, safety and feedback in one place	**2**
Tool content	Have phases and temporary situations modelled for site visualisation	**1**
	Distinguish the type and location of the risks for better overview	**3**
	Placement of exact virtual replicas of real-life safety objects	**1**

- **Design phase**
  The user needs relating to the design phase are partially satisfied. More knowledge, feedback and design choice motivation are somewhat provided through the FFH tool and the tool adds to an improving and more digitalised design process. However, limitations due to the lack of detail in the available 3D models limits full satisfaction of these needs.

- **HSE Plan (RI&E)**
  The user needs relating to the HSE Plan are nearly fully satisfied. For eliminating the source, manual design actions are required as this is not an automated function in the FFH tool. The risk sources are identified and visualised for further analysis and evaluation.
- **Communication**
  The user needs relating to the communication are fully satisfied. The tool is effective in improving collaboration within the team and involving external teams and parties in the safety discussion.
- **Documentation**
  The user needs relating to documentation are nearly fully satisfied. Decision making and information can be documented and managed within the view resulting from the use of the tool. This can be further developed to satisfy legal and company documentation requirements.
- **Tool content**
  The user needs relating to the tool content are partially satisfied. The type and location of the risks are identified and visualised through the tool. However, temporary situations and site visualisation is lacking detail and information as well as the shape of the safety warning signs. The user needs states exact virtual replicas of real-life safety objects, which is not part of this FFH tool prototype.

7.3 SIMULATION OUTCOMES

From the verification and validation it can be concluded that the FFH tool has large potential for future integration in the safety analysis process. There is no substantial amount of time needed to integrate the model at this stage, while it does provide extra information regarding the safety of the construction site and potential FFH risks within the project. However, this tool prototype does not produce infallible results that can be blindly relied upon without maintaining the current RI&E meetings and discussions. As from the validation it is evident that the meeting participants can become negligent to the detail in the safety analysis when solely relying on the results of the FFH tool. It is crucial that participants see the automated process in the tool as an addition to the manual process instead of a replacement of human inspection of the construction site design, as any oversights can potentially cause serious injury or fatal accidents. According to the validation results and industry expert feedback, the tool prototype provides great value when added to the safety analysis as a starting point for digitalisation of the construction site design regarding safety.

Currently, the lack of detail regarding temporary construction site situations in the 3D models restricts the tool from being implemented to a greater extent, as use of the tool is dependent on the availability of detailed coordination models for each project.

Concerning the tool prototype content and results of the safety analysis, one major shortcoming in the results of the FFH tool script run is the amount of safety warning signs that are placed in the model. For each edge at an interval of 4m where FFH risk occurs, a warning sign is placed. In some situations it can provide an overview of the extent of the risk, for example at the missing railing along one side of the superstructure, where it is clear that the full length of the superstructure requires fall protection. In other situations, the multitude of warning signs causes a disordered view of the situations and hinders speedy analysis and overview. Ideally, as mentioned in paragraph 0, the script places a singular warning sign for each risk or edge, instead of a warning sign for each point that lies at an interval on the respective edge.

The expectation is that especially on smaller projects it can be used as multiple double checks, as the time and costs of use of the tool are predicted to be low due to the ease of integration as a double check. The tool can be easily added to the design process and safety meetings, as it does not require a substantial amount of time to run the analysis and it will improve the overall knowledge and feedback on the construction site and design. Another added value is the extra information for the client regarding the projects' execution phase, potentially increasing the chances of winning the tender.

7.4 Other technologies

Besides the development of this FFH tool prototype there are more innovations and developments regarding construction site safety. These developments focus on different software, technologies or aspects of the safety analysis. Examples of these developments include virtual reality (VR), artificial intelligence (AI), machine learning (ML) and point cloud detection.

Virtual reality is being explored in combination with virtual safety walks, in development by Royal BAM Group, by allowing the viewer to walk through the model virtually and assess the design in proportion to the actual size in a virtual space. Additionally, virtual and artificial reality can be used for immersive learning and training for skill improvement and hazard response of construction site workers, as discussed in chapter 2, and improved workspace planning by construction activity simulation using VR and BIM. It has been determined that effective VR-based workspace planning and knowledge sharing with the use of digital technologies has a beneficial impact on a project's HSE plan (Getuli et al., 2020; Song et al., 2021).

Similarly, the research of artificial intelligence has experienced a significant boost in the past decade. With the six key subjects of digital twins, cloud VR/AR, smart robotics, 4D printing, blockchains and Artificial Intelligence of Things (AIoT), this field is expected to generate further research. These directions focus on automation, digitalisation and risk mitigation, ultimately resulting in an improve construction engineering management process in term of automation, time and cost effectiveness, self-modification and reliability. Specifically for safety, this means pattern recognition for risk identification through images and videos for condition assessment, potential risk prediction for proactive safety management and optimisation by using algorithms to provide constant recommendations to maximise project safety (Pan & Zhang, 2021).

Another element of AI is machine learning and point clouds, both explored by Royal BAM Group and academic research. Existing 3D environments can be analysed with the use of scanning technologies to produce 3D visualisations, mapping current situations and taking measurements. Within BAM, developments include digitalisation of asset management by creating digital visualisations of actual site situations with the use of remote sensing technology, 3D point clouds and cycloramas. The data can be processed in geographic information system (GIS) or software such as PowerBI to aid or replace the manual process relating to safety in asset management. Digital twins and automated maintenance plans are predicted to become focus subjects in the near future, according to BAM experts T. van der Scheer and A. Brouwer. The implementation of 3D point clouds on construction sites, specifically for scaffolding, determine that such structures can be successfully detected using point cloud data to identify hazardous situations and safety violations. Machine learning in the construction industry has mainly been implemented as a tool for object detection or feature extraction. Development and innovation can be found in using ML results for decision making, creating integral network models and added potential regarding site supervision and intelligent maintenance (Wang, 2019; Xu et al., 2021).

8 EVALUATION

8.1 CONCLUSIONS

The result of this ameliorative development is a software tool that is to be used for construction site safety analysis. Digital transformation consists of many different elements, of which digitalisation of the safety management and digitalisation of the design and planning process are one. The *fall from height (FFH)* tool is developed to add to the body of products that can be used for digitalisation of the construction process. The tool can be integrated in parts of the design and planning process for civil engineering projects to stimulate safety discussions and reduce hazardous situations on the construction site. It can be developed further in order to improve and innovate the automation of construction site safety design and management.

The requirements for the tool prototype have been formed through the needs of industry professionals and were then used to determine the concept and design. Through digital design and development this tool prototype has been created, fulfilling the following development statement:

To design and develop a prototype of a digital tool that improves fall from height accident reduction on construction sites during the execution phase of civil engineering projects.

The operations in the tool are aimed at FFH risk reduction by visualising potential hazardous situations. The prototype of the digital tool functions as an aid in the risk identification & evaluation (RI&E) process of Dutch civil engineering projects. The outcome of the use of the tool results in improved discussion and visualisation of FFH risk and hazardous situations, contributing to a more comprehensive and integral safety analysis.

The designed BIM tool aids the safety design and management process through adding an extra verification to the current design process and stimulating the discussion and collaboration in RI&E meetings. It is essential that the level of detail of the used 3D models develops further to support further development of the FFH tool and similar BIM solutions. The tool prototype represents a preliminary attempt in digitalising the construction site safety in early project phases. Together with developments in VR technology, machine learning and artificial intelligence, the digital transformation can take place step by step.

8.1.1 THE VALIDATION OF THE TOOL

It can be concluded that the application of the *fall from height (FFH)* tool in the design phase provides the designers with added information and feedback regarding the situations that might occur during the execution phase, and provides the HSE coordinator with insights that are valuable for discussing safety matters in the RI&E meetings. In the planning phases is provides a visual overview of potential hazardous situations that can occur during execution, this visualisation is of added value to the multiple involved parties in that it combines the views from different perspectives and allows for easier collaboration. The visualisation of the FFH risks is perceived as very useful and is determined to provide added value to the safety analysis, provided that the level of detail in the 3D models develops and improves further over time.

8.1.2 IMPACT ON THE SAFETY MANAGEMENT PROCESS

The tool automates detection of FFH risk and placement of visual signs that are iteratively used in the design and planning of civil engineering projects. It is important to note that the automated risk analysis does not replace the RI&E meetings or safety analysis, as the technology and models do not allow for unsupervised adoption of the FFH tool analysis results. The outcomes are subject to errors and dependent on project specific situations, making full dependency on the FFH tool unwise. However, the outcome aids the involved parties as it prompts detailed analysis and adds extra information to the coordination model of the project. The effective application and risk reduction data is to be determined when the tool is implemented in the design and planning process. The stated added value is determined through validation session on a singular pilot project. The success of integration and effective added value determines on the availability of 3D models and willingness of the project members to integrate the FFH tool in the design and planning process.

8.1.3 Limitations

The limitations of the tool are the design challenges that are not solved in this version of the tool prototype. The current script provides the expected results as the node groups produce the warning signs on the identified and evaluated FFH risk locations. However, for a number of these operations more effective alternatives might be available. It is recommended to further develop the tool by modifying the node groups to more efficient operations, potentially reducing the time needed to run the script. The time and computer specifications needed to run the script in Autodesk Dynamo for Revit are high, which can affect the willingness to integrate the FFH tool in the construction site design and planning process.

The 3D models that are used for the FFH safety analysis yield two types of limitations. The complexity of the used 3D models is a limitation of the tool as the node groups do not aid in great detail for highly complex or project specific structures. For more complex models, a specialist is needed to assist in implementing the tool prototype to account for any errors and unexpected results. Secondly, to analyse the safety of the construction site, ample temporary situations should be modelled in the coordination model that serve as the input for the Dynamo script. If no temporary situations are modelled, the outcome of the tool prototype is not sufficient enough to assess the FFH risks that might occur on the construction site. For the performed verification and validation, a 3D model of the definitive design of the project Bedum is used. This model contained the final situation of the design and no temporary structures. To simulate this, the model has been modified, appendix H, with removal of several elements, depicting an artificial situation in a digital environment.

Lastly, software used for designing, modelling and planning differ for each project within Royal BAM Group and might differ for projects outside of this company too. The tool prototype has been programmed in Autodesk Revit, however, within BAM projects other software is used, e.g. Inventor, Sketchup, to model the temporary structures and situations. Regardless of the option to export and import models as .IFC files, the use of different software can pose limitations to the implementation of the tool prototype.

8.2 Discussion

The verification of the tool is restricted due to the limited availability of suitable 3D models of former projects. The majority of the coordination models solely included the definitive design, lacking detail regarding the construction site and temporary situations. In order to create a more inclusive and extensive overview of the operations and effect of the tool prototype, a verification on a number of suitable 3D models should be conducted. Similarly for the validation of the tool, where the amount of participants and their roles within Royal BAM Group were limited within the time and scope of the development of the FFH tool prototype. To create a more inclusive and extensive overview of the effect and added value of the tool prototype, more validation sessions with expanded validation groups and applied on different 3D models should be conducted.

It should be taken into account that this design engineering project was conducted during the COVID-19 pandemic, resulting in digital meetings with the industry professionals and during the interviews and validation sessions. The outcome of these sessions can potentially be different from similar sessions if they were conducted as a physical meeting.

8.3 RECOMMENDATIONS

The digital transformation consists of many different elements. Automatic fall risk detection is one part of the bigger whole, which allows for a step in a more digitalised direction. The value of this tool prototype is the explored option of adding automation tools to the current design and planning process in safety management, allowing for further development and integration of similar tools in the future. The implementation of the tool prototype is to support the risk identification & evaluation process and the safety management process by automating operations that otherwise would be done manually. The recommendations consist of two parts, firstly the implementation needs and secondly the technical recommendations for further tool development.

For the implementation, it is recommended to integrate the FFH tool prototype for safety analysis in two ways. Firstly, letting the designers run the script during the design phase and use the automated FFH RI&E and warning signs as indicators for hazardous situations, providing insights in the situations that are created with the design. Using the FFH tool prototype during the design phase allows for iterative adaptations and redesign during the design process, without the need of waiting for the RI&E meetings. Secondly, using the outcome of the FFH tool prototype as a visual representation of the construction site and the identified FFH risks, allowing for better discussion and evaluation of the hazardous situations during the RI&E meetings. This provides not only the project designers and planners with an insightful overview, but also involves the contractor, subcontractors, site managers, stakeholders and client in the process. Allowing these other parties to gain insight and information on the safety management aspects and creating a better base for communication.

Besides the recommendations for integration of the tool prototype, it is highly recommended to improve the level of detail of the 3D models for the projects, including modelling temporary situations in one or more phases for the execution of the project. This is essential for the added value of the implementation of the FFH tool prototype, as greater model detail results in a more specific FFH analysis, better RI&E results and thus more useful information for design and planning of the construction site.

For further development, it is recommended to add more detailed operations to the tool prototype. In this version, the operations produce the expected outcome, however, different node groups can be developed. The following recommendations are considered to have the highest priority in further technical development of the tool, additional recommendations can be derived from the design challenges in paragraph 0.

- Creating nodes that can import linked models into the script for analysis
- Finding an alternative to the *RayBounce* operation to eliminate missing risks and including grouping the warning signs for each risk, instead of a sign on each hazardous point on the edge
- Increasing applicability on more complex projects

Concluding, the FFH tool prototype is considered to bring added value in digitalising an otherwise manual process regarding safety management. It is suggested to incorporate use of the FFH tool prototype or similar product to the design and planning process to proactively engage in digitalising and improving engineering processes.

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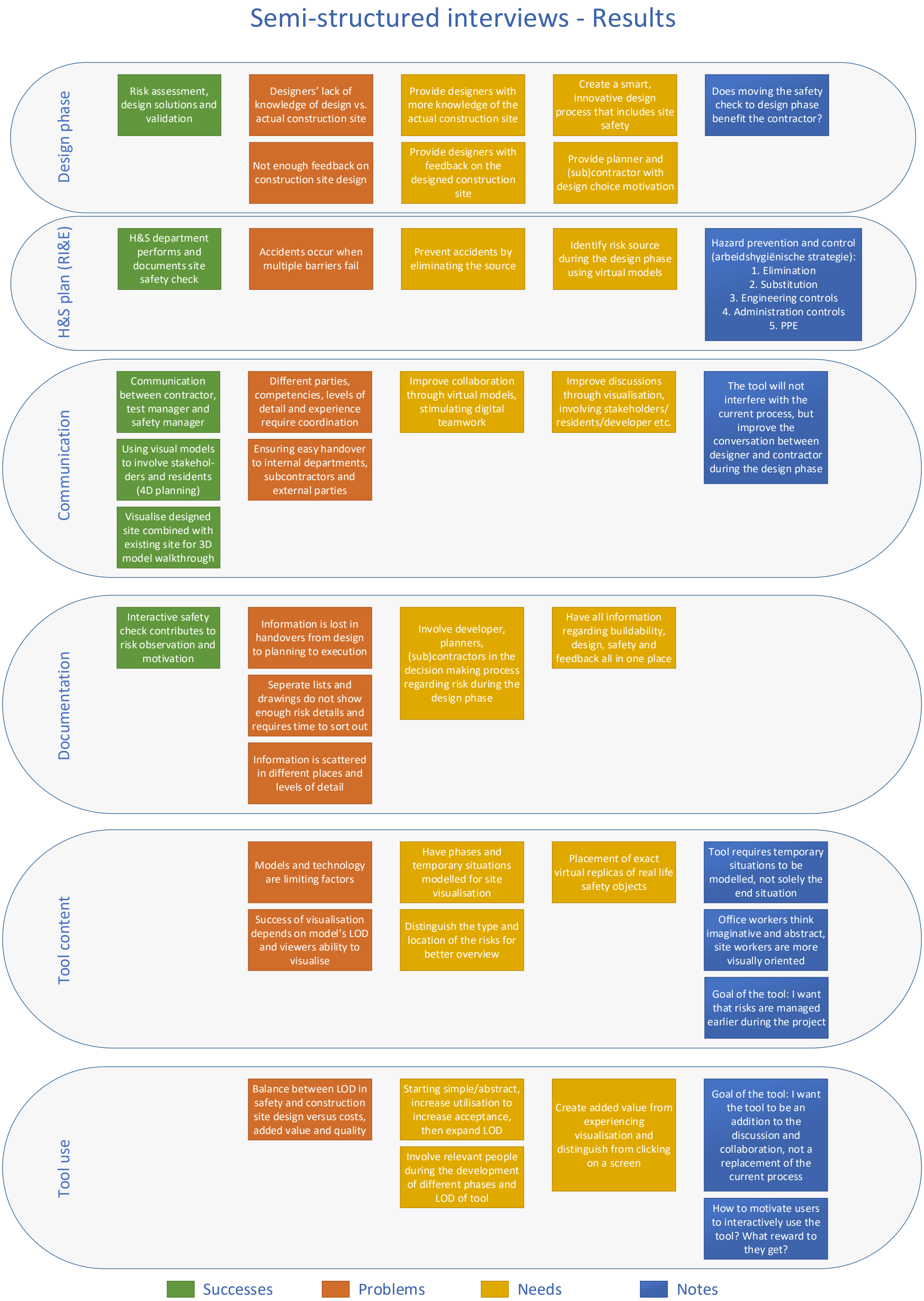
APPENDIX A: TYPE OF ACCIDENTS

Type of accidents and their occurrence between 1998 and 2009 (Rijksinstituut voor Volksgezondheid en Milieu, 2009).

type of accident	amount of accidents	amount of casualties			
		death	permanent injury	remediable injury	unknown injury
Fall from height; roof, floor or platform	986	64	133	501	314
Fall from ladder or steps	814	14	85	483	221
Fall from scaffolding	661	19	88	400	187
Contact with falling objects - not from crane / hoist	524	52	134	254	102
Contact with moving parts of a machine	439	1	351	58	29
Contact with ejected or flying object(s)	134	1	50	35	47
Contact with falling objects - from canes / hoists	131	16	47	52	21
Contact with electricity	131	7	29	54	31
Fall from moving platform	101	9	23	39	40
Fall on same level	99	1	6	58	28
Contact with hand tools	97	0	35	36	26
Contact with hanging and / or swaying objects	96	4	30	34	9
Fall from height - unprotected	93	4	12	47	33
Contact with object that is being worn or used	77	1	34	25	17
Entrapment between machine and another object	67	3	32	18	13
Collision (with a pedestrian) by a vehicle	56	8	9	21	18
Fall from height; by hole in the floor	53	2	9	29	13
Fall from stationary vehicle	49	2	5	27	15
In / on moving vehicle with loss of control	49	1	8	25	16
Fall from stairs or slope	46	0	4	28	14
Fire	39	2	5	21	7
Bumping against something	24	0	8	8	7
Contact with hazardous substance through spillage from normally closed container or shell	21	0	4	13	2
Explosion	17	0	8	5	4
Contact with hazardous substance without spillage	15	1	2	11	1
Buried underneath debris	12	0	3	5	2
Hit by a rolling or sliding object	11	1	4	4	2
Extreme pressure on body parts	11	0	1	4	6
Spillage of hazardous substance from an open container or enclosing system	9	0	4	4	1
Contact with harmful atmosphere in a closed area	6	0	0	8	1
Drowning	4	4	0	0	0
Contact with hot surface or open flame	2	0	1	1	0
Contact with harmful air through breathing equipment	2	0	0	2	0
Physical contact with an animal	1	1	0	0	0
total	**4877**	**218**	**1164**	**2310**	**1227**

Appendix B: Functional requirements

Based on semi-structured interviews with industry professionals, summarised and grouped per subject.



Appendix C: Requirements for external interfaces

For development of the prototype, Autodesk Revit and Dynamo are used. Built-in nodes and user-created packages with custom nodes are available through the software and online libraries[1]. The versions, packages and system requirements that are applicable are stated below.

- Front-end software: Autodesk Revit 2021.1 or later[2]
- Back-end software: Autodesk Dynamo for Revit version 2.6.1 / Dynamo Sandbox 2.11.1 or later[2]
- Installed packages:

Package Name	Version
Clockwork for Dynamo 2.x	2.1.2
Dynamo for Rebar	2.0.2
spring nodes	204.1.0
MeshToolkit	3.0.0
archi-lab.net	2019.2.17

Table 9 Installed packages for Dynamo

System requirements are as defined by Autodesk for Revit 2021 for large, complex models and Dynamo Studio. Since the FFH risk analysis is intended to be performed on large, civil models and the Dynamo script contains complex nodes, it is recommended to use the system requirements for higher performance. It is possible to run Autodesk Revit 2021 and Dynamo Studio with lower performance requirements, but good FFH tool performance cannot be guaranteed.

Operating System	64-bit Microsoft® Windows® 10	
CPU Type	Single- or Multi-Core Intel®, Xeon®, or i-Series processor or AMD® equivalent with SSE2 technology. Highest affordable CPU speed rating recommended	
Memory	32 GB RAM	
Video Display Resolutions	Minimum: 1920 x 1200 with true colour	Maximum: Ultra-High (4k) Definition Monitor
Video Adapter	DirectX® 11 capable graphics card with Shader Model 5 and a minimum of 4GB of video memory	
Disk Space	30 GB free disk space 10,000+ RPM Hard Drive (for Point Cloud interactions) or Solid State Drive	
Media	Download or installation from DVD9 or USB key	
Pointing Device	MS-Mouse or compliant device	
.NET Framework	.NET Framework Version 4.8 or later	
Browser	Microsoft® Internet Explorer® 10 or higher	
Connectivity	Internet connection for license registration and prerequisite component download	

Table 10 System Requirements for FFH detection tool (Autodesk Inc, 2016)

[1] download: https://dynamopackages.com/
[2] download: https://www.autodesk.eu/products/revit/

Appendix D: Royal BAM Group Dynamo Hackathon Script

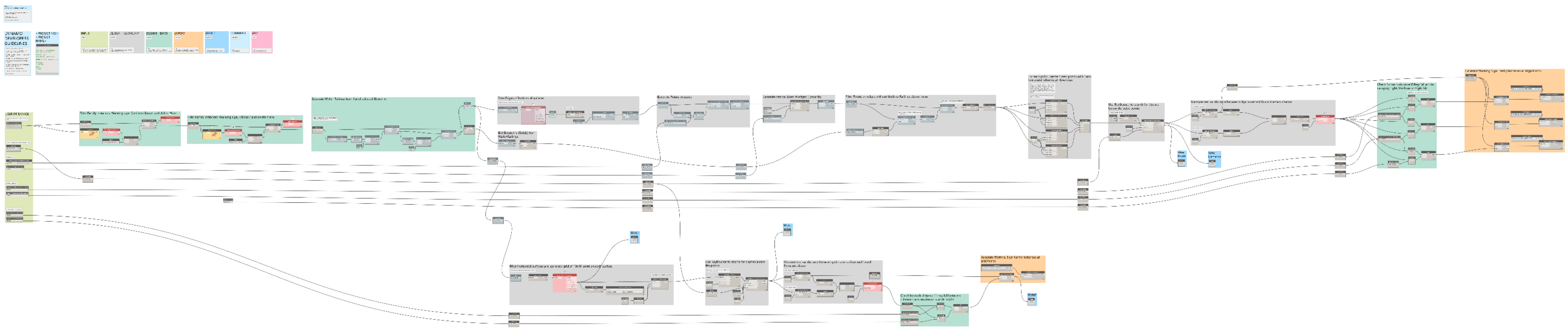


Figure 9 Royal BAM Group Dynamo Hackathon safety analysis script (Owner: Royal BAM Group, 2020)

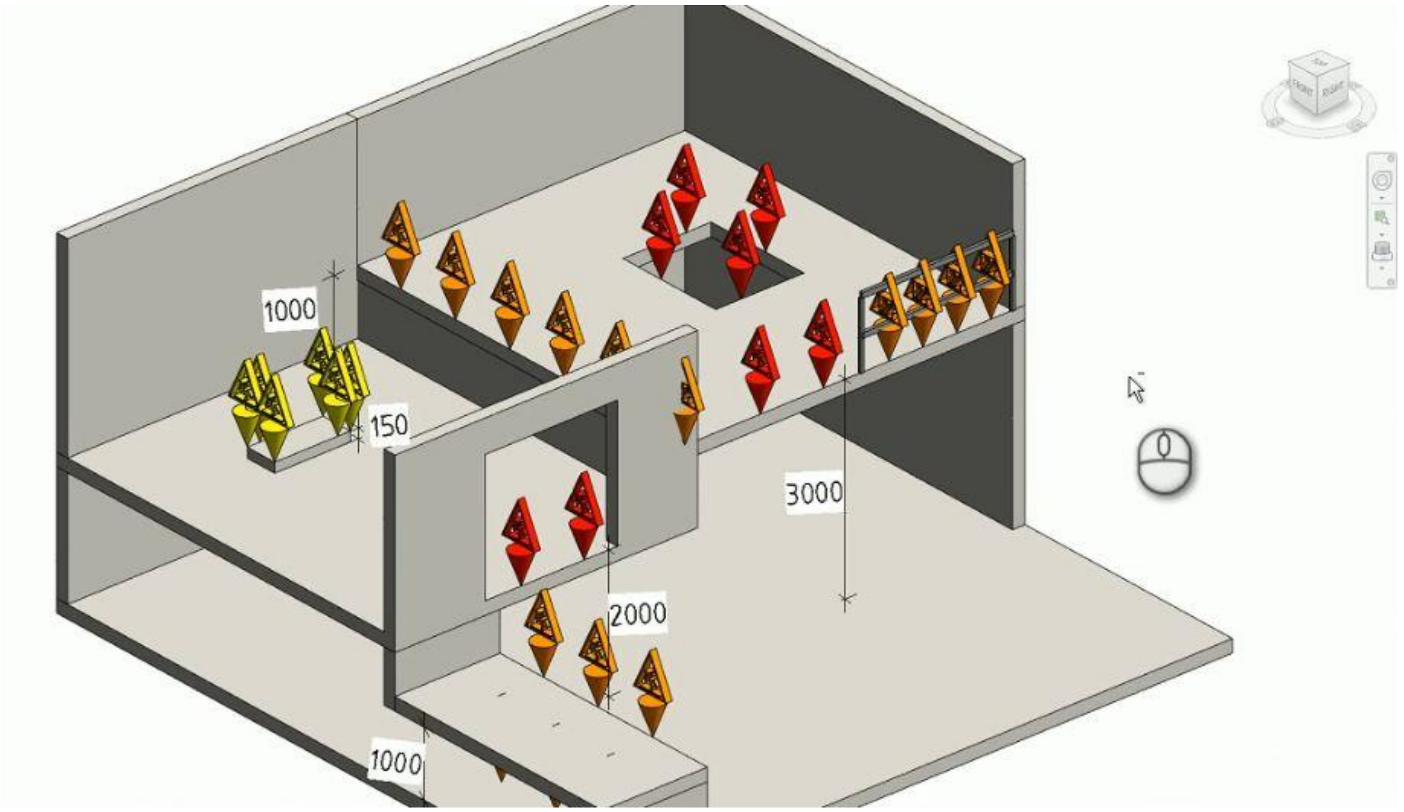
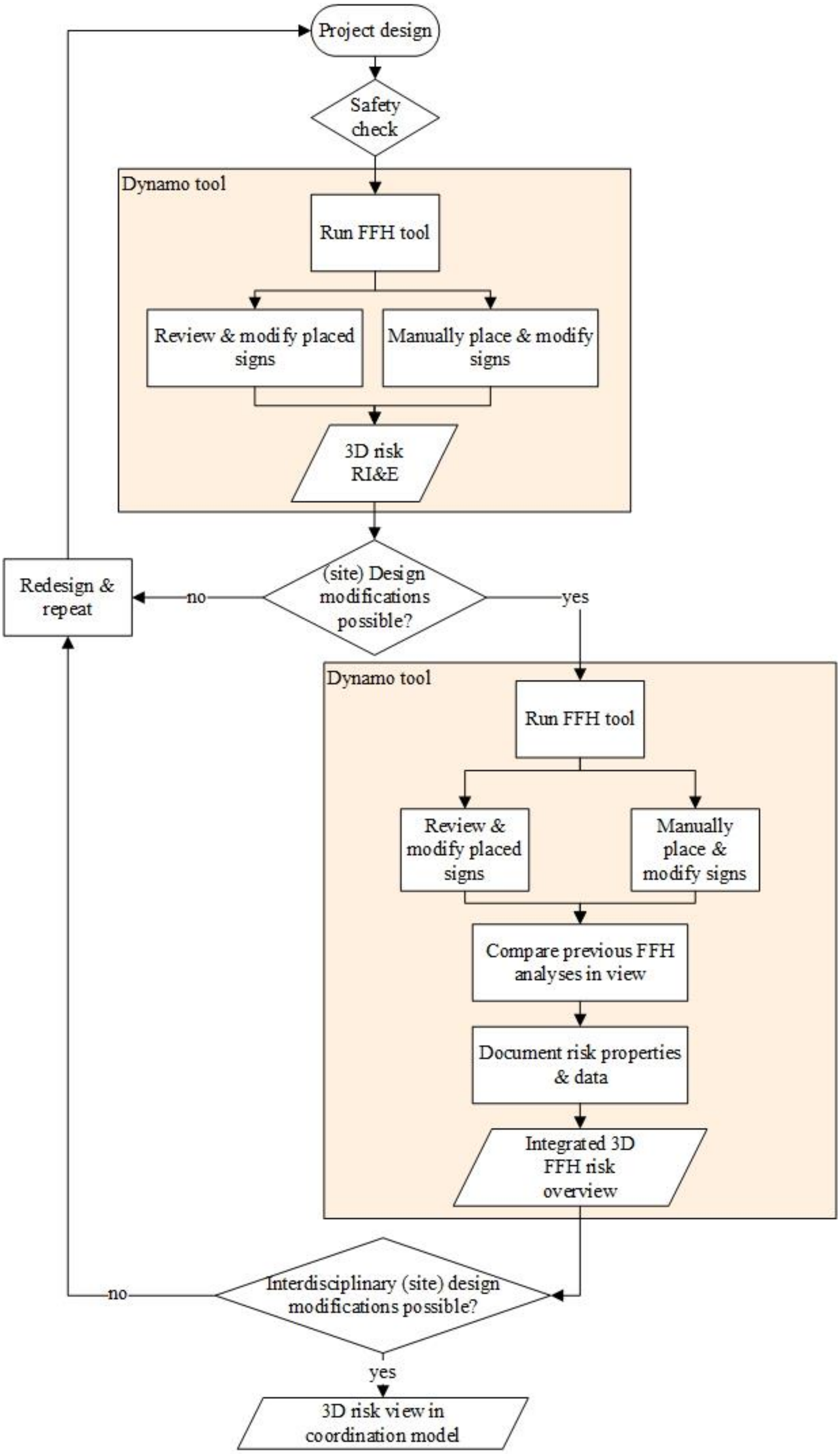


Figure 10 Royal BAM Group Dynamo Hackathon safety analysis script visualisation (Owner: Royal BAM Group, 2020)

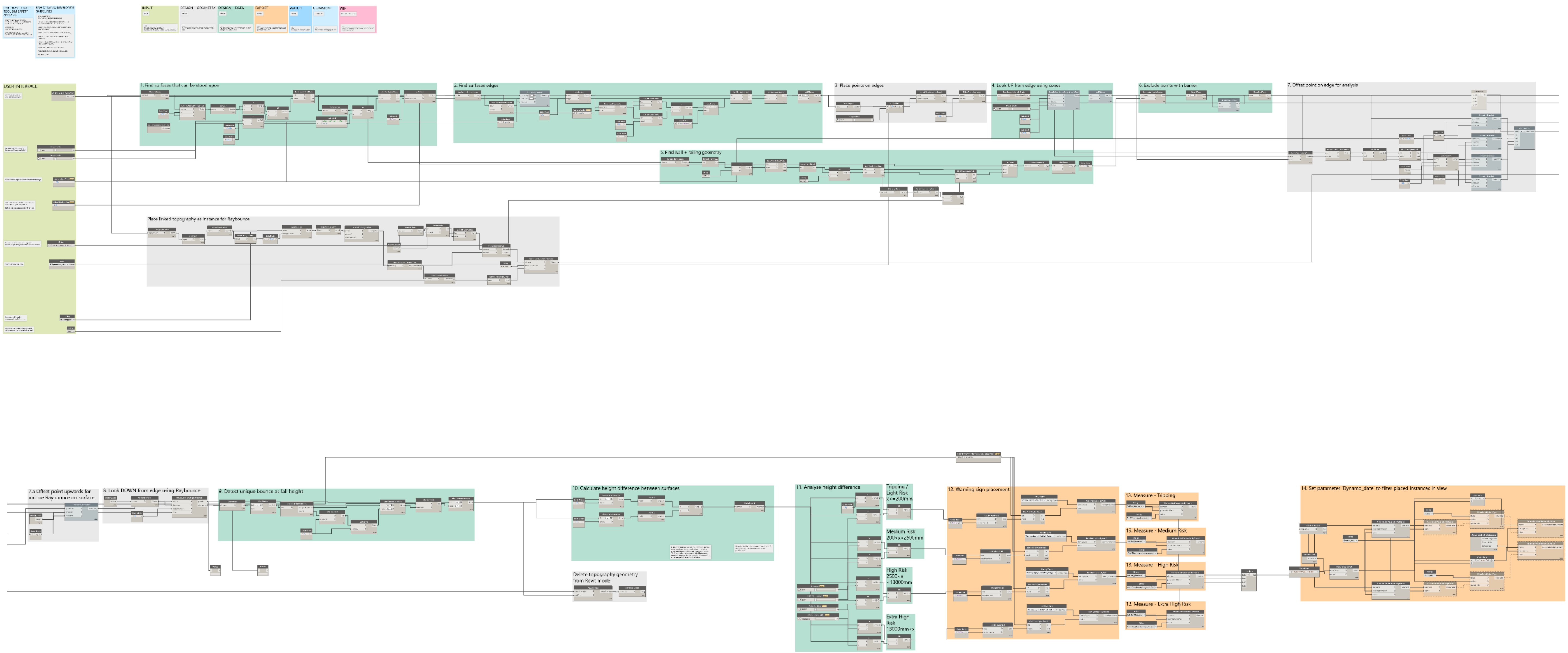
Figure 11 Royal BAM Group Dynamo Hackathon safety analysis script visualisation 2 (Owner: Royal BAM Group, 2020)

Appendix E: FFH tool prototype context

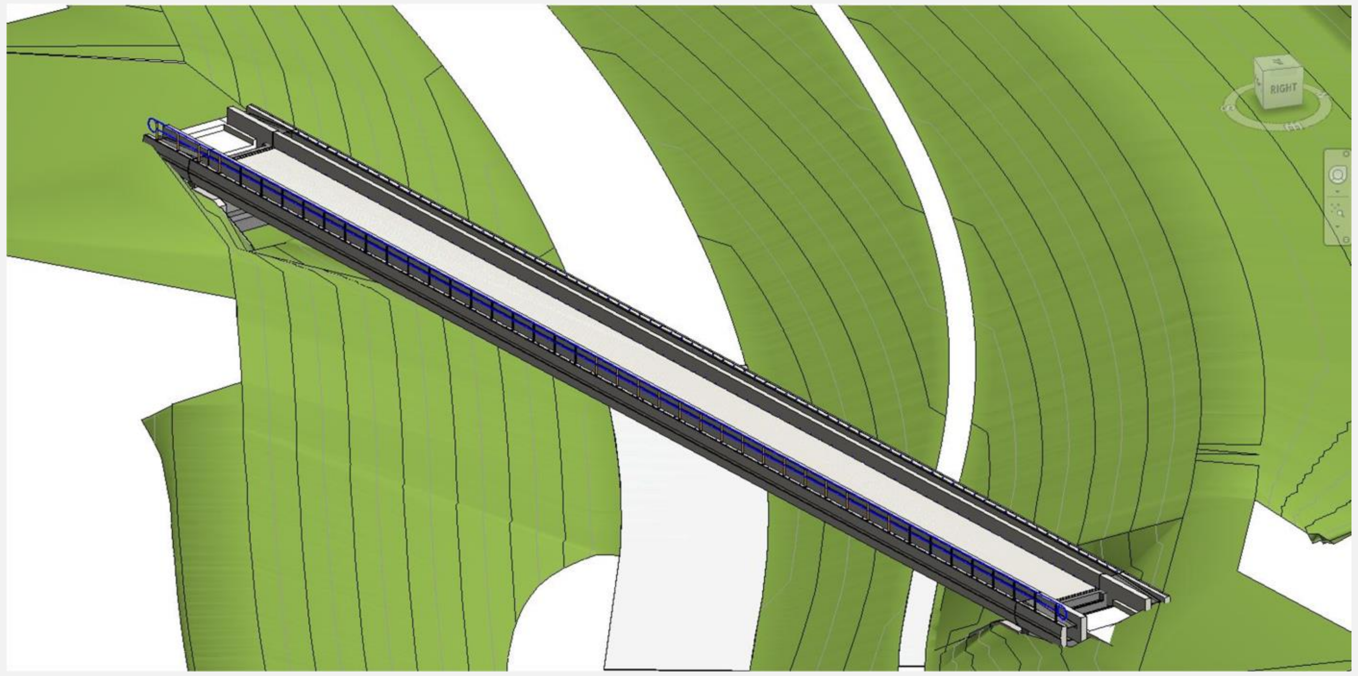
Recommended implementation of the FFH tool prototype within the safety management process.

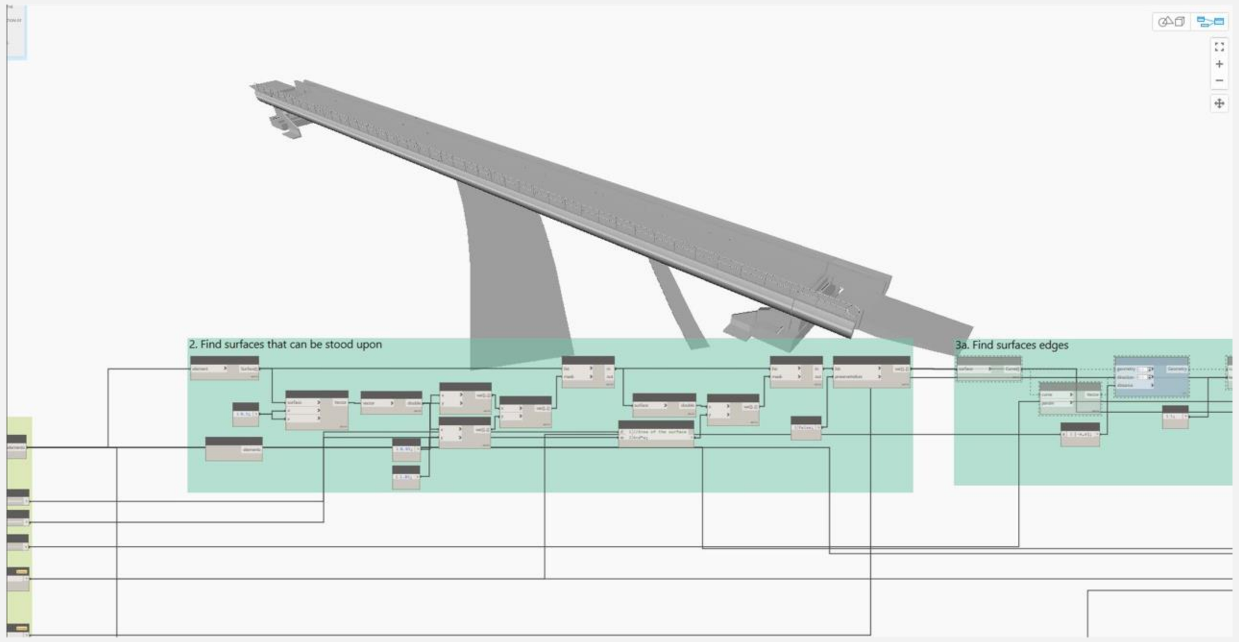


APPENDIX F: DYNAMO SCRIPT FOR FFH TOOL PROTOTYPE



APPENDIX G: DYNAMO SCRIPT FOR FFH TOOL PROTOTYPE, ILLUSTRATED OPERATIONS

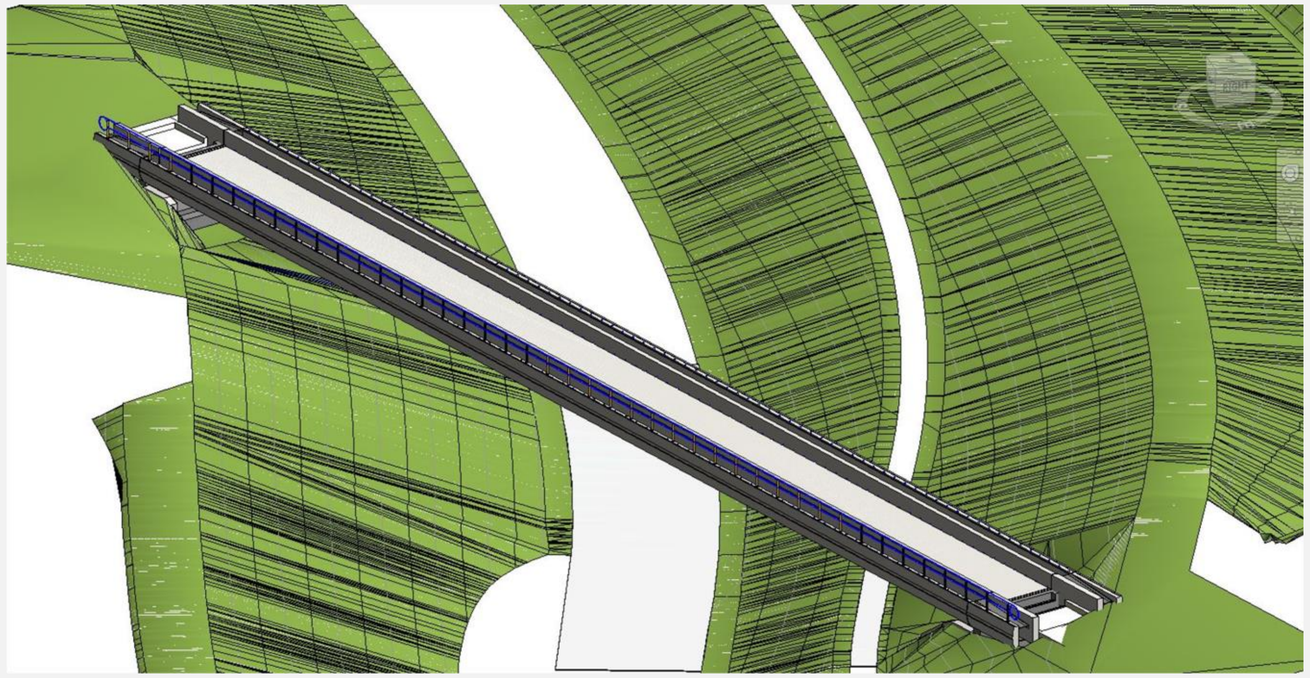


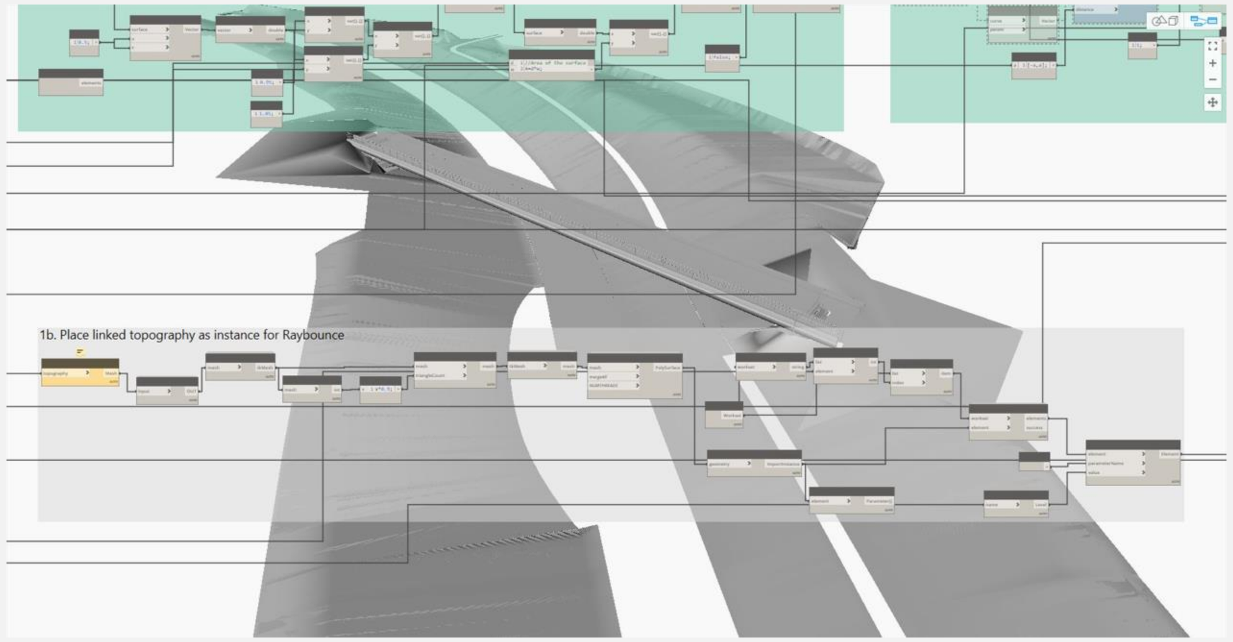


Step 1: Open workspace

Node groups: 1 & 2

Operations: Open workspace, load elements, find horizontal surfaces that van be stood upon

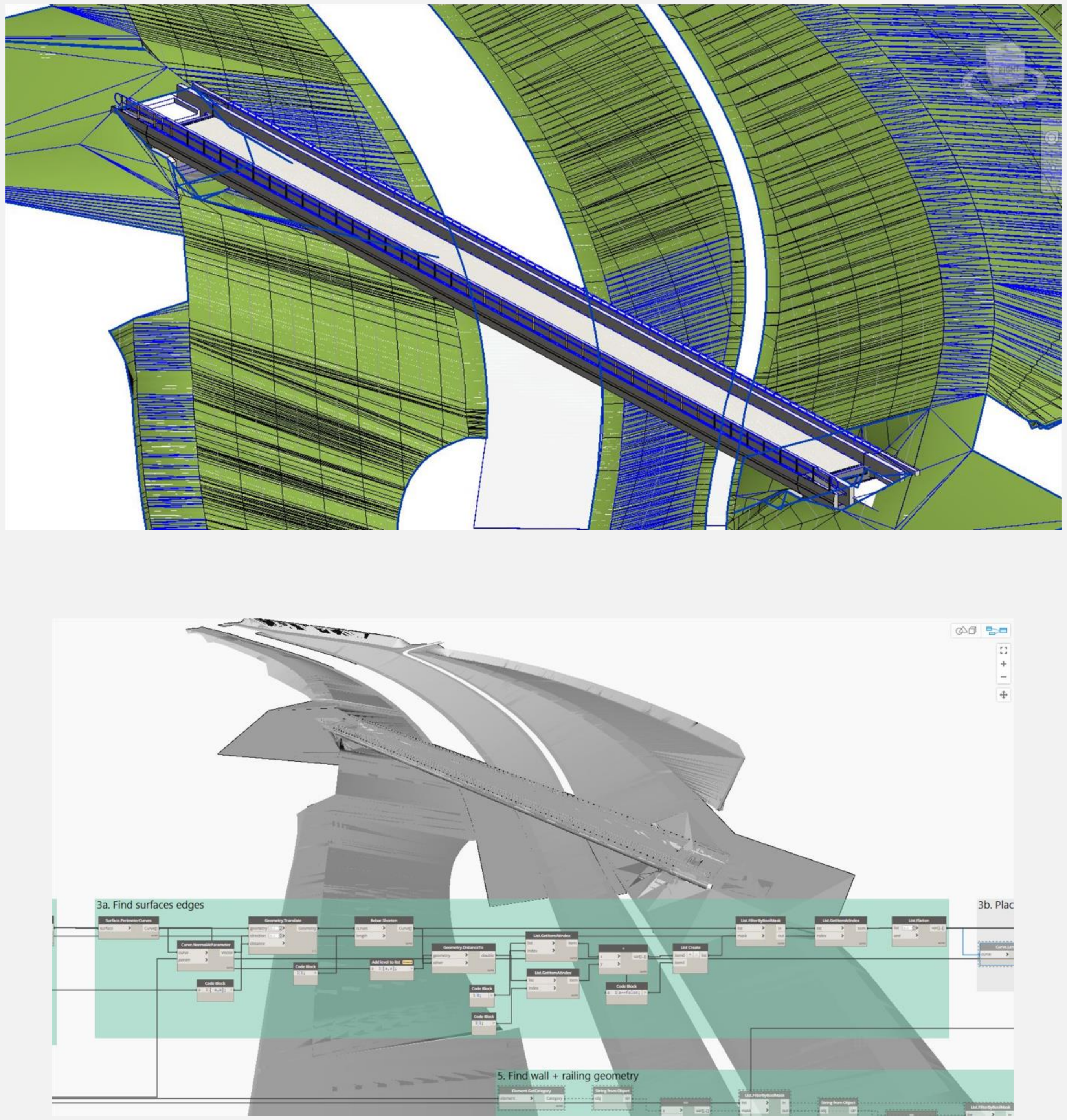




Step 2: Import linked topography

Node groups: 1

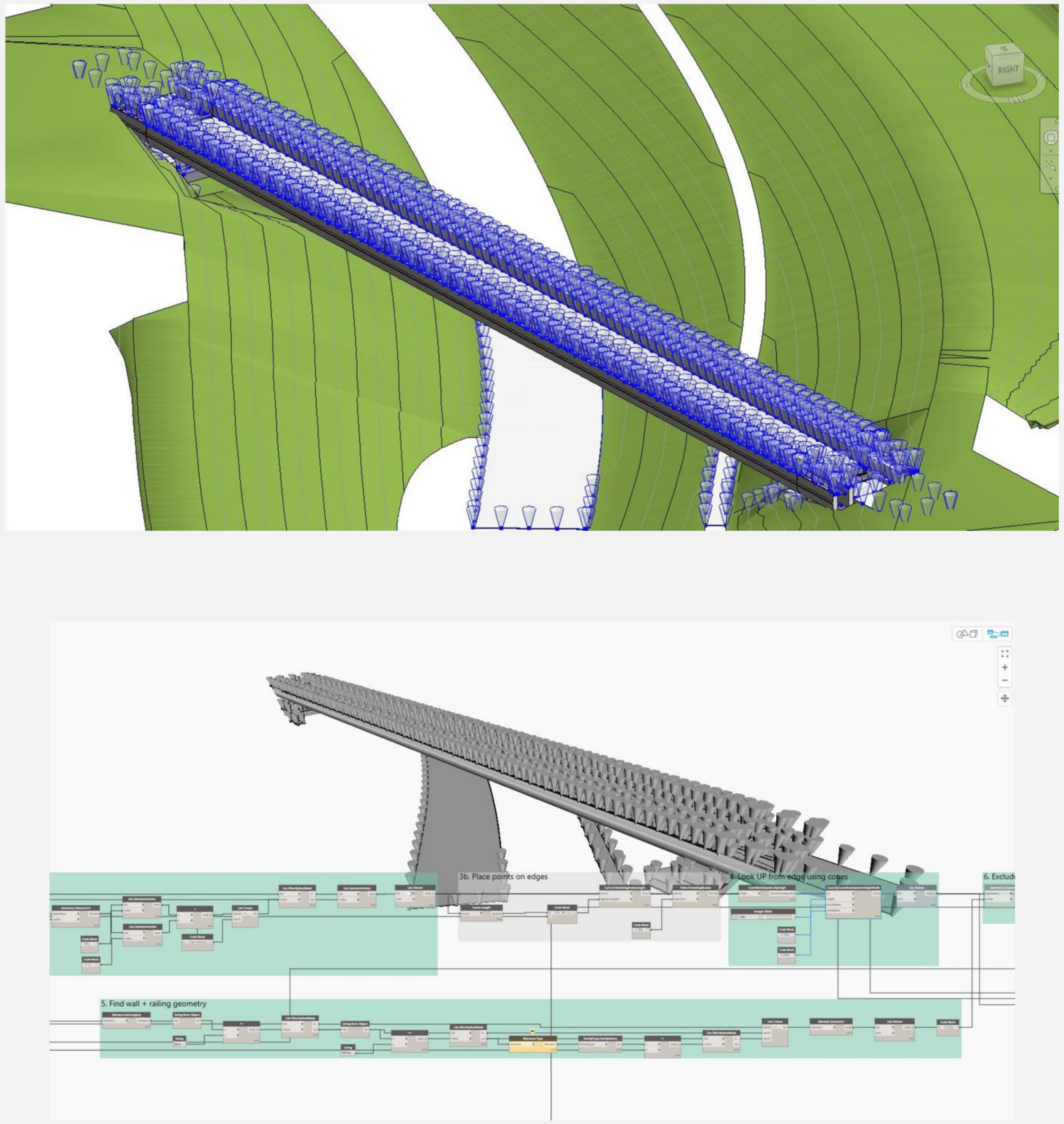
Operations: import linked file, convert topography to mesh, translate mesh to geometry, import geometry in Revit model, use geometry for the RayBounce, delete imported Revit geometry after the RayBounce operation



Step 3: Find surface edges

Node groups: 3

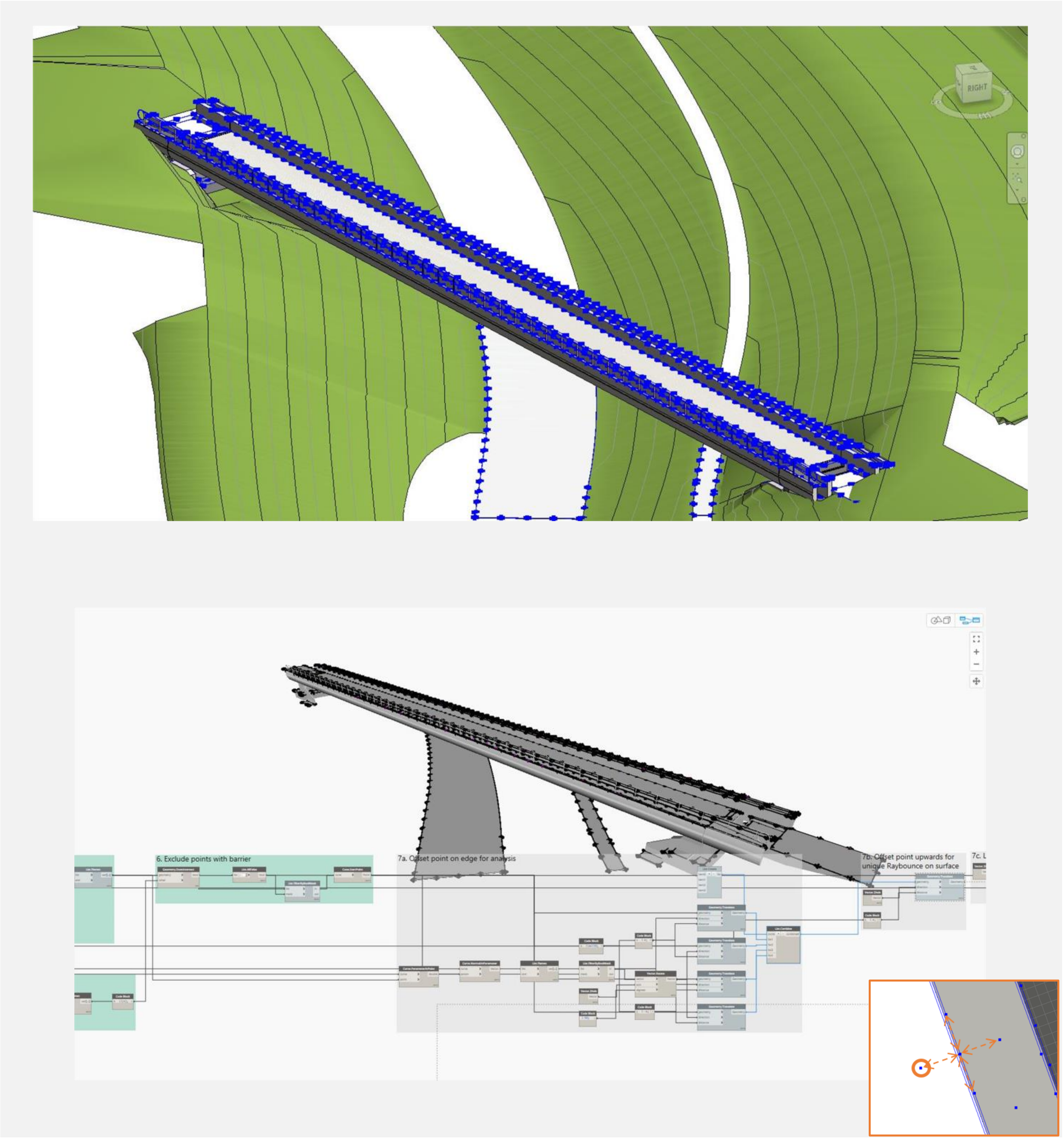
Operations: find edges of the surfaces, determine edge direction, translate by -10 and 10 mm, shorten line, use translated & shortened line that lies <u>on</u> the surface

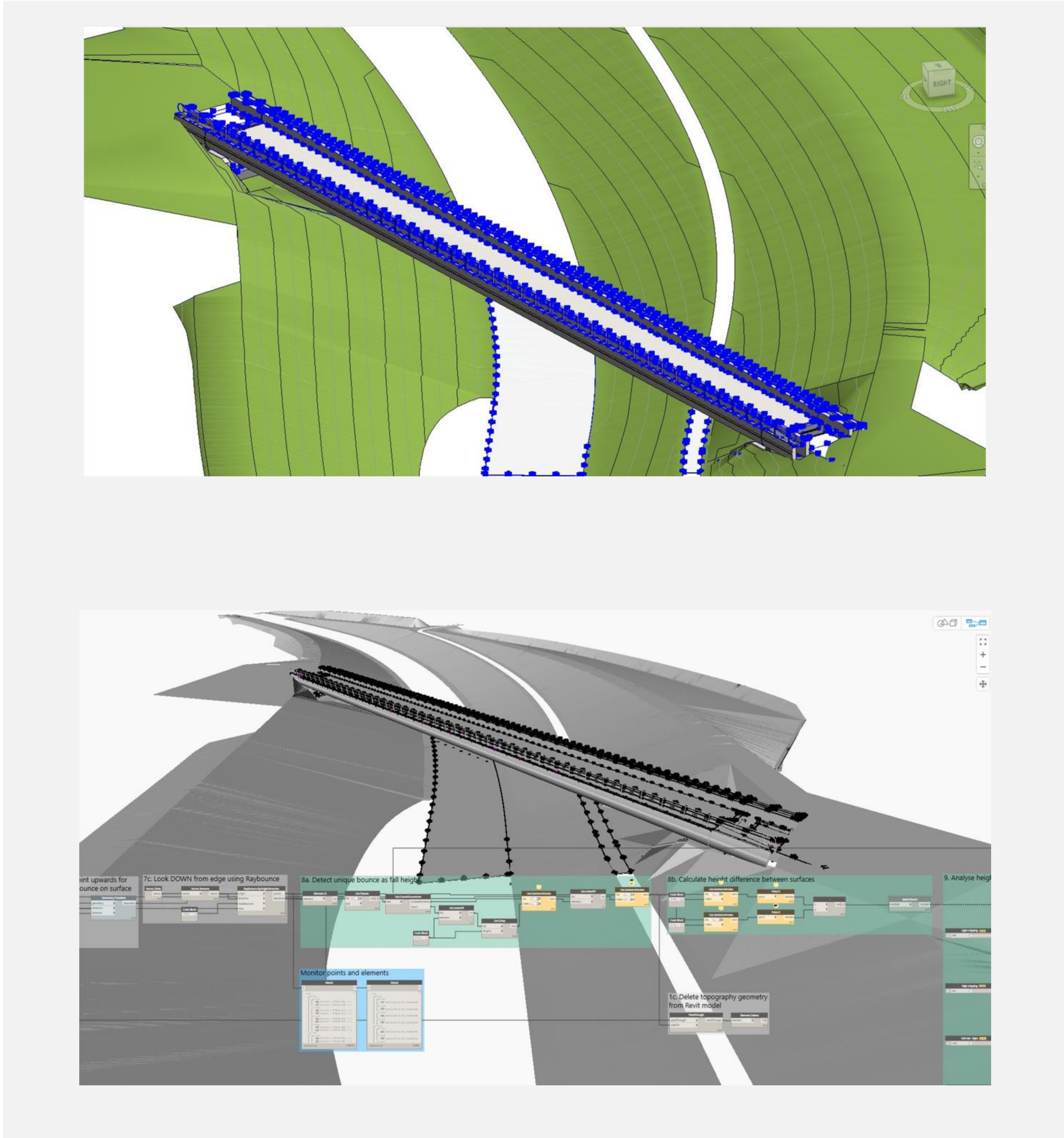


Step 4: Analyse edges

Node groups: 4 & 5

Operations: Place points on edges, look up using inverted cones, determine if barrier is present, use the points where no barrier is present for next operations





Step 5: Determine height – prepare points

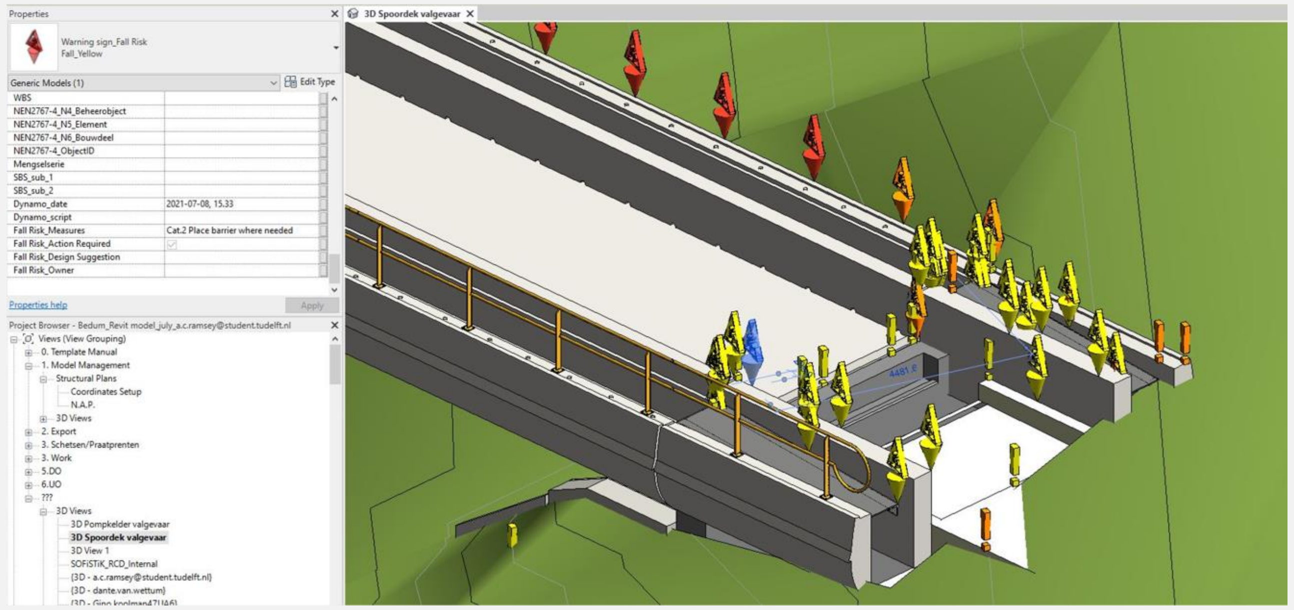
Node groups: 6 & 7

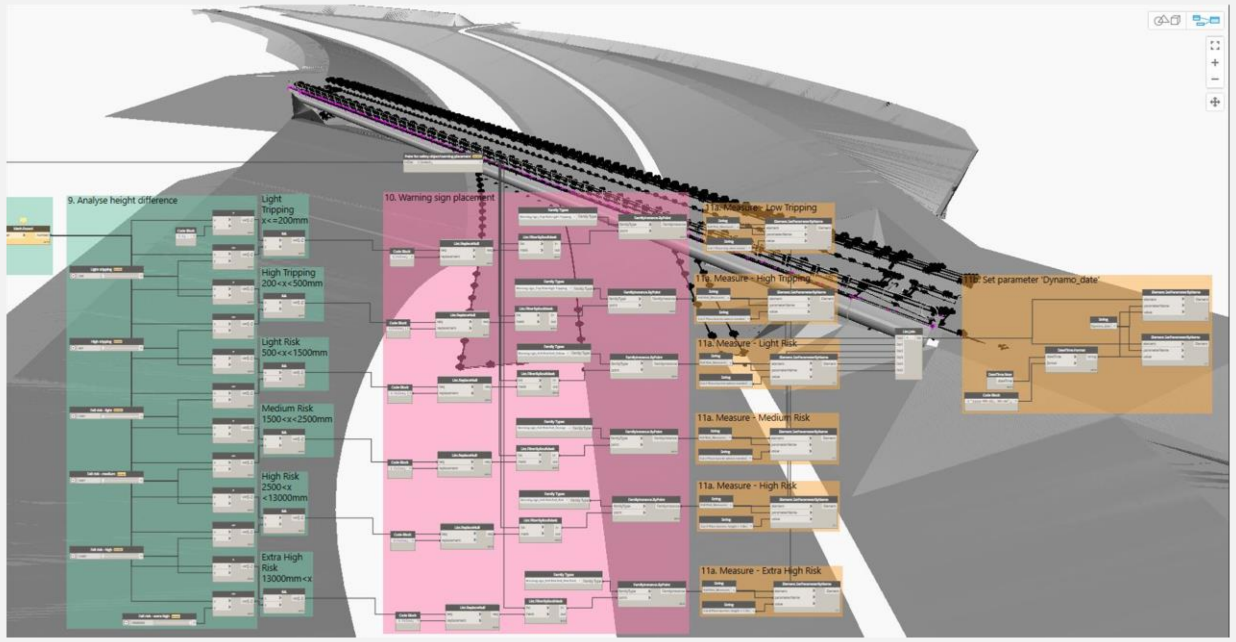
Operations: use the points where FFH risk occurs, offset points in 4 directions, one of the 4 points returns the fall height, if applicable

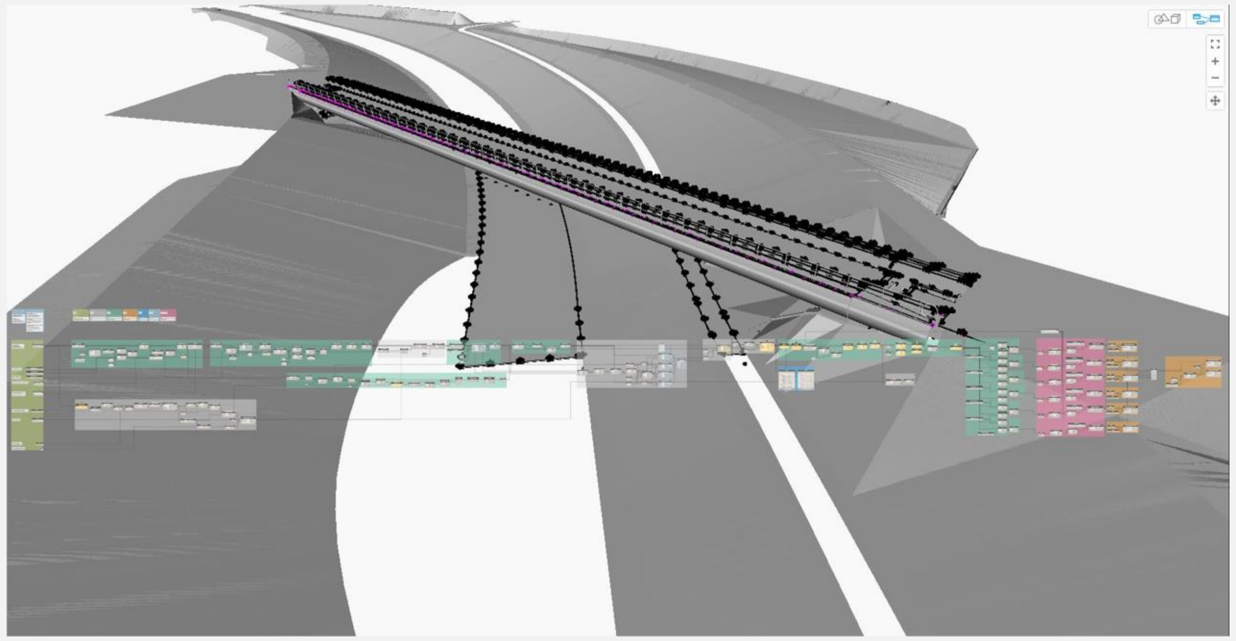
Step 6: Determine height – project downwards

Node groups: 7 & 8

Operations: Offset points upwards to increase correctness for unique bounce, project point on surface below (RayBounce), detect the origin point with a unique bounce







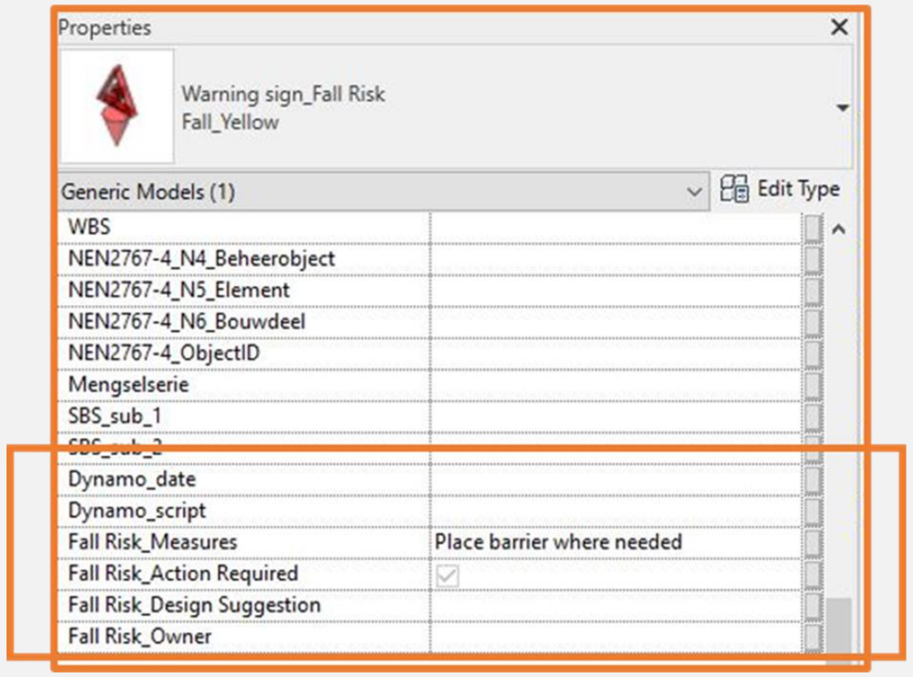
Step 7: Analyse height and place warning signs

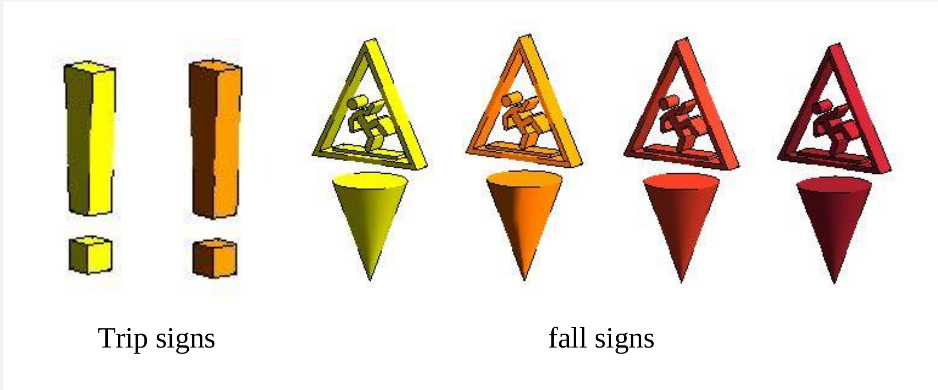
Node groups: 9, 10 & 11

Operations: calculate the height difference between lower and upper points, divide heights into categories, place a warning sign on each FFH risk point corresponding to the category

Final overview

Complete overview of placed warning signs and Dynamo script. Manually add parameters to individual warning signs.





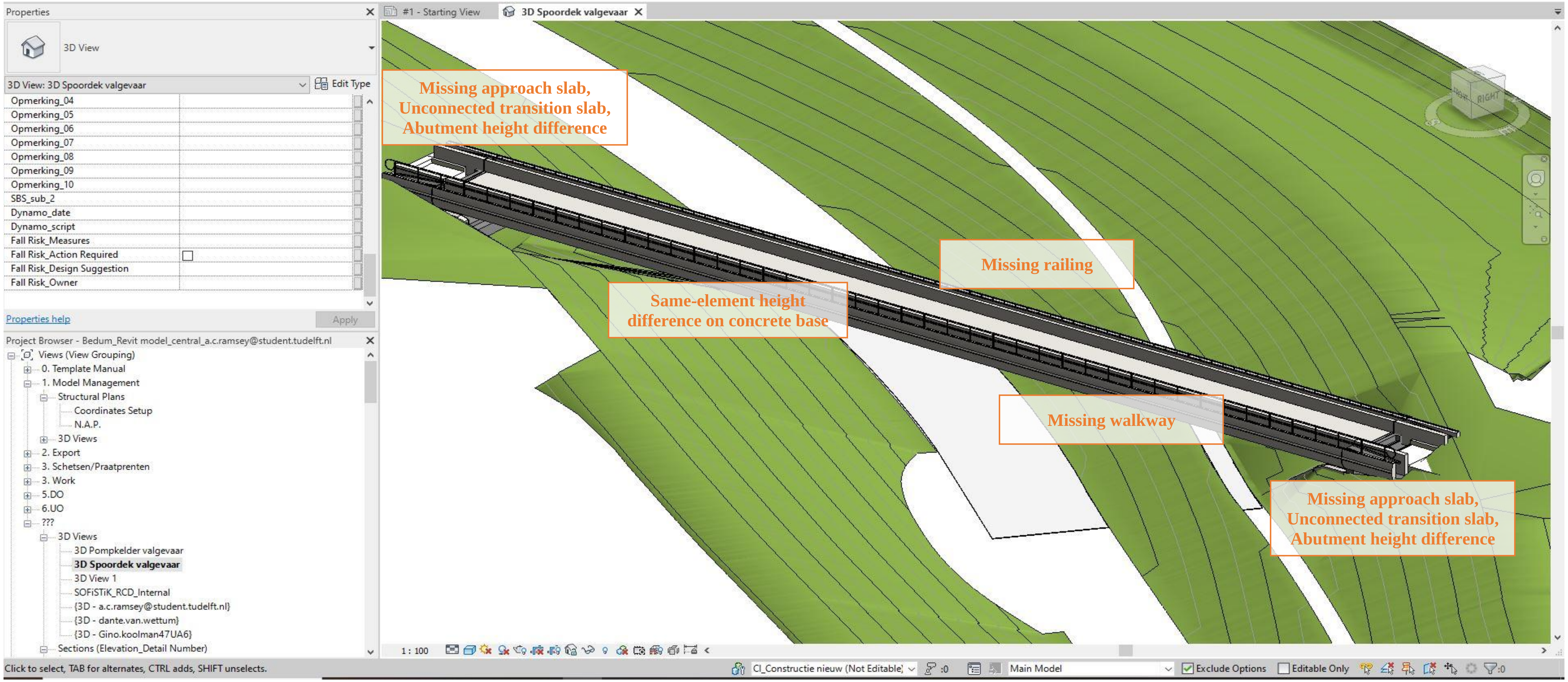
User interface

Project specific parameters, barrier names and topography data can be modified in the User Interface at the start of each project.

Details

Top picture: added parameters in individual family instance properties

Bottom picture: safety warning signs



The 3D coordination model is prepared for the validation sessions. Modifications have been made to ensure FFH risk situation in the model that can be identified. The situations are spread out over the model yet do not contain a high level of detail, such that it is feasible to recognise the situations for an expert who is not familiar with the project. In real-life situations the team members are familiar with the project and the design. In the validation sessions the design must be understood and FFH risk must be identified and analysed within the time span of 1,5 hours. The purposely placed risks are

1	missing railing along one side of the superstructure
2	missing approach slabs
3	unconnected transition slabs in the transition structure on both ends of the superstructure
4	height differences underneath the superstructure at the place of the abutment
5	a missing walkway exposing the cable trench
6	missing railway track exposing the raised edge within the concrete base

This prepared model includes at least 6 major FFH risks, that each contains more detailed situations that may or may not be identified by the industry professionals. The goal is to recognise, identify and evaluate the main 6 hazardous situation with as much detail as possible. More detail is considered to be better for the analysis, provided that the detail is correct and well documented for further use.

Appendix I: Validation sessions objective results

Criteria based results:

- The score for amount of risks identified is based on the total amount of FFH risks relating the 6 major FFH risks stated in appendix H and other hazardous situations that were identified during the sessions. The score can be (9-10) excellent, (7-8) good, (5-6) adequate, (3-4) inadequate and (1-2) poor.
- The category of the risk scoring is based on the severity and the height, and is indicated with a scale and score of: (5) extra high risk, (4) high risk, (3) medium risk, (2) other hazardous situation, (1) tripping. Tripping has been given a lower score due to the fact that other hazardous situations are potentially more severe and require more attention than tripping risk. The scale for risk category is based on the 4 categories that were embedded in the Dynamo script at the time of the validation sessions (tripping (0-0.2m), medium risk(0.2-2.5m), high risk (2.5-13 m)and extra high risk (13m and up)). After the sessions and feedback these categories have been modified to the 6 categories stated in paragraph 6.1.
- The score for correctness of the risks is based on the explicitness and traceability of the described risk. The correctness is indicated with on a scale and score of: (5) correct, (4) clear, (3) neutral, (2) unclear or (1) incorrect.
- The speed is scored based on the relative time that it took the team to identify the risks and complete FFH RI&E of the validation session. The maximum time available for the session was 90 minutes. The score is calculated with the formula: 10 – (time in minutes / 90 * 10)
- The score for the subjective results are based on a score of 1-10 given by the industry professionals.

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	1-10	20%	Score * %
Amount of risk, category	Amount	1-10	10%	Score * %
Correctness of risk	Amount	1-10	15%	Score * %
Speed of assessment	Minutes	1-10	20%	Score * %
User experience	1-10	1-10	10%	Score * %
Increased safety knowledge	1-10	1-10	5%	Score * %
Tool potential rating	1-10	1-10	20%	Score * %
Total rating				**SUM**

Session 1 – without use of the tool

Participant roles: HSE coordinator, project manager 2x, project controller, BIM specialist.

Objective: identify & evaluate *fall form height (FFH)* risks according to the current method in the Bedum model, prepared for the session by excluding barriers and elements (Appendix H). The current method differs in practice for each project or project team, the assumed method is with the use of a 3D model and Excel sheet. The model is analysed by navigating through the 3D view, then the risks and hazardous situations that are identified are documented in an Excel sheet.

The duration of the FFH risk analysis was 26 minutes.

Identified risks:
- Ontbrekende leuningen aan noordzijde van spoordek vormt risicogebied
- Overgangsconstructie maaiveld en landhoofd is een risicogebied
- Bij het landhoofd steunbermen plaatsen om te voorkomen dat materialen naar beneden rollen
- Kabelgoten en dek zijn naar schatting een halve meter diep en worden pas laat afgedicht
- Kabelgoten vormen risicogebied
- Stekken van reling vormen risicogebied

- Hoe komt men bij de ondersteuningen?
- Steunpunt onder het dek vormt geen valgevaar maar wel stootgevaar van het hoofd
- Ruimte onder het dek bij het landhoofd vormt een risicogebied
- Maaiveld naar looprooster sluit niet aan, zit aan beide kanten een hoogteverschil tussen
- Grond lijkt aan één zijde al aangevuld te zijn, dit is afhankelijk van het grondmodel en kan risico vormen
- Op de looprand is een schoprand (eventueel met hek) nodig om materialen niet naar beneden te schoppen
- Voldoet reling in de eindsituatie wel aan de norm m.b.t. schoprand?
- Als er geen stootplaten aanwezig zijn dan is er een groot hoogteverschil bij het landhoofd
- Overgang tussen spoordek en kabelgoot is groot, in de uitvoering wordt hier geen hek neergezet. Wel eens bordjes met symbolen of mogelijk pionnen. Er zal om de 25 meter een plakkaat moeten komen dat aangeeft dat je niet op het randje mag staan, er zal instructie vooraf gegeven moeten worden en toezicht zal dit moeten handhaven

Other:
- Borden en pionnen worden van tevoren wel ingepland, de spullen zijn tijdig nodig op locatie dus er wordt bedacht waar en wanneer het nodig is
- Hoe zit het met het wegdek? Als deze ook als werk weg gebruikt wordt da zijn er borden nodig zodat het spoordek niet geraakt wordt
- Valgevaar van materiaal naar beneden (bijvoorbeeld steentjes van het spoordek naar de werkruimte eronder) worden niet in de FFH tool meegenomen

After the RI&E of FFH risk in the prepared model, the FFH tool is demonstrated and the industry experts experienced the operations and results of the tool. The demonstration is used to gain additional feedback on the FFH tool to determine the subjective results and important modifications for the Dynamo script for future implementation.

Model feedback:
- Het model is moeilijk te lezen, liefste ziet men meer typeringen van elementen
- Er is inzicht in de bouwfaseringen nodig, de werkvolgorde is onduidelijk en dat maakt de RI&E onoverzichtelijk
- De stap tussen het plaatsen van de landhoofden en voordat het spoordek wordt ingeschoven is een risicovolle stap, deze tijdelijke situatie is niet inzichtelijk maar vormt wel veel risico voor valgevaar
- De toegangsroute voor personeel is niet zichtbaar, dit zorgt ook voor onoverzichtelijkheid
- Grote meerwaarde zal ook te vinden zijn in het uitvoeren van de FFH risk analysis in verschillende uitvoeringsfases en vergelijken hoe de bouwplaats veiligheid met het verloop van de uitvoering veranderd
- Sommige risico's worden door de FFH tool niet geïdentificeerd, een grote valkuil is het lui worden en risico's over het hoofd zien omdat er te veel op de tool vertrouwd wordt. Het is essentieel om zelf na te blijven denken
- De toegevoegde waarde van het model is dat het een sterke dubbelcheck is van de FFH RI&E, dus wel zelf blijven kijken en daarna te tool gebruiken om te controleren of er niets vergeten is
- Belangrijk om het wel als controle toe te voegen aan het proces en als hulpmiddel te gebruiken bij de discussie want het heeft een grote meerwaarde om de automatisch herkende risico's te zien en bespreken, en door bijv. voorafgaand aan de discussie naar alle teamleden te sturen ter voorbereiding
- De opstaande rand tussen de kabelgoot en spoor wordt niet herkent (doordat het onderdelen zijn van hetzelfde element met hetzelfde *ElemendId*)
- De categorie van 0,2m tot 2,5m is te groot en het visueel herkennen van verschillende gevaren categorieën is daarmee lastig. Het toevoegen van categorieën van bijv 0,5m of 1m zal bijdragen aan snelle visuele herkenning
- De grotere hoogteverschillen zijn mogelijk ook zonder FFH tool te herkennen, maar vooral de kleinere hoogtes zijn belangrijk om inzichtelijk en visueel in het model te krijgen voor betere discussie en RI&E
- Passende maatregelen is per situatie afhankelijk, dit specifiek kunnen aangeven per individueel risico heeft een meerwaarde

Risk	Amount	Category	Correctness
Missing railing along superstructure northside	1	High risk	correct
Transition structure and missing approach slab between ground level and superstructure is a hazardous area	2	Medium risk	neutral
Overpass abutment needs barriers to prevent material from rolling down	2	Other	correct
Height differences between cable trench, railway deck and edges is large and form hazardous situations	6	Medium risk	clear
Preinstalled base plates for missing railing is exposed and forms hazardous situation	1	Tripping	clear
Abutment underneath overpass forms confined space	2	Other	clear
Steps and space of abutment underneath overpass form hazardous situation	2	Other	unclear
Ground level to walkway transition does not connect	4	Medium risk	clear
Ground level surface groundworks can pose hazardous situations	2	Other	incorrect
Missing toe board on the superstructure edges	2	Other	correct

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	8	20%	1.6
Amount of risk, category	Amount	5	10%	0.5
Correctness of risk	Amount	7	15%	1.125
Speed of assessment	Minutes	7	20%	1.4
User experience	1-10	7	10%	0.7
Increased safety knowledge	1-10	7	5%	0.35
Tool potential rating	1-10	7	20%	1.5
Total rating				**7.2**

The amount of risk total has been scored an 8 out of 10. All 6 major risks have been identified to an extent and the identified risks cover a range of subjects throughout the entire project.

The amount of risk per category has been scored a 5 out of 10. The severity of the identified risks are important, as a singular high risk outweighs several tripping risks. Since 10 risks were identified and a scale of 1-5 applies to this category, a total of 50 points can be scored. The category score was 24 out of 50, which translates to 5 out of 10. A similar method applies to the score for correctness of the risk. Where the score was 37 out of 50, translating to 7.5 out of 10.

The score for speed of assessment is calculated with the following formula: 10 – (time in minutes / 90 * 10). The time in minutes is 26, so the final score is 7 out of 10.

Session 2 – with use of the tool

Participant roles: project controller, BIM specialist and project planner.

Objective: identify & evaluate *fall form height (FFH)* risks with the results of the FFH tool Dynamo script in the Bedum model, prepared for the session by excluding barriers and elements (Appendix H). The tool had been run before, showing the visual safety warning signs in the model and forming the basis of the discussion regarding project FFH risk. The model is analysed by navigating through the 3D view, then the risks and hazardous situations are identified, evaluated and documented in the 3D model.

The duration of the FFH risk analysis was 18 minutes, however, the total discussion time was 32 minutes due to the subjective feedback on and distraction relating the FFH tool. Since the FFH was demonstrated for the first time, the visual warning signs not only prompted FFH safety discussion, but also FFH tool operations, results and appearance. The precise time discussing the FFH risk analysis has been taken as the *speed of assessment* time in minutes.

Identified risks:

- Ontbrekende leuningen aan noordzijde van spoordek vormt risicogebied
- Kabelgoten vormen risicogebied
- Kabelgoten en dek zijn naar schatting een halve meter diep en worden pas laat afgedicht
- Overgang tussen spoordek en kabelgoot is groot, in de uitvoering wordt hier geen hek neergezet. Wel eens bordjes met symbolen of mogelijk pionnen. Er zal om de 25 meter een plakkaat moeten komen dat aangeeft dat je niet op het randje mag staan, er zal instructie vooraf gegeven moeten worden en toezicht zal dit moeten handhaven
- Stekken van reling vormen risicogebied
- Overgangsconstructie maaiveld en landhoofd is een risicogebied
- Maaiveld naar looprooster sluit niet aan, de reling zal (tijdelijk) doorgetrokken moeten worden
- Bij de overgangsconstructie is een getrapte constructie die zorgt voor struikel of valgevaar
- Aanbrengen en werken op randelementen vormen valgevaar risico's
- Op de looprand is een schoprand (eventueel met hek) nodig om materialen niet naar beneden te schoppen

Other:

- Schuifconstructie en andere hulpconstructies ontbreken, deze kunnen tijdens de uitvoering ook gevaarlijke situaties veroorzaken
- Valgevaar van materiaal naar beneden (bijvoorbeeld steentjes van het spoordek naar de werkruimte eronder) worden niet in de FFH tool meegenomen

Model feedback:

- Loopvlakken en looproutes zijn niet goed zichtbaar, waardoor niet duidelijk is waar iemand kan staan/lopen en waar er zich dus valgevaar kan voordoen
- Hulpconstructies en tijdelijke situaties zijn niet opgenomen in het model, die kunnen ook onveilige situaties veroorzaken en het geeft grote meerwaarde om de tijdelijke situaties inclusief hulpconstructies in het proces mee te nemen
- Er staan veel visuele tekens in het model, waardoor er veel acties nodig zijn om een goed overzicht te krijgen. Nu is er veel werk nodig om alle parameters in te vullen of tekens te verwijderen, omdat er meerdere tekens per risico geplaatst zijn. Een vlekkenkaart kan mogelijk een beter overzicht creëren.
- De precieze hoogte is niet goed zichtbaar, het toevoegen van categorieën, vooral tussen de 0.2 en 2.5 meter, zal een beter beeld kunnen geven van de relatieve hoogtes.
- Herkennen van getrapte constructies binnen eenzelfde element
- Het 3D model dat gebruikt wordt voor de analyse moet altijd eens sluitend en gedetailleerd model zijn. Als het geautomatiseerd wordt dan kan je het zo inlezen en is er een goed overzicht geïntegreerd in het model.
- De overgangen naar volgende uitvoeringsfases kan op bespaard worden door de veiligheidsmaatregelen tijdig visueel in het model te hebben, zodat deze niet meerdere keren geanalyseerd hoeven te worden tijdens de uitvoering zelf.

- In concept is de FFH tool een briljant idee, maar er moet een hoger detailniveau komen om dit goed uit te kunnen voeren. Doordat tijdelijke situaties ontbreken en de vele pijltjes afleiden, kan het gebruik van de tool in eerste instantie voor veel afleiding zorgen.
- Export naar Excel is niet zeer gewenst, met wolken en punten details in het 3D beeld kunnen toevoegen is van grotere meerwaarde dan de data exporteren naar Excel.
- De toegevoegde waarde wordt gezien als dubbelcheck en het controleren van de RI&E resultaten door middel van de FFH risk analysis. Zo kan tijdens een project steeds meer diepgang worden toegevoegd in een continue rond proces.
- Toevoegen van de analyse met gebruik van de tool tijdens de ontwerpfase, dan wordt men gedwongen om het gesprek te voeren en dat levert winst op.

Risk	Amount	Category	Correctness
Missing railing along superstructure northside	1	High risk	correct
Transition structure between ground level and superstructure is a hazardous area	2	Medium risk	neutral
Height differences between cable trench, railway deck and edges is large and form hazardous situations	6	Medium risk	clear
Preinstalled base plates for missing railing is exposed and forms hazardous situation	1	Tripping	clear
Stepped construction causes tripping or fall risk at the transition structures	2	Medium risk	neutral
Ground level to walkway transition does not connect	4	Medium risk	clear
Constructing and working on the edge elements forms a hazardous situation	4	High risk	clear
Missing toe board on the superstructure edges	2	Other	correct

Criteria	Result	Score	% of importance	Score total
Amount of risk, total	Amount	6	20%	1.2
Amount of risk, category	Amount	6	10%	0.6
Correctness of risk	Amount	8	15%	1.2
Speed of assessment	Minutes	8	20%	1.6
User experience	1-10	7	10%	0.7
Increased safety knowledge	1-10	6	5%	0.3
Tool potential rating	1-10	8.5	20%	1.7
Total rating				**7.3**

The amount of risk total has been scored an 6 out of 10. Only 4 out of 6 major risks stated in appendix H have been identified. No risks regarding the missing approach slabs or the abutment are mentioned, but several other risks covering a range of subjects throughout the entire project are identified, making this an adequate score.

The amount of risk per category has been scored a 6 out of 10. The severity of the identified risks are important, as a singular high risk outweighs several tripping risks. Since 8 risks were identified and a scale of 1-5 applies to this category, a total of 40 points can be scored. The category score was 23 out of 50, which translates to 6 out of 10. A similar method applies to the score for correctness of the risk. Where the score was 32 out of 40, translating to 8 out of 10.

The score for speed of assessment is calculated with the following formula: 10 – (time in minutes / 90 * 10). The time in minutes is 18, so the final score is 8 out of 10.

Revit schedule export:

Dynamo_date	Fall Risk_Action Required	Fall Risk_Design Suggestion	Fall Risk_Measures	Fall Risk_Owner	Opmerking_09	Opmerking_10
2021-04-29, 12.56	Yes	naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk

2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56		naar bouwfasering kijken, kan de reling al geplaatst worden	Cat.3 Place barrier, height = 1,0m		langs spoordek noordzijde	moet afzetting in fasering of tijdelijk
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
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2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed		looprand	struikelgevaar op element zelf, looprand naar spoordek
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
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2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56	Yes		Cat.2 Place barrier where needed		randelementen, zie notities	
2021-04-29, 12.56			Cat.2 Place barrier where needed			
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2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56	Yes		Cat.2 Place barrier where needed		getrapte constr. valgevaar	
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56		niets nodig	Cat.2 Place barrier where needed			
2021-04-29, 12.56	Yes	leuning van rand doortrekken tot aan het einde	Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.2 Place barrier where needed			
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2021-04-29, 12.56			Cat.2 Place barrier where needed			
2021-04-29, 12.56			Cat.1 Place trip alert sticker			
2021-04-29, 12.56			Cat.1 Place trip alert sticker			
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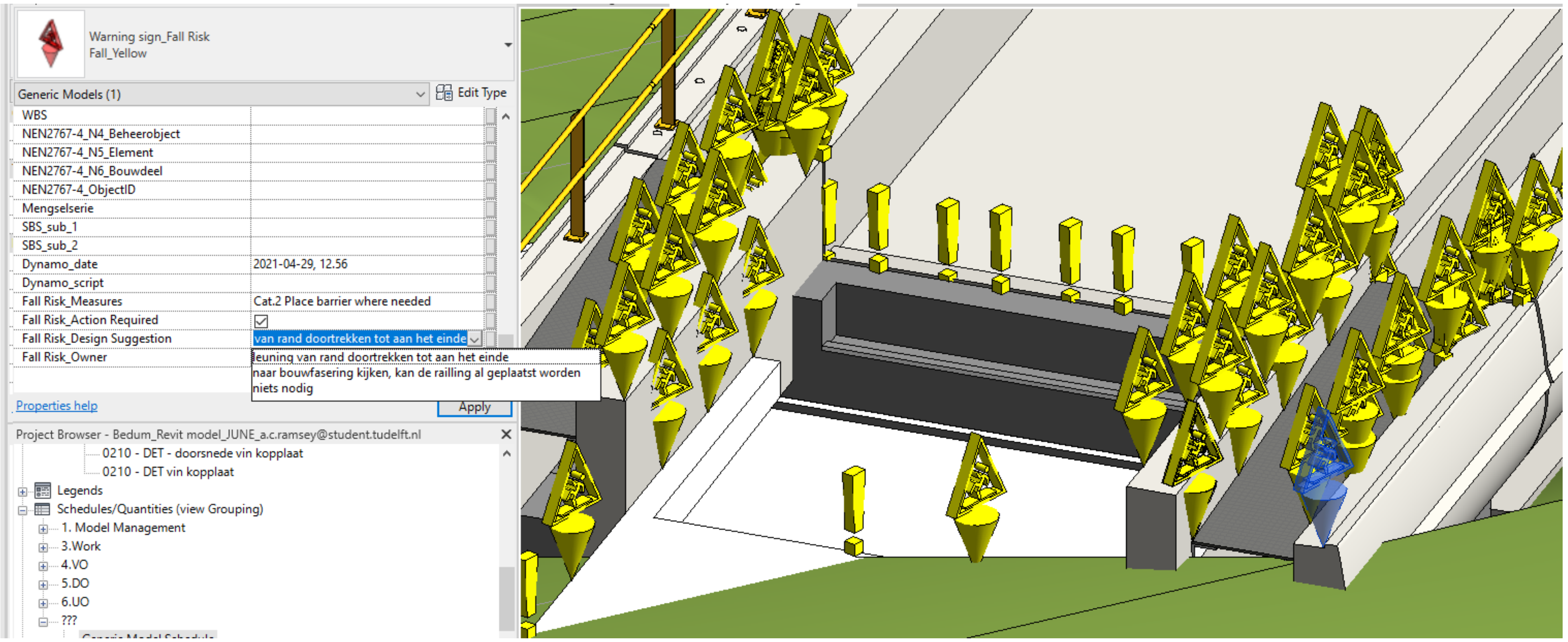

Figure 12 Validation result example: design suggestion

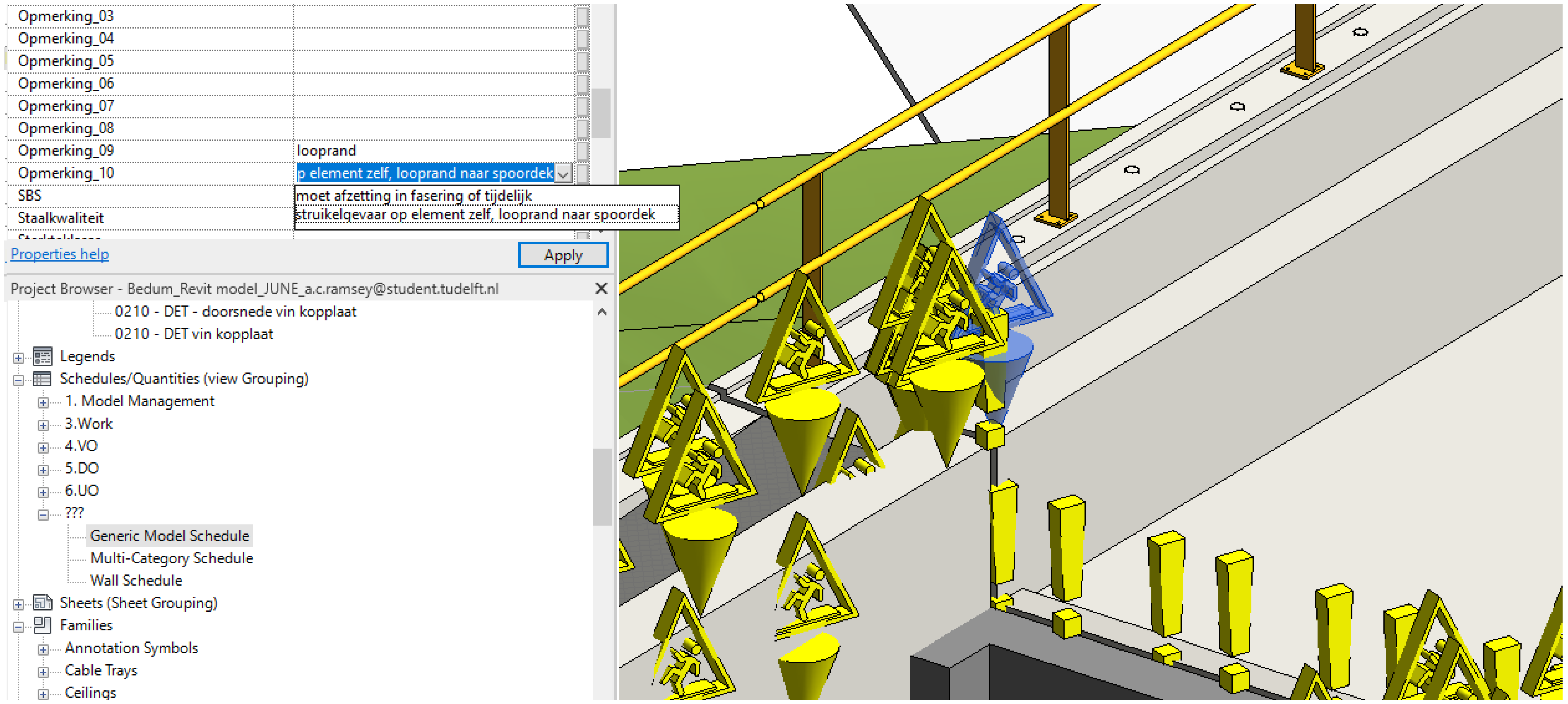

Figure 13 Validation result example: safety note

APPENDIX J: VALIDATION SESSIONS SUBJECTIVE RESULTS

Results from the validation session evaluation, used as subjective results for the validation criteria.

Wat is uw functie?	Hoeveel ervaring heeft u in deze functie?	Hoeveel ervaring heeft u met veiligheidsmanagement van valgevaar?	Hoe zou u de Dynamo tool voor valgevaar herkenning beoordelen?		In welke mate draagt de tool bij aan volledigheid van een risico identificatie op valgevaar?	Wat vindt u positief aan de tool en het concept?	Wat heeft volgens u nog verdere ontwikkeling nodig?	Ziet u toekomst voor verdere ontwikkeling en integratie van een tool die automatisch valgevaar detecteert en visualiseert?	Heeft u nog overige opmerkingen?
KAM CO	8	veel	6		6	zit geen oordeel aan - is feitelijk.	Tool miste nog een plek waar valgevaar was Is erg abstract Geeft geen opties hoe je het valgevaar kan oplossen	6	Blijft mensenwerk en tool zou de medewerker lui kunnen maken waardoor ze juist minder goed na gaan denken
Projectleider	20	30	6		8	het eenvoudig kunnen vaststellen van hoogteverschillen bij (complexe) constructies en situaties	faseringen, zowel in constructie als in omgeving (grondaanvullingen), meenemen; reeds voorziene (tijdelijke) valbeveiliging meenemen in het model; verfijnen van de stapjes wat betreft hoogteverschillen (kleine hoogteverschillen vragen geen of andere maatregelen)	9	goed bezig!
Manager Projectbeheersing	45	Gemiddelde ervaring, veiligheid is onderdeel van het ons werk. Ben geen expert, maar wel instaat om de situatie in te schatten omdat je uitvoeringservaring hebt	8		7	Hoogte verschillen zijn lastig in te schatten vanuit een model. Het is een hulpmiddel om de punten te lokaliseren dit impact kunnen hebben. De tool blijft een middel naast de bestaande inschatting, want werkervaring is nodig om het plaatje compleet te krijgen.	Voorbeelden benoemen van maatregelen, hoeveelheden en kosten.	8	
Manager projecten	3	20	7		7	Je leert van een theoretische invalshoek naar valgevaar en ziet dus wellicht zaken die je in de in de praktijk over het hoofd ziet	Volledigheid van het model inclusief de bestaande omgeving	7	
BIM Specialist	11	Beperkt. Als 3D-modelleur kun je situaties vaak eerder herkennen dan een gemiddeld ander teamlid, omdat je het 3D-model de hele dag voor je neus hebt. Hierdoor kan ik zelf af en toe actief iets aandragen: "kijk hier eens naar, gaat dit goed?" Het is dan aan andere experts om er een uitspraak over te doen.	8		7	- Ik denk zeker dat het kan helpen bij het herkennen van valgevaar, in één oogopslag zie je het resultaat, met heldere symbolen/kleuren. Wat wel in de sessie naar voren kwam, is dat het gevaar bestaat dat je blind gaat vertrouwen op de tool, i.p.v. zelf ook op zoek gaat naar gevaarlijke situaties. - Aan de andere kant is het een nuttige bevestiging als de tool met dezelfde resultaten komt, en mogelijk met nog meer gevaarlijke situaties komt die over het hoofd zijn gezien.	- Plaats ook een 3D-poppetje in het 3D-model (mogelijk zelfs automatisch op plekken met valgevaar), voor beter gevoel van de schaal. - Over doorgaande lijn met valgevaar (bijv. ontbrekend hekwerk) een lijnobject plaatsen, i.p.v. tientallen uitroeptekens. Dit kan bijv. een symbolisch hekwerk zijn. - Tijdens de demonstratie kwam de smalle wand tussen ballastbed en kabelkoker er niet uit als valgevaar (terwijl men er wel op zou kunnen lopen). Mogelijk omdat dit een rand is binnen 1 object (complete dek = 1 object). Ik denk dat het script alleen kijkt naar objecten onderling, en niet binnen 1 object. - Betere gradaties in struikelgevaar, valgevaar, grote hoogtes etc. De middelste gradatie had nu een range van ca. 0.2m tot 10m, dat is wel heel ruim. Pak ook bijv 0.2->2.0m	7	Aandachtspunt voor de presentatie: voor de doelgroep van de sessie vond ik de powerpoint-presentatie iets te technisch, te veel inhoudelijk op Dynamo. Probeer dat wat algemener te houden, in heldere stappen: van een object pakken we een bovenvlak, daarvan pakken we de randen, vanaf de rand kijken we naar beneden op zoek naar een ander object, rapporteren de hoogte, etc...
Programmaleider Digital Construction	3	Niet bijzonder veel in de laatste jaren in huidige/voorgaande functies. Als werkvoorbereider ongeveer 5 jaar.	7		5	Het concept is vooruitstrevend en heeft potentie om verder ontwikkeld te worden. Het feit dat je met goed geschreven scripts ruimtelijke analyses kunt uitvoeren die betrekking hebben op specifieke gemodelleerde situaties, biedt uitzicht op meerdere (toekomstige) mogelijkheden/toepassingen. Het kan zeker ondersteuning bieden bij het analyseren van mogelijk gevaarlijke situaties op de bouwplaats, maar het zou bijvoorbeeld ook mogelijk moeten zijn om tijdens verschillende fasen van het ontwerp/voorbereiding aan de hand van verschillende modelversies de (mate van) veiligheidsrisico's met elkaar te vergelijken.	Een completer model tijdens de bouwfase voor alle betrokken projectdisciplines. Modellen zouden niet alleen definitieve constructies of definitieve situaties moeten bevatten, maar ook tijdelijke situaties, materiaalopslag, verkeers- en looproutes, materieel en tijdelijke hulpconstructies. Daar zou per bouwstap of bouwfase een analyse moeten worden gedaan (lees: het inzetten van 4D-modellen die tijdelijke situaties in beeld brengen) Ook is het interessant om te kijken welke mogelijkheden er zijn m.b.t. het gebruik van modelproperties (bijv. elementtypes zoals "wand", "opstort" etc.) zodat die informatie ook gebruikt kan worden in de scripts. Verder is het de moeite waard om te kijken of algoritmes voor machine learning kunnen worden ingezet voor herkenning van risicovolle situaties.	9	Leuk onderwerp! Veel succes met je afronding!
Modelleur	4	Identificeren van risico's is met het ontwerp in 3D eenvoudiger geworden. In mijn rol als modelleur komt dit dan ook elk project weer terug.	7		7	Het automatisch signaleren van (potentiële) risico's. Dit zorgt ervoor dat de gebruiker het risico in beeld heeft en hier kritisch naar dient te kijken.	- Risico's overmatig aanduiden. Gevaar is dat teveel risico's bij elkaar worden samengevoegd en zodoende risico's vergeten worden; - Tool dynamischer maken; Bijv. in Revit de phasing mee laten nemen of een ander pakket gaan gebruiken (synchro/Navisworks). Voordeel van Synchro en Navisworks is dat ook meerdere disciplines (wegen, civiel etc.) in de modellen zitten.	7	-
Clustermanager	3	12,5 jaar	7		6	De cijfers zijn nog niet hoog, maar het is een start van automatische herkenning van veiligheidsrisico's om de bouw te helpen. Het heeft het ook in zich risico's specifiek te maken en visueel te tonen. Daarmee worden risico inventarisatie van een veel hogere kwaliteit	- Automatische herkenning dient beter gemaakt te worden. Nu kloppen zaken nog niet. - Risico inventarisatie komt er nu als lijst uit, maar juist het visuele maakt het een meerwaarde. Acties die je vanuit dergelijke sessies afspreek kun je wel als lijsten exporteren. - Een project kent vele tijdelijke fasen waarin veiligheid beoordeeld dient te worden. Een dergelijke tool zal dus ook toegepast moeten worden tijdens al deze fasen om effectief te zijn. - Nadenken over zelflerend vermogen. Bijvoorbeeld zoals het algoritme van schade herkenning van de weg (Kitting Lee)	9	Geloof in het concept is er. Nu verder ontwikkelen.

Image: BAM Infra Digital Construction

TUDelft

bam