A BIM-based tool to support time risk management in construction projects

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Thesis to obtain the Master of Science degree in

Civil Engineering

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May 2017

Acknowledgements

I would like to thank all the people that helped me finishing my master thesis. I could not have done it all by myself. A special thank you is in place for my supervisor, Prof. António Costa, for his time and expertise. He was always available for clarifying my doubts, giving advices and guiding me through the thesis process. Without him I would have never been able to successfully finish this project.

Two other people greatly helped me with their technical knowledge in writing my thesis. First, Rúben Santos, who taught me the basics of Revit, it is possibilities and how to use it. And second, André Antunes, who explained me how to use the Dynamo software and helped me with writing my Dynamo code. They were always willing to assist me and both attributed greatly in reaching my thesis objectives.

On a personal level, I would like to express my appreciation to my friends and family for their moral support despite the distance between us. Special thanks go to Telma Pereira who is not only an amazing friend but also contributed greatly to my integration in a new university and a new life here in Lisbon.

Abstract

Risk management can have an enormous effect on the outcome of a construction project. By controlling risks, cost overruns can be limited, time can be saved and quality can be increased. Risks always existed in the construction industry but with the use of new construction methods and the increase of stakeholders, such as designers, contractors, engineers and managers whereby collaboration became more complicated, the risks increased. This thesis presents a tool which can help risk managers to control the time related risks of a construction project and will help improving the communication between different stakeholders.

Risk analysis information is often presented as a complicated numerical analysis, which is difficult to apply to practical work, a lot of time is lost trying to understand the different risks involved and their respective impacts. To tackle this problem, the proposed tool allows visualizing different time and cost risks during the design and construction process by presenting a map of colors based on the impact of the risks related to different elements of the BIM model. The different construction tasks can be analyzed in terms of their risk by applying a Failure Mode Effect Analysis in an interface where they will receive a risk color which categorizes them in terms of their importance. These colors are then transferred to a 3D BIM model and a 4D model where they can be can be easily analyzed, documented and discussed with all the relevant stakeholders in a clear and efficient way.

Keywords: Building Information Modelling, Failure Mode Effect Analysis, Construction management, BIM programming

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List of abbreviations

2D: Two dimensional (X-Y direction)

3D: Three dimensional (X-Y-Z direction)

4D: Four dimensional (X-Y-Z direction + time)

5D: Five dimensional (X-Y-Z direction + time + cost)

AEC: Architecture, Engineering and Construction

BIM: Building Information Modeling

D: Detection

FMEA: Failure Mode Effect Analysis

ID: Identification

ISO: International Organization for Standardization

O: Occurrence

OCCS: OmniClass Construction Classification System

REN: Risk Evaluation Number

RPN: Risk Priority Number

S: Severity

Described software

Dynamo: Dynamo Studio 0.9.1.4062 (Autodesk)

Excel: Microsoft Excel 2016 (Microsoft Office)

MS Project: Microsoft Project 2016 (Microsoft Office)

Navisworks: Navisworks manage 2017 (Autodesk)

Revit: Revit 2017 (Autodesk)

1. Introduction

1.1. Background

Traditionally, the collaboration between Architecture, Engineering, and Construction (AEC) industries has revolved around the exchange of 2D drawings and documents. Even though the separate design disciplines have been using 3D models and applications for visualization and design development, the communication have remained mostly less 2D-based, until recently. Building Information Modeling (BIM) plays an important role in this transformation from 2D designing to information modeling (Singh, Gu, & Wang, 2011). Dodge data & analytics (2015) studied the percentage of BIM users in the biggest economies worldwide for building and non-building projects. The number of users for commercial buildings varied from 50-70% whereas the use of BIM in infrastructure varied between 13% and 33%. The main advantages that arise with the use of BIM are:

- Better owners' engagement and understanding of the project;
- Better documentation and constructability;
- Better understanding of the design for contractors;
- Less unplanned changes during construction.

On the other hand, in the last four decades the research about risk management in the construction industry has grown considerably (Forbes et al, 2008). Risk has always been involved in the construction sector but during time the risks increased due to the involvement of many contracting parties such as owners, designers, contractors, among others (El-Sayegh, 2008). It is possible to analyze project risks from the perspective of the project owner on one hand, an important stakeholder in the decision maker of construction project, and from the contractors on the other hand (Bryde & Volm, 2009). Traditionally, contractors used high mark-ups to cover for risks but as their margins decreased this approach is no longer effective (Baloi & Price, 2003). Schieg (2006) states that when risk management is successfully applied it provides an information basis for the quantitative data. For this it is necessary that quality information is always available to enable better decision making based on this comprehensive information (Serpella et al., 2014).

Analyzing risks can be time consuming and therefore expensive, hence, it is important that the parties involved quickly understand the risk framework. Risk analysis methods often consist of brainstorming sessions to identify risks, threats and vulnerabilities. These sessions involve system users, developers and decision makers which often have different backgrounds and view the system from different perspectives. Furthermore, risk analysis information is often presented based on complicated numerical analysis, which reduce its usability in practical work (Hogganvik & Stølen 2006). In this thesis a BIM-based risk management tool will be proposed that can analyze the degrees of risks using objective quantifying methodologies for gathering risk information. The information is then presented by color in a 3D and 4D model, based on the degree of risks involved. This system can be utilized as a tool to effectively respond to various types of construction risk information.

1.2. Scope and objectives

The objective of this thesis is to provide a deeper insight in the use of BIM in construction management, focusing on risk management. According to ISO 31000 (2009) risk includes different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process). This thesis focuses on a specific, but important part of risk management, namely time and cost risks at the project level which have a negative impact.

This thesis studies the possibility of implementing a Failure Mode Effect Analysis (FMEA) process based on a BIM model by creating a tool that can be used by construction managers to have a better overview of the risks and their importance. The manager can than share this overview with the stakeholders with a less technical background. It can improve the communication between different stakeholders and help determining adequate risk measurements.

With a FMEA, risks can be analyzed and prioritized by level of importance where after the risks will be linked to the elements in the BIM model in which they are involved. Each risk level will be assigned with a risk color and BIM will visualize these risk colors in the 3D and 4D design. This results in two design models that provides the user an overview which can be easily analyzed, documented and discussed with all the relevant stakeholders involved.

1.3. Research methodology

The presented study aims to support risk managers by creating a tool that allows the visualization of time and cost related risks directly in the design. A literature review is conducted to fully understand risk principles in construction projects and the definition and possibilities of BIM. Also papers with similar approaches are studied to understand the challenges and identify an opportunity for a contribution.

After the literature study, a conceptual model of the proposed tool is designed to outline the context of its use, the used software and how the tool should operate. Based on this conceptual model, an interface is designed and developed where, using the FMEA technique, several risk statuses for each element of the BIM model are generated. The interface consists of an Excel spreadsheet where the user can link the construction schedule and perform the FMEA. The results of this analysis will be computed directly and different colors will be attributed automatically to the BIM model. To make the connection between the tasks in the FMEA and the BIM elements that eventually need to receive the risk color two option are studied, the OmniClass approach and an approach creating an extra parameter in the BIM model where a Task ID number can be inserted.

A Dynamo programming code is created to make the connection between the Excel file and the BIM model. Dynamo is a visual programming add-in for Revit that can automatically alter different aspect form a BIM model and is able to read data from Excel. In this thesis, it will be used to transfer information about the risk colors, which tasks lay on the critical path and additional information from the FMEA and will attach this to their corresponding elements in Revit. Figure 1 shows the methodology that is used in the thesis in the form of a diagram.

To create the 4D model, Navisworks is used to link the tasks of a construction schedule to the elements of a 3D BIM model. When each task is represented by a different risk color (attributed in Excel, based on the FMEA) then the elements in the 4D model will automatically receive this color. Navisworks allow the user to scroll throughout the timeline of the model and visualize the different risks at each stage of the project.

To test the prototype, a simulation is performed using a residential house where the outcome is presented in a 3D BIM model in Revit and a 4D model in Navisworks.

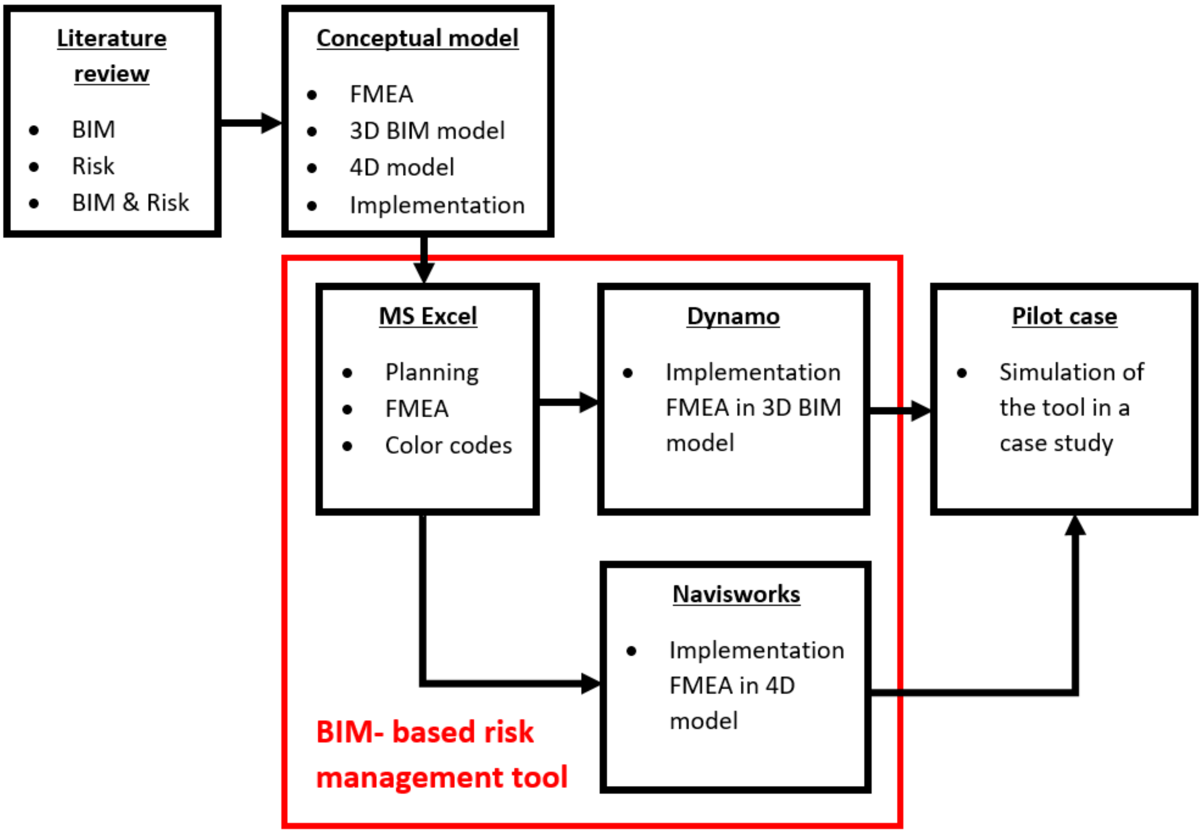


Figure 1 - Research Methodology

1.4. Structure of the thesis

The thesis is divided into seven chapters. The current chapter, chapter one, describes the background, the scope and objective, the methodology and the structure of the thesis.

In the second chapter a literature review is performed. It explores the definition, the users, the possibilities and advantages of BIM. Then risk management will be analyzed, first the definition of (project) risk will be established, then the goals of risk management, risk identification and risk analysis and evaluation. To conclude the risk management section, the concept, advantages and shortcomings of the FMEA are highlighted. The final part of the chapter aims to highlight the challenges described in the different literature and how a BIM/ Risk tool can help tackling some of these challenges.

The third chapter describes the development of the BIM-based risk management tool in a 3D and 4D environment. It presents the FMEA interface, the link between tasks and elements and how the connection is made between Excel and Revit using the Dynamo software. Then the development of the 4D model is discussed along with the guidelines for the use of the tool before the construction phase and during the construction phase.

In the fourth chapter the tool is tested in a pilot case. All the steps, as described in chapter three, are applied to see how the prototype performs and if the guidelines are described in a clear way. After a brief description of the model, it explains the different steps that are taken during the use of the tool. The last part of this chapter is dedicated to present the results and for a small discussion about the observations and limitations of the tool.

The conclusions of this thesis are described in chapter five. It involves the final considerations, the challenges faced in the process and possibilities for a further development of the tool.

In chapter six and seven all the references, such as journal articles, books and so forth are presented among with the annexes that are referred in this document.

2. Literature review

To collect the necessary background information and knowledge to support the development of the BIM-based risk management tool a literature review is performed. Firstly, the concept of building information modelling is explained along with the advantages, how it can be applied in construction management and its potential. Secondly, the risk management is addressed with its components, project risk, risk management and how to identify/ analyze different risks. In the end of the sector risk, the management tool FMEA is described. Thirdly, the role and influence that BIM can have on risk management are discussed.

2.1. Building Information Model (BIM)

2.1.1. Definition of BIM

There are many definitions about BIM which often have some contradictions between them. So, a complete and correct definition is important to prevent confusion during the project whereby various parties are working together in BIM.

With BIM technology, virtual models of a structure are constructed digitally. They support design through its entire lifetime, allowing better analysis and control than manual processes. This provides the basis for new design and construction capabilities and changes in the roles and relationships among a project team. When adopted well, BIM facilitates a more integrated design and construction process that results in better quality structures at lower cost and reduced project duration (Eastman et al., 2011).

To better explain what BIM means it is pertinent to refer Carmona & Irwin (2007): *'BIM can be viewed as a virtual process that encompasses all aspects, disciplines, and systems of a facility within a single, virtual model, allowing all design team members (owners, architects, engineers, contractors, subcontractors, and suppliers) to collaborate more accurately and efficiently than using traditional processes. As the model is being created, team members are constantly refining and adjusting their portions according to project specifications and design changes to ensure the model is as accurate as possible before the project physically breaks ground'.*

The National BIM Standard- United States (2016) explained BIM on their website as follows: *'Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition'*

BIM is all about the cooperation between different disciplines and several parties must work together to fully implement the BIM methodology. BIM enables that anyone involved can process information immediately into the model, making the sharing faster and more efficient (Eastman et al., 2011). Therefore, the parties involved in the building process will work more intensively with each other which stimulates working in a more collaborative manner (Kolarevic, 2009). Besides this, a better insight into the cost and construction schedule is obtained as the model can be detailed till the last screw and installation times and element pricing can me inserted into the model. BIM acts as an integrated model that stores information such as drawings, specifications, construction details and more, in a centralized database. Information management in this form changes the procedure for the design and documentation, because all relevant information is organized in a central way instead of different sets of drawings and specifications (Aksamija & Iordanova, 2011).

In conclusion, BIM can be described as a 3-dimension (3D) model of a construction project which can contain all the necessary data of that structure during its entire lifetime, from planning to demolishing. All the parties involved in the project can work in, and extract information from the model at any time in the process which greatly improves the communication between them and in the end, reduces the cost and time of the project.

2.1.2. Users of BIM

BIM can be used throughout the lifetime of a building; each phase has its own use for such an information model. Eastman et al., (2011) describes the use of BIM for each of the parties in the construction process as shown in table 1:

Table 1 - Advantages of BIM (Eastman et al., 2011)

Type of User	How BIM is used
Owners and facility managers	• Increase building performance • Reduce financial risk • Shorten project schedule • Obtain reliable and accurate cost estimates • Assure program compliance • Optimize facility management and maintenance
Architects and Engineers	• Conceptual design • Spatial design • Easier generation of complex building shells • More thorough exploration and assessment of preliminary design • Integration of engineering services • Construction level modeling (including detailing, specifications and cost estimation
Contractors	• Better planned construction process (saves time, money and potential errors) • Better cooperation with architect and engineers and subcontractors • Potential conflicts temporary structures (clash detection) • Enables increased offsite prefabrication (reduces field cost and improves accuracy)
Subcontractors and fabricators	• Enhanced marketing and rendering through visual images and automated estimating • Reduced cycle times for detailed design and production • Eliminating of almost all design coordination errors • Lower engineering and detailing costs • Data to drive automated manufacturing technologies • Improved preassembly and prefabrication

2.1.3. Possibilities and advantages of BIM

BIM models can also be used to analyze structural parts and to provide solutions for problems that can arise in the early stages between, for example, the structural design and the installation design. Construction schedules can be integrated in the model to determine the sequence of activities. This is also referred to as 4D models, because the time dimension is included in the model. Another dimension in the cost provision, commonly referred to as 5D because the materials and components can be directly analyzed and linked to cost prices. In this way, important financial information can be extracted from the model which helps making early design decisions (Aksamija & Iordanova, 2011). Other possibilities of BIM are described by Azhar (2011) in table 2.

Table 2 - Possibilities of BIM (Azhar 2011)

Possibilities of BIM	Description
Visualization	3D renderings can be easily generated in house with little additional effort.
Fabrication/shop drawings	It is easy to generate shop drawings for various building systems. For example, the sheet metal ductwork shop drawings can be quickly produced once the model is complete.
Code reviews	Fire departments and other officials may use these models for their review of building projects.
Cost estimating	BIM software has built-in cost estimating features. Material quantities are automatically extracted and updated when any changes are made in the model.
Construction sequencing	A building information model can be effectively used to coordinate material ordering, fabrication, and delivery schedules for all building components.
Conflict, interference, and collision detection	BIM models are created in a 3d space which allows the instant and automatically checking of interferences. For example, this process can verify that piping does not intersect with steel beams, ducts, or walls.
Forensic analysis	A building information model can be easily adapted to graphically illustrate potential failures, leaks, evacuation plans, and so forth.
Facilities management	Facilities management departments can use it for renovations, space planning, and maintenance operations.

In terms of advantages of BIM, the most frequently mentioned in the literature are described as followed (Azhar, 2011; Technische Raad van TVVL, 2011):

- Applying BIM provides a higher quality of work performance;
- Applying BIM improves coordination between design and engineering disciplines;
- The use of BIM ensures that there are cost savings in the design and the engineering;
- The use of BIM ensures an increase of the speed of the delivery;
- Applying BIM makes the process faster and more efficient.

One of the most referred advantage when applying BIM is the quality increase of the design. This is because the design can be better analyzed and simulations can be carried out more easily. This makes it possible to analyze and adopt innovative solutions. Also, a better visualization of the project can be given from the designer to the client which has the advantage that the proposed design will be easier understood (Azhar, 2011; CRC Construction Innovation, 2007).

Having described the several purposes of BIM it is also relevant to describe what is not BIM, but often is used in that context. BIM is not a software; this is just a small part of the larger whole. BIM is collaboration, an organizational challenge on which everybody must work together in the process in a transparent and open way. BIM is also not the same as working and drawing with Revit. Revit is just one of the possible technical products that supports the BIM process. BIM cannot, at the click of a button automate the construction coordination, there is a prior process required. Although it is evident that BIM helps with reducing some of the failure costs, some errors like wrongly placed orders or when products are not delivered on time, cannot be avoided by just using BIM (Technische Raad van TVVL, 2011).

In short, BIM is a management tool and not just a computer program. To ensure that BIM can work as a management tool, it is important that from the beginning of the process the different parties work closely together in a transparent environment.

2.2. Risk management

All types and sizes of organization face internal and external influences that make it uncertain whether and when they will achieve their objectives. The effect this uncertainty has on an organization's objectives is called 'risk'. All activities of an organization involve risk. Organizations try to manage risk by identifying, analyzing and evaluating whether the risk should be modified by risk treatment to satisfy their risk criteria. Throughout this process, they communicate and consult with stakeholders, monitor and review the risk to ensure that no further risk treatment is required (ISO 31000, 2009).

2.2.1. Definition of risk

ISO 31000 (2009) describes risk as '*effect of uncertainty on objectives' (p.1).* Van Well-stam et al. (2013) say that a risk is an event that may or may not occur and may result in: higher costs, prolongation of the project, not meeting the quality-, information- or organization requirements. Serpella et al., (2014) describes risk as an umbrella term with two varieties; an opportunity, which is a risk with positive effects and a threat, which is a risk with negative effects. Tomek & Matějka (2014) plotted this varieties in a diagram (figure 2) along two risk dimensions. The first dimension is the likelihood, which means the probability that an event will occur. The second dimension is the consequences, which means the severity of impact in case a risk scenario happens. The combination of risk likelihood and consequence results in the creation of a risk level. The risk matrix is when levels of all identified risks are plotted into a diagram where the two dimensions are represented by the two diagrams' axis. All basic risk relations are displayed graphically in the middle vertical column.

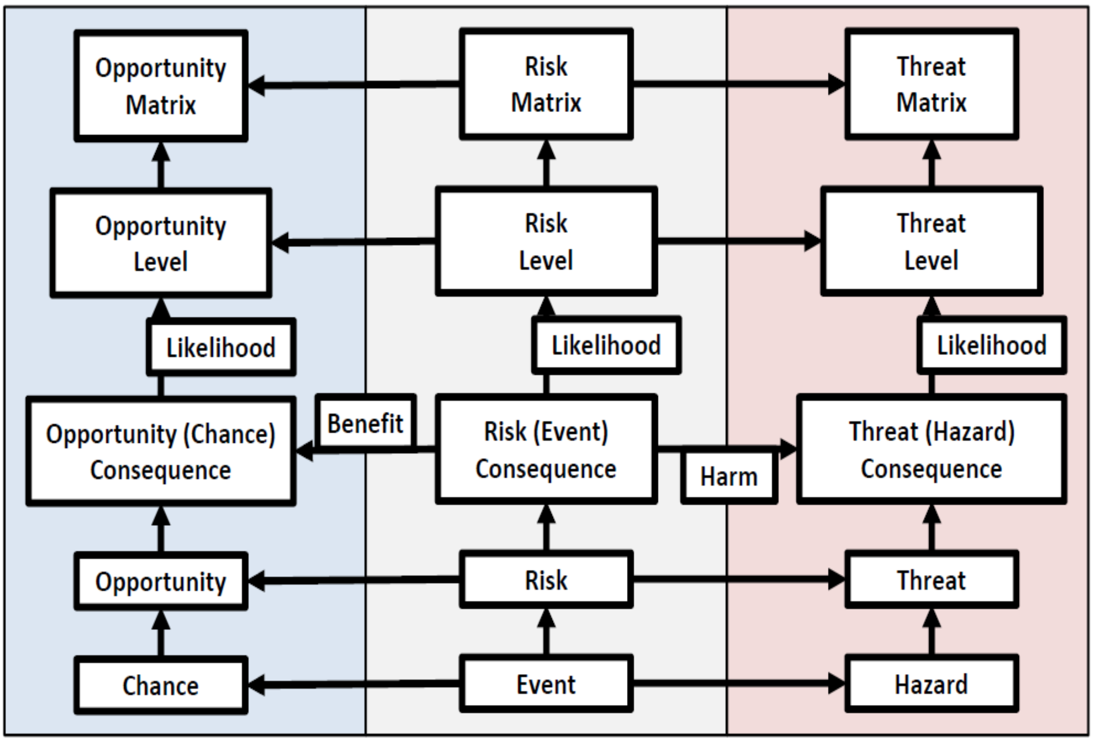


Figure 2 - Relation in risk terminology (Tomek & Matějka 2014)

Project risk is described by The Project Management Institute (2008) as: *'an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives'* (p.446). Kliem & Ludin (1997) have a similar definition for a project risk, namely the occurrence of an event with consequences for, or effects on, projects. This shows that risk also has a link with the final goals, the same as with an effect and uncertainty. A project activity is, according to Keizer et al. (2002), perceived as risky when:

- The likelihood of a bad result is great;
- The ability to influence it within the time and resource limits of the project is small;
- Its potential consequences are severe.

Halman (2008) defines project risks as unique and dynamic, which means that a project is an infrequently occurring, dynamic risk. This means that project risks are to be assessed subjectively, and can be affected during the process.

2.2.2. Categorizing of risks

Analyzing the risks based on the ISO standard refers to the understanding of the risks involved, the effects and the likelihood of these effects. Depending on the circumstances, the analysis of the risks can be qualitative or quantitative, where ISO 31000 (2009) does not state a preference for either of the two approaches (Purdy, 2010).

A qualitative risk assessment is characterized as the process of prioritizing risks for further analysis of action. A quantitative risk assessment is the process of numerical analysis for the effects of identified risks on overall project goals. A quantitative risk analysis generally follows the qualitative analysis. In certain cases, a quantitative analysis is not necessary to establish effective measures against risks. Factors for determining the method(s) to use are the availability of time and budget, and the need for qualitative or quantitative statements about risk and impacts (Project Management Institute, 2008). The categorization of the various risks is based on the following properties (Halman, 2008):

- Ability of assessment (objective or subjective);
- Ability to be influenced;
- Frequency of occurrence.

Table 3 provides a summary with all the relevant tasks, with frequent risks are objectively measurable since there is sufficient historical data available. The infrequent risks are subjective and are assessed based on expectations (Halman, 2008).

Table 3 - Risk categorization (Halman, 2008)

	Frequent	**Infrequent**
Static (gamble vision)	Objectively measurable For example: unworkable days in a construction planning	Subjectively measurable For example: buying a share in a stock market
Dynamic (management vision)	Objectively measurable For example: quality procedures in a process industry	Subjectively measurable For example: project management

2.2.3. Definition and goal of risk management

Serpella et al. (2014) and Banaitiene & Banaitis (2012) defines risk management as: 'the process of Identifying and assessing risk, and to apply methods to reduce it to an acceptable extent'. This needs to be done with the goal to identify, evaluate and control the risks within a project which should lead to project success. Marcelino-Sádaba et al. (2014) give risk management the following definition: *'risk management is a systematic process that aims to identify and manage risk, in order to act on its appearance (eliminating, minimizing or controlling it), by implementing systems and procedures to identify, analyze, evaluate and address the risks inherent to any project'* (p. 329).

Risk management should be applied to have a clear view on the risks, to improve the management process of projects and for an effective use of resources (Banaitiene & Banaitis, 2012). Based on Sousa, et al. (2012) Risk management is used to reduce uncertainties in construction projects to meet the needs of the stakeholders. According to Marcelino-Sádaba et al. (2014) risk management should contribute to define the project goals, to improve project control, to increase the success rate, to improve communication between project participants and to facilitate decision-making and prioritizing of actions.

Based on the similarities in the definitions it can be concluded that risk management is a systematic and cyclical process to identify, assess and ultimately manage risks. The goal of this can be summarized in achieving the defined project goals in terms of time, money and quality, but also to improve communication among the stakeholders in the project.

2.2.4. Applying risk management in a construction project

The risk management process contains standard risk concepts, terminology and processes (Jamieson & Jones, 2013). The process begins with the determination of the context, which starts with the preparation of project goals, identifying success factors, assessing of stakeholder relations, and the identification of the risk area. The first step in risk assessment is to identify risks, their risk drivers and the risk categories. The second aspect which is covered by risk assessment is 'risk analysis', in which identified risks are evaluated by probability of occurrence and potential impact. The third aspect is the prioritization of risk and identifying the risks on which intervention is needed. After these three components risk assessment also addresses the treatment of risks, including acceptance, avoidance, reducing or removing, or transferring and sharing of risks. A diagram of the aspects described is shown in figure 3. In addition to these steps communication and consultation plays an important role in the process. The involvement of stakeholders is required to achieve the project goals, to secure involvement and to distribute risk information. Monitoring and review investigates the changes in risks and the emergence of new risks due to changes in the external environment, risk management and project goals (Scannell, et al., 2013). In the initial phase of a project there is the greatest degree of uncertainty about the future (Uher & Toakley, 1999). Essential in the application of risk management is thus that it should be applied from the initial stage of a project, simply because there can be exerted a bigger influence at that stage on choices in the coordination and selection of construction methods (Banaitiene & Banaitis, 2012). With applying risk management, it's important that it is clear who is responsible for performing risk management and at what point attention should be paid to it. According to Gehner (2008) risk management should be performed at any time and requires close cooperation between the project manager and the corresponding project team members.

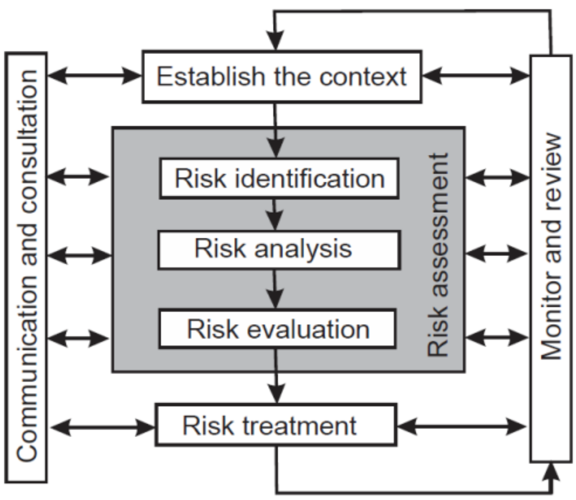


Figure 3 - Risk management process, grey area represents scope of this thesis (ISO 31000, 2009)

2.2.5. Risk identification

Risk identification is the process of finding, recognizing and describing risks. It involves the identification of risk sources, events, their causes and their potential consequences. In the process, historical data, theoretical analysis, informed and expert opinions, and stakeholder's needs can be evaluated (ISO 31000, 2009). Purdy (2010) indicates that the identification of risks requires a systematic process to understand what might happen, how, when and why. Van Well-Stam et al. (2013) adds that there should be looked at a project in a systematic manner and from different angles to get a risk identification as complete as possible. The purpose of the identification phase is to identify sources of risk, areas of impacts, events (including changes in circumstances) and their causes and their potential consequences (ISO 31000, 2009). Identifying risks is an iterative process because as the project progresses new risks may arise or become known (Project Management Institute, 2008).

Although, a remark should be made when identifying risks. El-Sayegh (2008) says that identifying all the risks is time-consuming and can work counterproductive. The trick is to identify the most critical risks in the construction project and control them.

2.2.6. Risk analysis and evaluation

The objective of risk analysis is to determine the influence of risk factors on the system as a whole. Risk analysis involves consideration of the causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences can occur (ISO 31000, 2009). There are several tools available to identify and/ or analyze different risks. As mentioned before, risks can be analyzed in a quantitative and a qualitative way but organizations tend to use qualitative assessment techniques to identify risk because an expert opinion is the best source available (Ahmed et al., 2007). Several techniques in the literature that are currently applied for project analysis can also be applied for risk analysis, see table 4.

Table 4 - Techniques for Risk analysis

Tool	Description	Sources
Estimation of project reliability	In a project, most of the elements are integrated together in a serial or parallel way. The project reliability is established as the cumulative effects on its critical components.	• ISO 8402 • Ahmed et al., 2007
Event tree analysis	In an event tree analysis, a sequence of events that could occur is identified that represents the possible scenarios in a tree diagram where each branch represents an alternative possibility. The probability of occurrence of a particular outcome is determined as a product of all probabilities of occurrence in the associated branch.	• Chapman & Ward 2004 • Ahmed et al., 2007
Fault tree analysis	A fault tree analysis works in the same way as the event tree analysis but then in a reversed way, working backward from a particular event (the top-level event) that might occur. From that point, the analysis is worked down by passing through logical gates to identify all possible sequences of events that lead to this top-level event. In the end, this analysis gives an overview of the risks in the overall project and the specific components in the lower levels.	• Ahmed et al., 2007 • Chapman & Ward 2004
Decision tree analysis	Decision tree analysis is used to evaluate outcomes from uncertain events. By using decision nodes, future managerial decisions can be made after some uncertainty has been resolved and more information has been obtained, before proceeding to the next stage. It includes probability of returns associated with decisions and estimation of expected returns.	• Ahmed et al., 2007 • de Reyck et al., 2008
Portfolio management	Portfolio management compares risks of multiple projects in terms of investment and returns. Projects are positioned on a graph with on the horizontal axis the magnitude of risk, and the on the vertical axis the magnitude of the return. Projects with a high risk and low return are placed at a different position than low risks with high return allowing managers to take better decisions based on the company's strategy.	• Ahmed et al., 2007 • De Maio et al., 1994
Multiple criteria decision-making method	Multiple criteria decision-making method considers the negative and positive factors of a decision. These project attributes are weighted according to predefined criteria. The product of the relative weight and the score for an attribute gives a weighted score for that attribute. The project is then evaluated through a difference from a standard project attribute. If the total weighted score is positive, the project should be selected, if the score is negative the project should be rejected. This technique can be applied to risk analysis if risk events are compared to standard events and weighted against them.	• Ahmed et al., 2007
Failure mode effect analysis (FMEA)	FMEA provides a structure for determining causes, effects and relationships in a project. FMEA is used to define, identify and eliminate known and/ or potential failures, problems, errors and so on from a system/\, design, process and/ or service so that solutions for rectifying these problems can be visualized.	• Ahmed et al., 2007 • Chin et al., 2009

2.2.7. FMEA

The management tool to address risk that is proposed in this thesis is the Failure Mode Effect Analysis (FMEA). It is developed to identify and prioritize risks in a construction project. Besides this, is can be used to come up with possible solutions to avoid or minimize these risks. When applied properly, FMEA can anticipate and prevent problems, reduce costs, shorten product development times, and achieve safe and highly reliable products and processes (Carlson, 2012). In the construction sector this technique could be the most important tool in managing quality plans to obtain a suitable, adequate and subsequently more efficient system to build in conformity with specifications (Mecca & Masera 1999). The main advantage of FMEA is the fact that it addresses budget, schedule and technical risk together where as other techniques are usually limited to addressing risk relating only to cost, schedule, or technical performance individually (Guikema & William, 2009).

2.2.7.1. FMEA Concept

In a FMEA there are three main objectives; identifying and evaluating the risks, and determine the possible actions to eliminate or reduce the effect and the impact of failure. After the part of the analysis is completed the risks will be prioritized based on risk priority number (RPN). Generally, the RPN is ranges from 1 to 1.000, calculated as the product of the severity (S), occurrence (O), and detection level (D) of a failure mode, where each of the three parts is evaluated on a scale from 1 to 10. Thus, elements that are assessed to have a high RPN are assumed more critical than those with lower values.

2.2.7.2. Occurrence

The occurrence (O) rating is the frequency or probability that a failure related to a risk actually happens during construction. It is based on the criteria from the corresponding occurrence scale, see table 5. The occurrence ranking has a relative meaning rather than an absolute value and is determined separately from the severity or likelihood of detection (Carlson, 2012).

Table 5 - Rating for occurrence of a failure (Chin et al., 2009)

Rating	Probability of occurrence	Possible failure rate
10	Very high: failure is almost inevitable	≥ 1/2
9		1/3
8	High: repeated failures	1/8
7		1/20
6	Moderate: occasional failures	1/80
5		1/400
4		1/2000
3	Low: relatively few failures	1/15.000
2		1/150.000
1	Remote: failure is unlikely	≤ 1/1.500.000

2.2.7.3. Severity

The severity (S) rating represents the potential effects associated with the occurrence of a failure mode, see table 6. The severity is ranked to the seriousness of the failure effect on the next level in construction or the effect for the end use (Peláez, 1995). The traditional FMEA talks about a Hazardous effect but since the scope of the thesis is cost and time, the severity is based on the expected impact of the project end goals in terms of cost and time in case of failure and is scaled from (virtually) none to extreme.

Table 6 - Rating for severity of a failure

Rating	Effect	Severity of effect
10	Extreme	>15% increase of the planned project time/ cost
9	Major	10% increase of the planned project time/ cost
8	Serious	5% increase of the planned project time/ cost
7	Significant	4% increase of the planned project time/ cost
6	Moderate	3% increase of the planned project time/ cost
5	Low	2% increase of the planned project time/ cost
4	Very low	1% increase of the planned project time/ cost
3	Minor	0,5% increase of the planned project time/ cost
2	Very minor	0,1% increase of the planned project time/ cost
1	None	< 0,05% increase of the planned project time/ cost

2.2.7.4. Detection

The detection level (D) represents the probability of not detecting the failure, see table 7. It is an assessment of the ability to identify potential weakness before the element is constructed (Peláez, 1995). The detection is an important part of the FMEA and the way the detection will be assessed is based on information from the companies' database about previous projects. Therefore, it is important that after a project is completed the FMEA is analyzed and the database is updated with the relation between the predicted detection and the information about what actually happened in the project.

Table 7 - Rating for detection (Chin et al., 2009)

Rating	Detection	Criteria
10	Impossible	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control
9	Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
8	Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
7	Very low	Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode
6	Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
5	Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode
4	Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode
3	High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode
2	Very high	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode
1	Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode

The evaluation of the risks is done by a team of experts and selecting the right team is one of the most important steps in preparing for an FMEA. Carlson (2012) states that there are three main reasons why it is important to form a proper team;

- People have 'blind spots', with a well-defined cross-functional team the risk of not detecting or not evaluating risks well is minimized;
- In a construction project, there are many elements and disciplines which each requires a specialist to address them;
- One of the essential values of an FMEA is the cross talk between different experts that occurs during a meeting. Well defined groups van discover things that individuals often miss.

2.2.7.5. Limitations/ shortcomings

The FMEA is not a perfect tool, many researchers have studied the tool and came up with some shortcomings. Liu et al. (2013) collected these concerns and they are described in table 8.

Table 8 - Drawbacks FMEA (Liu et al., 2013)

Drawbacks of FMEA	Description
Hidden risk implications	Different sets of O, S and D ratings may produce the same value of RPN but can have hidden risk implications that may be totally different because of the different severities of the failure consequence. This may cause a waste of resources and time, or in some cases, a high-risk failure mode being unnoticed.
Relative importance O, S, D	The relative importance among O, S and D is not taken into consideration. The three factors are assumed to have the same importance.
Mathematical formula	The mathematical formula for calculating RPN is questionable and debatable. There is no rationale as to why O, S and D should be multiplied to produce the RPN.
Conversion of scores	The conversion of scores is different for the three factors. For example, a linear conversion is used for O, but a nonlinear transformation is employed for D.
Effects of small variations	Small variations in one rating may lead to vastly different effects on the RPN, depending on the values of the other factors. For example, if O and D are both 10, then a 1-point difference in severity rating results in a 100-point difference in the RPN.
Precise determination	The factors are difficult to precisely determine. Much information in FMEA can be expressed in a linguistic way such as likely, important or Very High and soon.

In this thesis, an extra element will be added to a traditional FMEA to address some of these problems. In the FMEA interface a cell will be added which can be filled with important information for the understanding of a particular risk. This information will present itself in the 3D BIM model by a pop-up screen. The problems of the 'hidden risk implications', the 'effects small variations' and the difficulty with 'precisely determining the factors' will be solved by the addition of this extra information.

2.3. BIM and Risk management

There is not much literature addressing risks and BIM in detail because it is usually based on the know-how of experts within a company. When BIM related risks are mentioned, specific BIM tools are described. For example, clash-detection tools or safety planning. (Tomek & Matêjka 2014). Although, BIM can play a very important role in risk management. It has a big influence on standard risk levels but it also creates new threats and opportunities. BIM could not only be used to support the project development process as a risk management tool, but it could also serve as a platform to allow other BIM-based tools to perform further risk analysis (Zou et al., 2016).

2.3.1. Contributions of BIM in risk management

As described in section 2.1.3 the use of BIM has several advantages compared to traditional design methods. Besides this, working with BIM can have some advantages specifically related to risk management. The risk of wrong measurement or inaccurate generation of cost can be minimized due to the elimination of manual extraction of drawing through data exchange platform or other method of integrating process. BIM applications utilize parametric modeling. Parametric modeling involves the use of a relational database containing information regarding the elements of a structure and their relationships. The capture and management of objects relationships is useful in enabling a high level of model analysis beyond object properties. Therefore, the model can be used to generate space calculations, energy efficiency, structural analysis details and traditional design document. By using BIM, the design deficiency through data exchange platform can be reduced: the main benefit of BIM is its ability to decrease errors made by design and construction teams by employing the mechanism of conflict detection through visualization techniques, referring to relevant parts in relations to the whole building model. Integrating the design process with construction and engineering can be achieved when a builder simulates a building before and during the actual construction process. 4D or 5D models which integrates time and cost in addition to the 3D geometry models. In this way, changes cannot only be controlled in the design and engineering stages, but also can be controlled to some extent in the built environment lifecycle. It is ideally suited on projects with high cost and high risk and which can lead to high rewards for mitigating those cost and risk. When BIM is made accessible to all stake holders it will improve communication and cooperation and thereby decreasing the risk of defragmentation among project actors (Hammad et al., 2012). Financial risk associated with the project using the BIM model can be reduced by obtaining earlier and more reliable cost estimates and improving collaboration of the project team. Furthermore, schedule related risks can be reduced by allowing quick response to unforeseen field conditions with 4D-coordinated BIM models and by using BIM object libraries in the design stage the risk for errors and omissions will be decreased (Eastman et al., 2011)

Eastman et al. (2011) states that in the design stage BIM also provide opportunities based on automation and communication with different stakeholders, especially in prefabrication. Also *'a detailed building model is a risk-mitigation tool for estimators that can significantly reduce bid costs, because it reduces the uncertainty associated with material quantities'* (p. 276). For subcontractors, the risks '*associated with parts not fitting properly when installed' are reduced* (p. 322). Besides this there are some BIM tools that can help identifying risks, for example clash detection and safety planning (Tomek & Matêjka 2014).

2.3.2. Communication

Communication and consultation are an important consideration at each step of the risk management process. Effective internal and external communication is important to ensure that those responsible for implementing risk management, and those with a vested interest understand the basis on which decisions are made and why particular actions are required. Perceptions of risk can vary due to difference in assumptions and concepts and the needs, issues and concerns of stakeholders as they relate to the risk or the issues under discussion. Since stakeholders can have a significant impact on the decisions made, it is important that their perceptions of risk, as well as their perceptions of benefits, be identified and documented and the underlying reasons for them understood and addressed (Joint Technical Committee OB/7 1999).

Nowadays the exchange of information is still based on a 2D-environment. One of the most common problems associated with this is the considerable time and expense required to generate critical assessment information about a proposed design. These analyses are normally done last, when it is already too late to make important changes (Eastman et al., 2011). Adopting BIM brings opportunities in an increased level of communication because the models are 3D and therefore much closer to everyday reality which improves the understanding of the design such as owners, architects and their consultants, contractors, fabricators, and potentially, operators. People who not all have a background in the construction sector (Deutsch, 2011; Eastman et al., 2011).

Since a BIM model can also be designed in a 4D environment, it has a huge advantage in visualizing the construction process which can increase communication: Eastman et al. (2011) describes: *'Planners can visually communicate the planned construction process to all project stakeholders. The 4D model captures both the temporal and spatial aspects of a schedule and communicates this schedule more effectively than a traditional Gantt chart'* (p. 285).

Bryde et al. (2013) studied some case studies about BIM and communication and the results were merely positive. *'The effects of BIM on the Communication success criterion were all positive. Communication improvements were mentioned 15 times in 13 (37.14%) of the 35 case studies'*. Some of benefits on communication were: *'information exchange saving up to 50% of effort'*, *'information is a lot easier to find compared to traditional 2D drawings'* and *'better communicate changes with the owner' (p. 977).*

McGraw-Hill constructions (2010) also has studied the advantages in construction projects according to Western European BIM users. The biggest advantage in construction management which was found in the study is that a better collective understanding of the design arises when BIM is used and that it becomes clearer what the underlying thoughts of the different parties are (see figure 4). Now parties often work alongside each other where one party not always understand what the idea or thoughts are of the other party. An improvement in this interface ensures automatically an improvement in the collaboration between parties, where fewer conflicts and clashes will occur in the design and between the different parties. In the end, this will improve the quality of the total project.

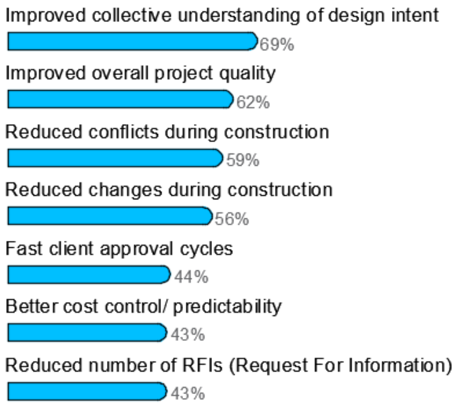


Figure 4 - Biggest advantages according to BIM users, (McGraw-Hill constructions 2010)

2.3.3. Opportunities for a BIM-based risk management tool

Based on the literature review it can be concluded that communication plays an important role in management of risks. Tah & Carr (2001) states that communication of construction project risk is poor, incomplete, and inconsistent throughout the construction process. Also, project participants usually do not have a shared understanding of the project risk and therefore are unable to implement effective measures and mitigating strategies to adequately deal with problems resulting from decisions taken elsewhere in the process.

Different stakeholders with different backgrounds and knowledge about construction need to communicate in a clear and efficient way. This study aims to develop a tool that can be implemented in every BIM-based construction project whereby the risks can be easily identified and be made visible for all the people involved. This helps risk managers to respond to risk in a more efficient way and helps the stakeholders to better understand which actions need to be taken and what the underlying reasoning of the actions is. It also helps to make the risk management activities easier traceable, which is important to provide the foundation for improvement in methods and tools, as well as in the overall process (ISO 31000, 2009).

There are several studies that investigate the implementation of BIM tools to visualize different aspects in construction management. Hartman et al. (2012) studied the implementation of a BIM-based tool to address management problems on a large scale. Most of the BIM-based risk management tools as proposed by, among others, Zhang & Hu, (2011), Park & Kim, (2013), Zhang et al. (2013), Zhou et al. (2013) focuses on safety. Kang et al. (2013) developed a 4D object-based system to visualize risk information focusing on time, cost and work conditions. Other authors discuss the use of BIM to visualize part of the management process during construction. For example, Mushamalirwa (2016) proposed in her research work a tool to visualize cost and time performance of construction works in a 3D model using a color code system and Sacks et al. (2013) proposed a 'KanBIM' tool to connect lean management with BIM. The tool proposed in this thesis is based on, among others, this research, but distinguishes itself by focusing on time and cost in a 4D environment and using a color code system to visualize the degree of risk.

3. Development of BIM-based risk management tool

The focus of this thesis is the development of a risk management tool using BIM. This tool allows the user to visualize the different risks and the degree to which they affect the project. First, a conceptual model is developed presenting the different actors involved and how the tool will be used. Secondly, the tool itself is developed consisting of an FMEA interface, a Dynamo code and a 3D BIM model made in Revit and a 4D model made in Navisworks. Thirdly, the instructions for the use of the tool before and during the construction phase are explained step by step.

3.1. Conceptual model

The aim of the BIM-based risk management tool is to provide a clear overview of the cost and time risks in a project for all the stakeholders involved. Ultimately the different risks involved will be presented in a 3D BIM model where the user can navigate through the building model and a 4D model in which the user can scroll throughout the timeline of the construction process. The center of the tool is a FMEA interface in Excel in which the risk analysis will be performed. The construction schedule can be loaded into this FMEA interface and for each task the related risks can be analyzed in terms of their importance. The interface will automatically assign a risk color to the tasks based on the outcome of this risk analysis. The several risk colors will, along with extra information that can be filled in manually in the FMEA interface, be distributed to the element in the design corresponding to the evaluated task.

The tool involves several steps in linking the different software with each other and performing the risk analysis. By using the FMEA, the risks can be analyzed and prioritized and a severity color can be assigned based on a numerical outcome in an effective and clear way. This helps with an efficient translation from the analysis to the BIM model. Therefore, FMEA is found to be the most suitable technique to be used in this tool, although, through the separation of the analysis and visualization different techniques can be used according to the users' preferences. The process starts with a construction schedule and a 3D BIM model. The construction schedule will be linked to the interface where the FMEA can be performed. Using Dynamo, the information obtained will be exported to the 3D BIM model. For the elements to receive the correct information a link will be established in Revit between the tasks and their corresponding elements. In Navisworks, the BIM model containing the link between tasks and elements will be combined with the information from the FMEA interface to create the 4D model. The different steps and data flow are presented in figure 5. In the second left column, the proposed software is presented. Although different software can be used, this is the software that is advised for an optimal use of the tool.

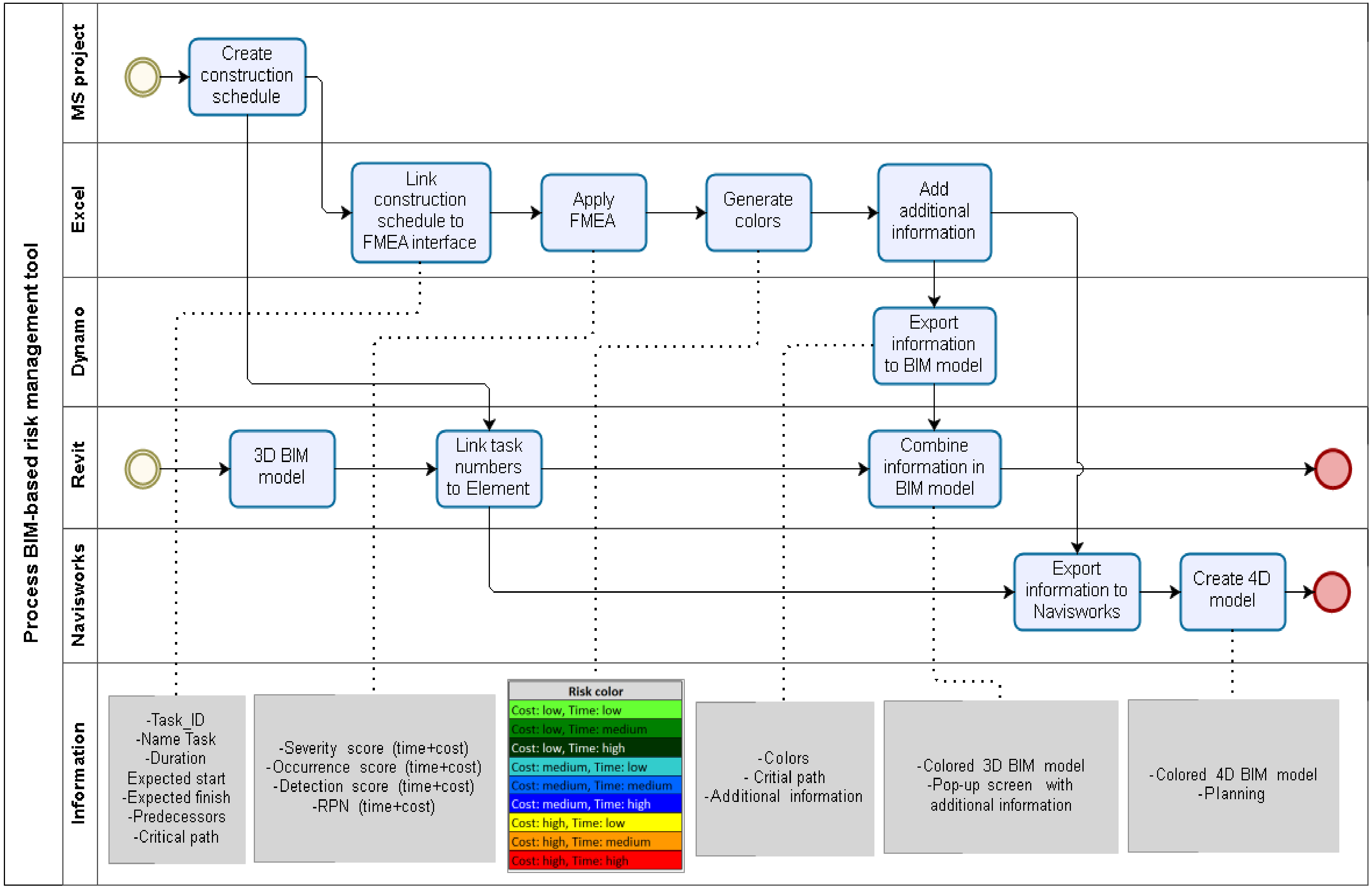


Figure 5 - Data flow conceptual model

3.2. FMEA Interface

The FMEA interface will perform as the center of the tool and contains the following information:

- The construction schedule;
- The FMEA;
- The results of the FMEA;
- Column additional information;
- Legend Color coding system;
- Guidelines for the use of the interface.

In figure 6 an example of the FMEA interface is presented along with the explanation of the formulas that are applied. If the construction schedule is made in MS Project, it can directly be linked to Excel so every change in the construction schedule will be shown immediately in the FMEA interface. The construction schedule contains columns with Task_ID, Name, Duration, Start date, Finish date, Predecessors and if a task is part of the critical path. All this information will help the user to verify the risks.

Next to the construction schedule, the FMEA will be performed which will be divided in a cost analysis and a time analysis. Each analysis is divided in columns for the assessment of occurrence, severity, detection and the RPN. For each of the columns the risk will be rated with a value between 1 and 10. These 3 values multiplied with each other form the RPN. In the next column, the RPN will automatically be evaluated in terms of low, medium and high. Since the evaluation of risk is always somewhat subjective and some users prefer to take more risks than others, a cell is included for the user to decide which RPN will be considered as low, medium or high. The default evaluation is presented in table 9 and it is determined by evaluating the different factors individually. For the occurrence, detection and severity an evaluation of low (smaller than 3), high (bigger than 6) and medium (between 3 and 6) can be determined. Since there are 3 factors, these values receive the exponent 3 which makes: $3^3 = 27$ and $6^3 = 216$. The analysis in figure 6 is filled with random numbers to show different outcomes in the colors.

Tabel 9 - Risk evaluation

RPN	Risk evaluation
<27	Low risk
Between 27 and 216	Medium risk
>216	High risk

Link with MS project	
Fill in manually	

Risk evaluation	value
'Low' <	27
'High' >	216
'Medium'	

Planning linked with Ms Project

RPN automatically calculated by multiplying Occurence, Severity and Detection number

Risk automatically evaluated by Low, Medium or High depending on RPN. Evaluation is equal to the highest risk of the onderlaying tasks

Color automatically assigned based on the two risk evaluations

Risk evaluation number (REN) automatically assigned based on the two risk evaluations

Planning							Cost					Time							
Task_ID	Name	Duration	Start_Date	Finish_Date	Predec.	Cr. path	O	S	D	RPN	Risk	O	S	D	RPN	Risk	Color	Additional Information	REN
2	**Footings**	**6 days**	**22-12-16**	**29-12-16**		**Yes**	**9**	**1**	**1**	**9**	**Low**				**81**	**Medium**	LowMedium	**Weather conditions**	**2**
2.1	Formwork footings	2 days	22-12-16	23-12-16	4	Yes					Low	1	9	9	81	Medium	LowMedium		2
2.2	Reinforcement footing	1 day	26-12-16	26-12-16	7	Yes					Low	1	2	10	20	Low	LowLow		1
2.3	Casting concrete footing	1 day	27-12-16	27-12-16	8	Yes					Low	7	1	1	7	Low	LowLow		1
2.4	Removing Formwork	1 day	29-12-16	29-12-16	9FS+1d	No					Low	2	4	8	64	Medium	LowMedium		2
3	**Foundation pillars**	**8 days**	**29-12-16**	**9-01-17**		**No**	**4**	**1**	**8**	**32**	**Medium**				**432**	**High**	**MediumHigh**	**Weather conditions**	**6**
3.1	Formwork pillars	3 days	29-12-16	2-01-17	9FS+1d	Yes					Medium	7	7	2	98	Medium	MediumMedium		5
3.2	Reinforcement pillars	2 days	3-01-17	4-01-17	12	Yes					Medium	1	6	6	36	Medium	MediumMedium		5
3.3	Casting pillars	1 day	5-01-17	5-01-17	13	Yes					Medium	8	6	9	432	High	MediumHigh		6
3.4	Casting pillars	2 day	5-01-17	5-01-17	14	Yes					Medium	2	5	1	10	Low	MediumLow		4

Risk	Risk color
Cost: low, Time: low	1
Cost: low, Time: medium	2
Cost: low, Time: high	3
Cost: medium, Time: low	4
Cost: medium, Time: medium	5
Cost: medium, Time: high	6
Cost: high, Time: low	7
Cost: high, Time: medium	8
Cost: high, Time: high	9

Rating	Detection	Criteria
10	Impossible	Impossible Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control
9	Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
8	Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
7	Very low	Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode
6	Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
5	Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode
4	Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode
3	High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode
2	Very high	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode
1	Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode

Rating	Effect	Severity of effect
10	Extreme	>15% increase of the planned project time/ cost
9	Major	10% increase of the planned project time/ cost
8	Serious	5% increase of the planned project time/ cost
7	Significant	4% increase of the planned project time/ cost
6	Moderate	3% increase of the planned project time/ cost
5	Low	2% increase of the planned project time/ cost
4	Very low	1% increase of the planned project time/ cost
3	Minor	0,5% increase of the planned project time/ cost
2	Very minor	0,1% increase of the planned project time/ cost
1	None	< 0,05% increase of the planned project time/ cost

Rating	Probability of occurrence	Possible failure rate
10	Very high: failure is almost inevitable	≥ 1/2
9		1/3
8	High: repeated failures	1/8
7		1/20
6	Moderate: occasional failures	1/80
5		1/400
4		1/2000
3	Low: relatively few failures	1/15.000
2		1/150.000
1	Remote: failure is unlikely	≤ 1/1.500.000

Figure 6 - FMEA interface (in Excel)

Next to the cost and time analysis the evaluations will be combined into one term (LowLow, MediumHigh etc.) where the first part refers to cost related risks and the second to time related risks. Based on this term, a corresponding color will automatically be assigned. These colors will be applied to the 3D BIM model and the 4D model to show the degree of the involved risks. Since the risks related to cost are valid for an entire element and the risks related to time vary within an element, the colors are chosen in such a way that the type of color is related to the cost and the intensity of the color is related to the time. This deviation will allow the user to have a more natural understanding of the risks involved. The colors used in the tool are presented in table 10. Multiple tasks and therefore multiple risks can relate to the same element. To evaluate the color of the element, the highest time related risks of the element is combined with the cost related risk in the 3D BIM model. This evaluation is done automatically in the FMEA interface. In the 4D model this loss of information does not exist because the time related risks will appear as the project progresses.

Table 10 - Assigned risk colors

Risk Cost	Risk Time	REN	Risk Color	RGB code		
Not evaluated	Not evaluated	“null”	White	255	255	255
Low	Low	1		102	255	51
Low	Medium	2		0	128	0
Low	High	3		0	51	0
Medium	Low	4		51	204	204
Medium	Medium	5		0	102	255
Medium	High	6		0	0	255
High	Low	7		255	255	0
High	Medium	8		255	153	0
High	High	9		255	0	0

An extra column is available in the FMEA interface (Additional information) to fill in extra information about the risks involved. For example, what the specific risk involves, information about the entity who is responsible for managing this risk (risk owner), the possible cause of the risk (risk source), the entity who will suffer the consequences when a risk is realized (risk recipient) and so forth. This information will pop-up in the 3D BIM model when a specific element is selected.

3.2.1. Task paths and predecessors

To make an accurate estimation of the risks involved it is important that the user has a clear overview of all the factors involved. For the risks related to time the user need to be able to consult the construction schedule to see the duration of a specific task, if a task is critical and how the tasks are related to each other. If a task has multiple predecessors, one or more of those predecessors will directly affect the scheduling of that task; these predecessors are called driving predecessors because they determine (or drive) when the task starts or finishes. Similarly, when a task has multiple successors, one or more of the successors’ start or finish dates will be directly affected (or driven) by the task. These successors are called driven successors because the selected task determines exactly when the successor task is scheduled to occur (Howard 2013). This information is important for the user because a task can influence the risk of several other tasks in the construction schedule. To see which, and how, tasks are related to each other the column predecessors is introduced. The drawback of this column is that it only shows how one task is related to the next task, not for example to the task two steps further. When a construction schedule is straightforward this column will provide enough information for the user to reach a proper risk evaluation. When a construction schedule is more complex the user can consult the construction schedule in MS Project where there is a special option (Format- Task path) to show all the different task paths.

The tool involves an extra feature in which the elements that have tasks which are not on the critical path will receive a transparency. This will improve the overview of the time related risks, since the risks that are on the critical path will become clearer compared to the risks that are not on the critical path and therefore can be assumed to be less critical.

3.2.2. Schedule information import in FMEA interface

To perform the FMEA, the construction schedule information should be imported in the interface. To be able to perform the FMEA the construction schedule need to contain, a task identification number, a task name, the duration of each task, the start and finish date, the predecessors and if the task is located on the critical path. For the tool to be operable this information should be imported to the FMEA interface coming from a Project management software. The advisable software to use is Microsoft Project because it can directly link the construction schedule to an Excel spreadsheet and has the option to automatically generate task numbers, the critical path and the different task paths. The advantage of creating a link between the two software's is that a change in the construction schedule will immediately be visible in the FMEA interface.

In the FMEA the tasks will be evaluated in terms of their time and cost related risks. The results of this analysis will be shown in color (see table 10) of the building elements in the 3D BIM model and the 4D model. To visualize the colors related to the tasks in the respective models there must be a connection between the construction tasks in the construction schedule and the construction elements in the BIM model. Current software is not able to automatically link the building processes with the corresponding building elements (Kim et al.,2013, Lin & Golparvar-Fard 2016, Sigalov & König 2017). Therefore, this must be done manually. In this thesis two options to do so are analyzed, the standardized OmniClass system and a proposal to use task numbers.

3.2.3. Linking using OmniClass system

The OmniClass Construction Classification System (OCCS) is a strategy for classifying and organizing all this information for the entire built environment. It forms the standardized basis of the North American AEC industry throughout the full facility life cycle from conception to demolitions or reuse, and encompasses all the different types of construction that make up the build environment (OmniClass 2006). The system was developed because building projects are getting more and more complex and activities that are performed during the life cycle of a structure generate more and more data that needs to be stored, retrieved, communicated and used by all parties involved. The amount and type of information generated demands an organizational standard that can address the full scope of this information. The OmniClass system is divided in several tables that cover different parts of the built environment. Some of the tables that cover the OmniClass system are presented in table 11. Construction results are organized in tables 11 and 22, construction resources in table 23, 33, 34 and 35 and the construction processes or classified in tables 31 and 32. The tables contain a list of subjects with each a OmniClass number which will be used by all the users of this system (OmniClass 2006).

Table 11 - Example OmniClass tables (OmniClass 2006)

OmniClass table	Name	Examples
Table 11	Construction Entities by function	• Hotels • Single family residences • Interstate Highway
Table 13	Spaces by function	• Office • Kitchen • Highway
Table 23	Products	• Door • Metal window • Pipe culvert
Table 31	Phases	• Design phase • Construction phase
Table 34	Organizational Roles	• Owner • Supervisor • Facility manager
Table 36	Information	• Reference standards • CAD files • Catalogs
Table 49	Properties	• Color • Diameter • Weight

The OmniClass system can also be used to link building elements with building tasks. In Revit, all the building elements can be categorized with their respective OmniClass number. By selecting an element, a list of proposed OmniClass numbers (from table 23 in the OmniClass system) will pop-up in which the user can select the number it desires. With Dynamo, this list of elements and OmniClass numbers can be exported to an Excel file, an example is given in table 12.

Table 12 - Example list of elements with OmniClass number

Name element	OmniClass number
Masonry structural walls	23-13 35 21 13
Masonry Fixed Partitions	23-15 11 11 15
Doors	23-17 11 00

The project construction schedule can be exported to the same excel file. For each task, the OmniClass number of the element to which the task is related need to be filled in manually. Then for each task the FMEA can be made and the evaluation of the risks can be calculated, an example is given in table 13.

Table 13 - Example list of tasks with OmniClass number and FMEA analysis

Task name	Omniclass number	FMEA		Performance
		RPN cost	RPN time	
Laying Masonry exterior	23-13 35 21 13	40	180	MediumMedium
Laying Masonry Internal walls	23-15 11 11 15	70	5	MediumLow
Finishing internal walls	23-15 11 11 15	10	4	LowLow
Placing interior doors	23-17 11 00	3	15	LowLow

In the FMEA interface, the OmniClass numbers can be compared with the list of elements and the list of tasks. Where the OmniClass number matches, the element will take the color of the corresponding risk performance. When multiple tasks relate to one element, the element will take the color of the most severe risk performance. For example, the tasks applying formwork footing, applying reinforcement footing and concreting footing will receive the same OmniClass number as the element footing. The colors relating to the tasks and their OmniClass numbers can be exported back to the BIM model using the dynamo Software.

The main advantages of using the OmniClass system is that it is standardized and can be used internationally. It is a complete and widely accepted system (in addition to being openly available to the public), offering global electronic commerce standards. It also provides for future expandability and can easily be implemented (Eric C.W. Lou & Jack S. Goulding 2008).

The main drawback of this system is that it is not very flexible in terms of applying different tasks to different elements in the same group. For example, the columns of the foundation will have the same number as the columns of the first and second floor. Because the risk colors are linked to the OmniClass numbers all the columns will receive the same color. This is undesirable because the columns under the ground may have different risks involved as the columns on the first floor.

3.2.4. Linking using task identity numbers

The main difference between the method using the task numbers and the OmniClass system is that the connection is made within the Revit software instead of in the FMEA interface. Therefore, each task need to be attributed with a Task ID number which can be easily done in the MS Project software by inserting a column with the name ‘number’. It is important that the construction schedule will be converted to a format with main tasks and sub tasks where the main tasks will refer to an element or a set of elements. This is necessary because it will allow an easy use of the FMEA since risks related to the costs are evaluated per element and the risks related to time per task. An example of the desired construction schedule format is shown below:

1. Constructing footing (main task)

1.1 Placing formwork (sub task)

1.2 Placing reinforcement (sub task)

1.3 Concreting (sub task)

1.4 Etc. (sub task)

In Revit, it is possible to add parameters to the elements to describe the specific element which later can be filled in. For this method, it is necessary to add the parameter Task_ID to each element. As with the OmniClass system the actual link between task and elements need to be done manually. This can be done by filling the task numbers to the 4d_Task_ID parameter of the corresponding element. With this additional parameter, the elements can be selected and modified by searching for the task ID number in the model. An example of a concrete footing is shown in figure 7, the corresponding task is ‘Task ID 2’

This method is straightforward, easy to understand and easy to use. Task numbers can easily be attributed to specific elements and when selecting an element in Revit the related task number is immediately shown in the properties menu. The user can consult, when necessary, the FMEA interface to see which tasks are related to this specific element

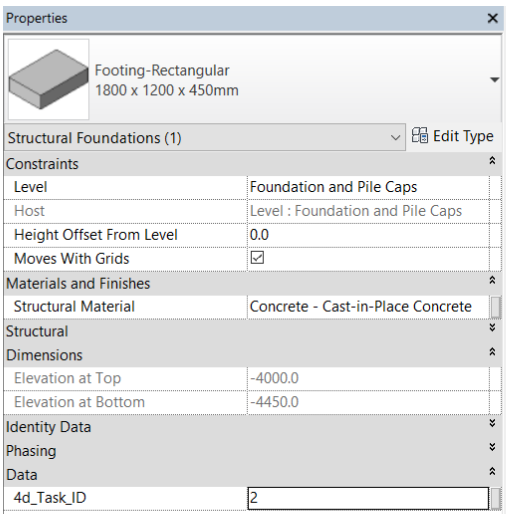


Figure 7 - Task ID parameters in Revit

3.3. Connection between FMEA interface and Revit

To translate the information from the FMEA interface to the 3D BIM model a visual programming software is used. It can link the colors generated based on the risks list, the tasks on the critical path and additional information to the Revit software in an automatic way enabling the user to see changes in the FMEA almost instantly in the 3D BIM model.

3.3.1. Visual programming

In general, a visual language can be described as a "formal language with a graphical notation". This means that it represents a modular system of signs and rules using visual elements instead of textual codes. Information systems described by a visual language can be interpreted much faster and easier by non-programmers which includes most of the stakeholders in a construction project. Visual programming languages are also often called flow-based. They replace the conventional coding with a visual metaphor by connecting small 'nodes' of independent functions displaying a flow of information. The most known software products in the construction sector are the plug-in Grasshopper for Rhinoceros3D, Dynamo for Autodesk Revit and Marionette for Vectorworks (Borrmann & Preidel 2016).

3.3.2. Dynamo module

Dynamo can be used as a stand-alone software or as a plug-in for Revit. It gives users the ability to visually script behavior, define custom pieces of logic, and script using various textual programming languages. Autodesk (2015) defines it as a visual programming extension that allows to manipulate data, sculpt geometry, explore design options, automate processes, and create links between multiple applications. Figure 8 shows the interface of the Dynamo software. The actual code is presented in the workspace in the middle of the screen. On the left, different packages of nodes can be selected to build the code and to let the data flow through the code a "run" button is present on the left bottom of the screen.

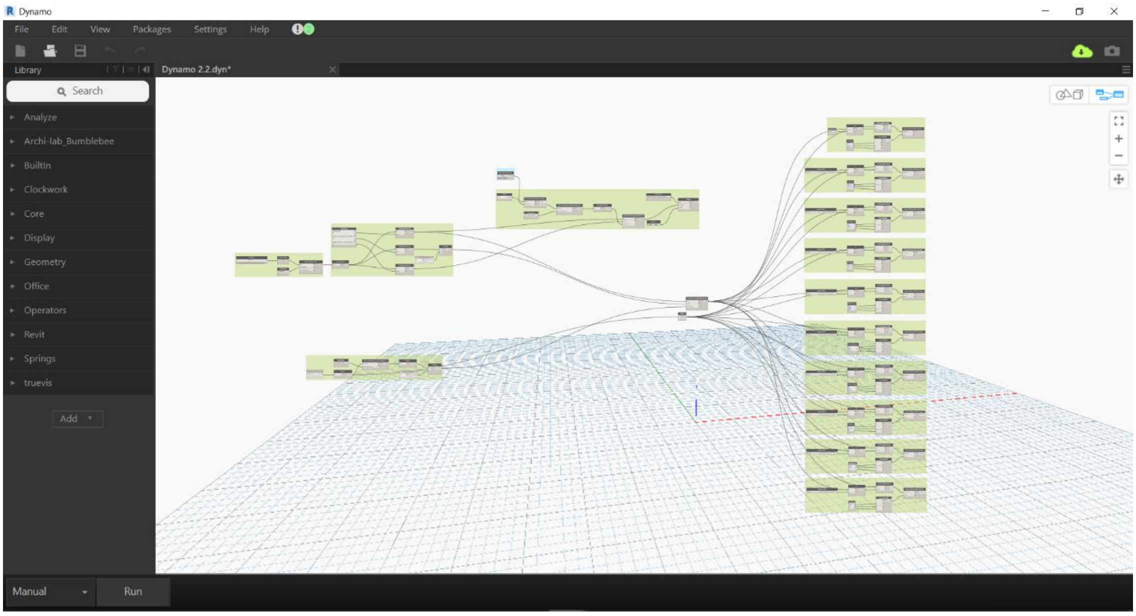
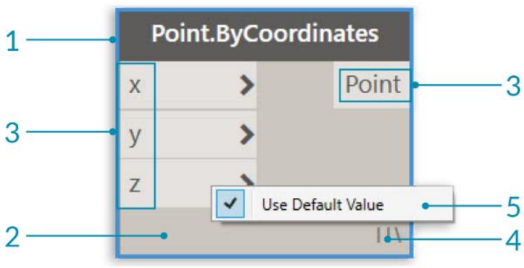


Figure 8 - Screen shot of the Dynamo interface

A Dynamo code is built by connecting nodes with wires in a workspace to specify a logical flow of the resulting visual program. Each node performs an operation, this can be as simple as storing a number or it may be a more complex action such as creating or querying geometry, see figure 9 for an example.

The inputs and outputs for nodes are called ports and act as the receptors for the wires. Data comes into the node through ports on the left and flows out of the node, after it has executed its operation, on the right. Ports expect to receive data of a certain type. For instance, connecting a number such as 2.75 to the ports on a 'Point By coordinates' node will successfully result in creating a point. However, if the name 'Blue' is inserted to the same port it will result in an error.



1. Name - The name of the node
2. Main - The main body of the node
3. Ports (In and Out) - The receptors for wires that supply the input data to the node as well as the results of the node's action
4. Lacing Icon - Indicates the lacing option specified for matching list inputs
5. Default Value - some nodes have default values that can be used or not used.

Figure 9 - Example node (Autodesk 2017).

Wires connect the output port from one node to the input port of another node. This establishes a flow of data in the visual program. Although the nodes can be arranged freely in the workspace, because the output ports are located on the right side of nodes and the input ports are on the left side, in general the program flow moves from left to right. Figure 10 shows an example to draw nine circles in an automatic manner. On the left the characteristics of these circles are inserted and the nodes in the middle allow that the circles will be drawn automatically. The node on the right shows the characteristics of the circles.

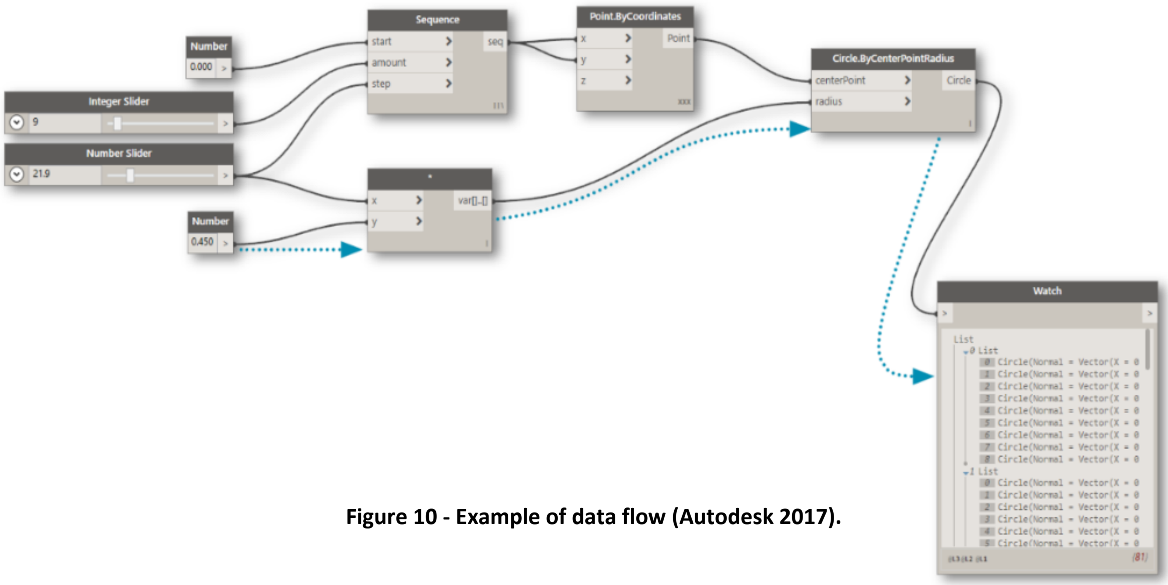


Figure 10 - Example of data flow (Autodesk 2017).

Dynamo has a built-in library where various node packages are available. Because Dynamo is an open software, nodes that are created by other users can be downloaded and used freely. However, if a node cannot be downloaded or is not available in the library, it is possible to create custom nodes with the Python programming language and add them in the Dynamo code, see figure 11. This can be very helpful to simplify the data flow or perform complicated tasks for which specific nodes aren't available (yet).

Edit Python Script...

```
#script 2
import clr
import sys

from System.Collections.Generic import *
# Import RevitAPI
clr.AddReference("RevitAPI")
import Autodesk
from Autodesk.Revit.DB import *

# Import DocumentManager and TransactionManager
clr.AddReference("RevitServices")
import RevitServices
from RevitServices.Persistence import DocumentManager
#from RevitServices.Transactions import TransactionManager

# Import ToDSType(bool) extension method
clr.AddReference("RevitNodes")
import Revit
clr.ImportExtensions(Revit.Elements)

doc = DocumentManager.Instance.CurrentDBDocument


viewcoll = FilteredElementCollector(doc).OfCategory(BuiltInCategory.OST_Views)
ex = []

for e in viewcoll:
    try:
        if e.IsTemplate == True:
            ex.append(e.Id)
    except:
        ex.append(e.Id)
ex = List[ElementId](ex)

collection = FilteredElementCollector(doc).WhereElementIsNotElementType().Excluding(ex).ToElements()

output = []
for e in collection:
    if e.Category != None:
        output.append(e)

OUT = output
```

Accept Changes | Cancel

Figure 11 - Python script of node 'selecting all elements' (screenshot Dynamo)

The role of Dynamo in the BIM-based risk management tool is to extract the data from the FMEA and convert this to specific elements in the 3D BIM model. The Dynamo software is chosen because it can read and extract data from an Excel file and, since it is a plug-in from Revit, is able to easily select and modify elements from the 3D BIM model. As described before, the link between the elements in the FMEA interface and the elements in the 3D BIM model is made by the common parameter Task ID. Dynamo will also provide a function that, when an element is selected, this element will be shown in a separate window with a pop-up message which contains the additional information entered in the FMEA interface. The main advantage of this is that the user will still get the full information that is needed even from (small) elements, for example lighting fixtures, that aren't very visible in the complete 3D BIM model.

The dynamo code used in the tool is created by several steps. First a list of elements is extracted from the Revit model, then the relevant information is extracted from the FMEA interface. After this, the information is compared and filtered and the 3D model is updated with the correct risk colors. The last step is the creation of a pop-up screen of a selected element with the corresponding additional information extracted from the FMEA interface.

<u>Step 1:</u> Extract information from Revit

The first step is to extract the elements from the 3D BIM model. This can be done in 3 ways.

- Select the elements manually using a node called “Select Model elements”;
- A more automated option is to select by category using a node called “All Elements of Category”; Figure 12 shows an example with the elements from the category structural foundations. By selecting all the categories that are present in the BIM model, all the elements are automatically selected. For all the elements that aren’t selected automatically an extra node “select model element” is added to select elements manually;
- Another method is to create a custom node using a python script that select all the elements in the model, see figure 11. Since not all the elements in the model are elements that are used directly for the construction this list will be much bigger than when selecting specific elements. Once the list of elements is obtained, the elements are sorted by the parameter “4d _Task_ID”

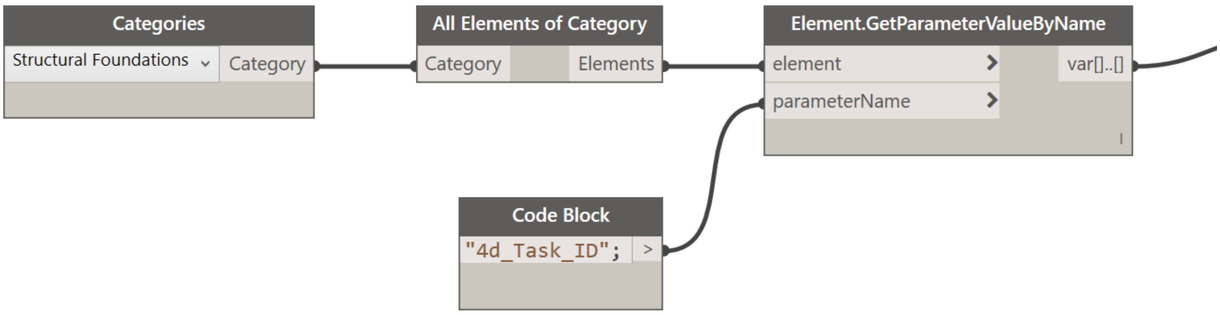


Figure 12 - Extraction information by selecting element categories (screenshot Dynamo)

<u>Step 2:</u> Extract information from Excel (figure 13)

In the FMEA interface, the four columns that are relevant for the connection with the 3D BIM model are the task ID, if a task is on the critical path, the Risk evaluation number (REN), and the column with additional information. They are linked to a different sheet in Excel to simplify the extraction of the information by Dynamo. The titles are removed and columns are placed next to each other so Dynamo can start reading the date from the first cell (A1). In Dynamo, it is more convenient to work with numbers than with text so in Excel, the risk evaluation is converted to a number between 1 and 9, see table 10. To extract the information from excel the node “File Path” is used where a file can be selected, then the node “Excel.readFromFile” will allow the program to get the information from the selected sheet. To ensure that Dynamo get the right column with information the node “List.GetItemAtIndex” is added where the desired column numbers are inserted by a code block. The result of this group of nodes are four lists with all the Task ID numbers, if the task is on the critical path, the REN and additional information.

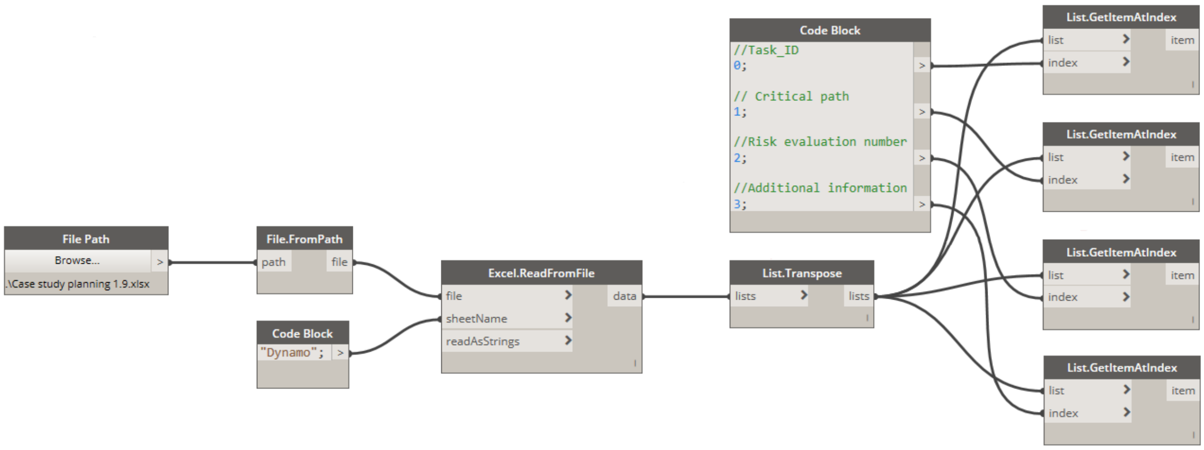


Figure 13 - Extraction of the information from Excel (screenshot Dynamo)

<u>Step 3:</u> Compare information from FMEA interface and Revit (figure 14)

To compare the information the node "Springs.Dictionary.ByKeysValues" is used which has three input lists and one output list. In the input "SearchKeys" the list of elements from Revit with their corresponding Task ID numbers is imported, (from step 1). In the input "Keys" the list of Task ID numbers from Excel is imported and in the input "Values" the list with REN is imported (both from step 2). Both lists that are taken from Excel have the same length and this node recognize that the first REN belongs to the first Task ID number, the second REN belongs to the second Task ID number etc. Then the node compares the Task ID numbers, and where they match, the element will receive the REN. Thus, the outcome of the node is a list with all the elements in the Revit model with their corresponding REN.

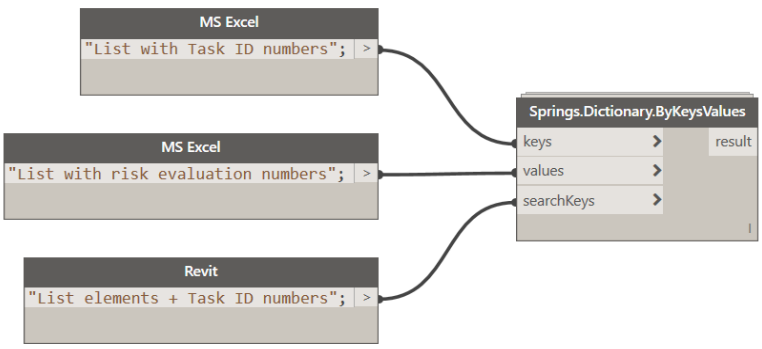


Figure 14 - Comparison of information (screenshot Dynamo)

Step 4: Filter the elements (figure 15)

The objective of this step is to filter the elements in 10 different groups (0 to 9) according to their REN. First the node "==" is used to compare the list with REN with a specific REN, in the example this number is 4. This node will create a list with true, for all the value's that match the number 4 and false for the rest of the numbers. Then, with the node "List.FilterByBoolMask" the list of all the elements in the 3D BIM model will be filtered where only the elements that are true will remain. Thus, the outcome of this node is a list with all the elements that have a REN of 4. This filtering process is repeated for all the REN between 0 and 9 where 0 refers to elements without a REN.

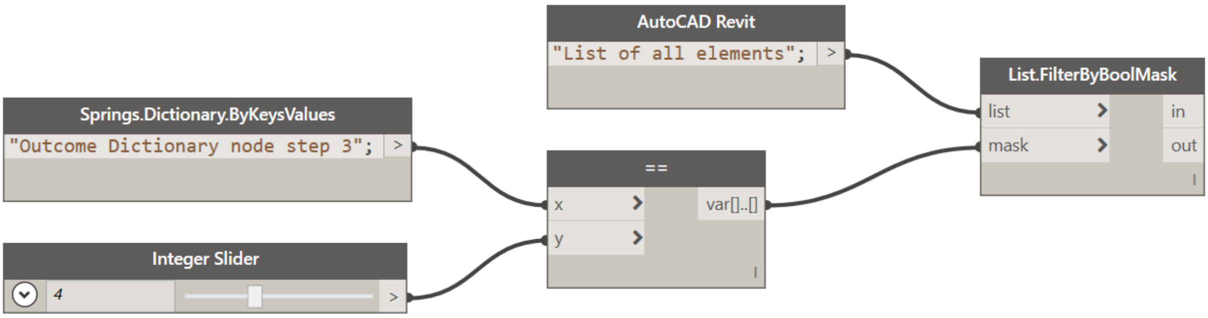


Figure 15 - Filter of the elements (screenshot Dynamo)

Step 5: Update 3D BIM model with colors and transparency (figure 16)

To update the BIM model with the specific risk colors the node "Element.OverrideColorInView" is used. In the input "elements" the list of elements from the node "List.FilterByBoolMask" is used as discussed in step 4. This results in a list of elements with the same REN. In the input "color" the desired color of the element is specified by its corresponding RGB code, see Table 10. To add transparency, a list of elements with tasks that are not critical is obtained from Excel with the same procedure as described is step 4. This list is compared with the list from the node "Element.OverrideColorInView". The node "SetIntersection" compares the two lists and will create a new list with elements that are present on both the input lists. This results in a list with elements that have the same REN and are not on the critical path. The elements of this list will receive the same risk color and by using the node "OverrideGraphicSettings.ByProperties" a transparency is added. This filtering process is repeated for all the REN between 1 and 9.

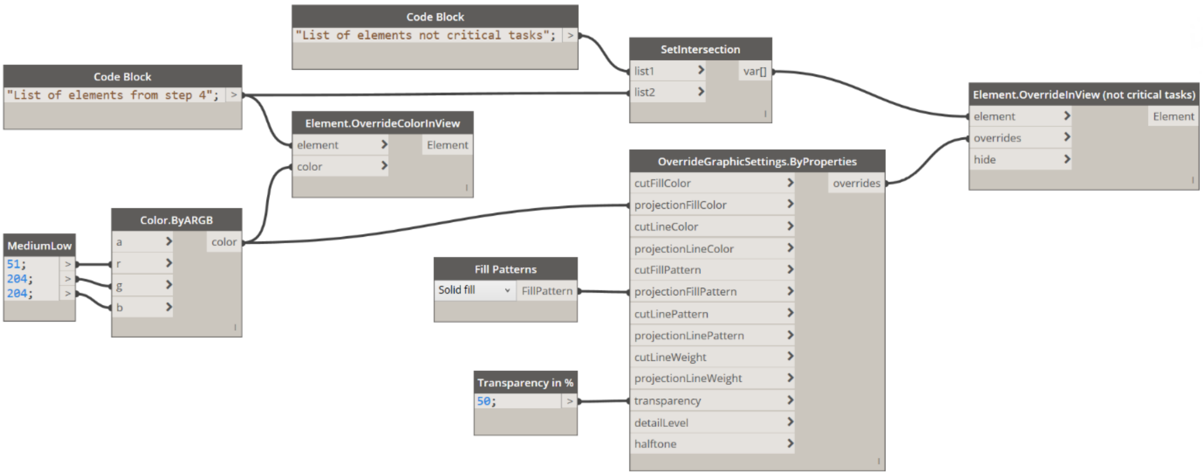


Figure 16 - Update BIM model with colors (screenshot Dynamo)

Step 6: Isolate element in separate window (figure 17)

To isolate a specific element in a separate window, the node “Element.TemporarilyIsolateInView” is used. In this node, the view can be chosen by connecting the node “views” to the input of the node. In this case, a 3D view of the element is chosen. To select the element that needs to be shown in the separate window the node “Select Model Element” need to be connected to the input “element”. The user needs to select a specific element that he wants to study more carefully by clicking on the “change” button after which he can select an element in the 3D BIM model.

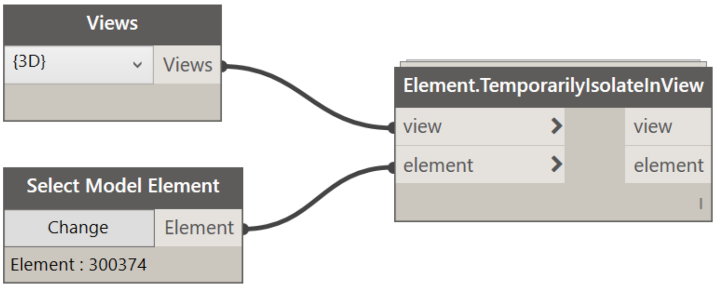


Figure 17 - Isolate element in separate window (screenshot Dynamo)

Step 7: Adding a pop-up message with additional information

The message with additional information will pop-up in the 3D BIM model when an element is selected and shown in a separate window, see figure 18 for an example.

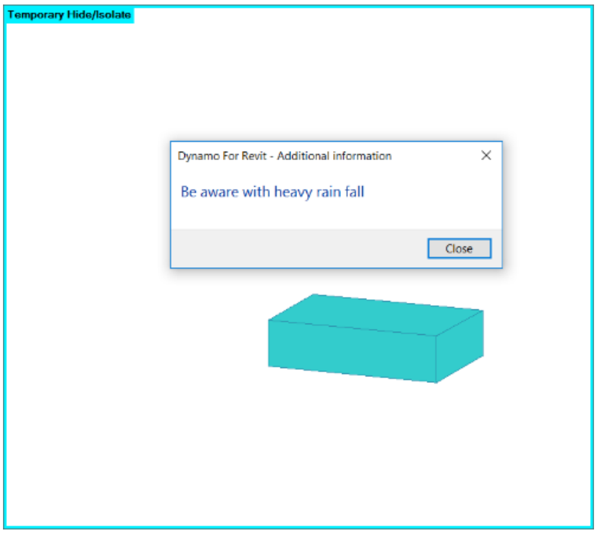


Figure 18 - Temporary view in Revit (screenshot Revit)

Therefore, the node “Select Model Element” is the same as in step 6. To know which message needs to be shown with which element a link need to be made between the task in the FMEA interface and the element in Revit. This link is the common value of the Task ID number and as in step 3 the node “Springs.Dictionary.ByKeysValues” is used. The input “searchKeys” is the task ID number directly taken from the selected element by the node “Element.GetParameterValueByName”. The input “Keys” is given by the list Task ID numbers and the input “Values” is given by the list Additional information as described in step 2. The “Springs.Dictionary.ByKeysValues” node will filter the list with additional information and by the comparison of the Task ID numbers the corresponding information will be linked to the selected element. To show the message in Revit the node “Dialog” is used. the input “Message” is the output of the node “Springs.Dictionary.ByKeysValues”. The title of the pop-up message is given by a code block which is “Additional information”. The input for “runMe” is a Boolean which indicates if the message need to be shown, true means to show the message and false means not show the message. The group of nodes is presented in figure 19.

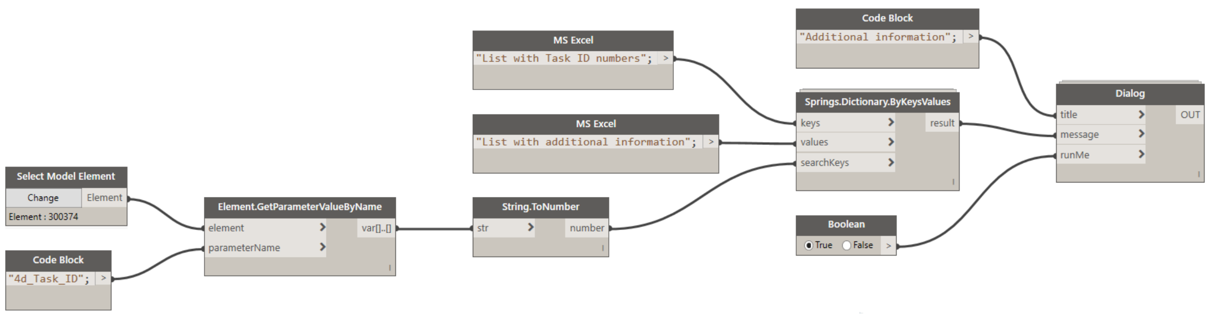


Figure 19 - Adding a pop-up message (screenshot Dynamo)

Figure 20 summarizes the Dynamo process. In practice, the user should just run the dynamo software to update the colors in the 3D BIM model. If a user wants to inspect a specific element and receive the adjoining information the user need to select an element using Dynamo (step 7) and run the software again. The complete Dynamo code is presented in Annex I.

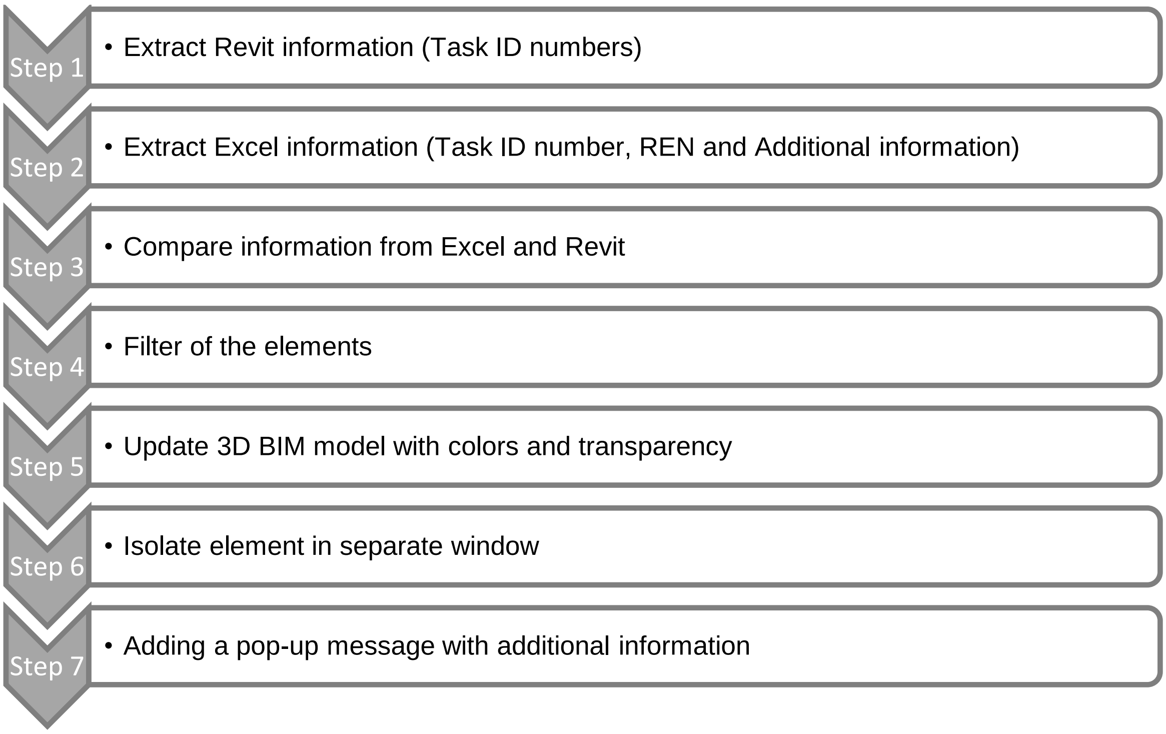


Figure 20 - Summary of the Dynamo process

3.4. Development of the 4D Model

Within Navisworks, a 4D model can be created by linking a construction schedule with a 3D BIM model using the Timeliner option. The construction schedule can be imported directly from MS Project or by Excel using a .CSV file. Since the REN are added in the FMEA interface it is advisable to use the .CSV file. In Navisworks the different columns of the FMEA interface can be linked to the default columns in Navisworks. To do so, the information contained in the .CSV file must be separated by commas. The default separation by Excel is point-comma, this is due to the regional configuration of the operating system. To overcome this problem, the .CSV file must be opened in the application notepad. This application contains a 'search' and 'replace all' option which allows the user to easily replace all the point-commas by regular comma's. In figure 21 the linking of the Navisworks columns with the FMEA interface columns is presented. On the left, the default columns of Navisworks are presented and on the right in the column 'External Field Name' the columns from the FMEA interface can be inserted. In this case, for example in row 4, the column 'Synchronized ID' in Navisworks is linked to the column 'Task_ID' in the FMEA interface.

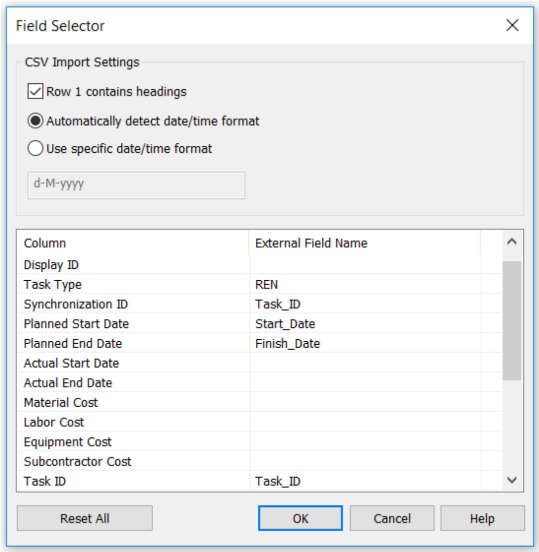


Figure 21 - Link between Navisworks and FMEA interface columns (screenshot Navisworks)

The link of the tasks imported from the construction schedule and the elements from 3D model must be made again manually. This can be done in a straightforward manner since the elements in the BIM model already have a task ID number. In Navisworks it is possible to search elements based on their parameters. In figure 22 an example is given to find all the elements with the Task ID number ‘2’. In the “Find Items’ application the category and property (parameter) are selected. Then the value ‘2’ is inserted and by clicking on the ‘find all’ button all the elements with the parameter ‘2’ are selected. These group of elements can then be saved as a ‘search set’. Afterwards, the search sets can be linked to the corresponding tasks in the construction schedule where search set ‘2’ will be linked to tasks 2.1, 2.2, 2.3 and 2.4. The advantage of this way of linking is that when a change is made in the BIM model this also changes in the 4D Model.

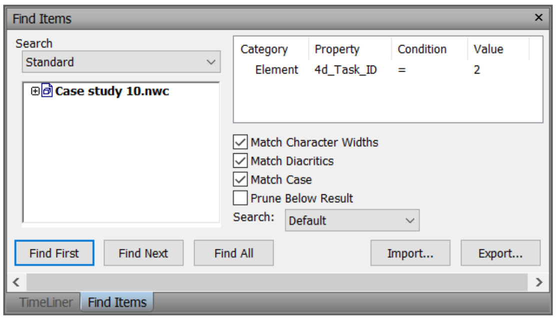


Figure 22 - Searching for parameters (screenshot Navisworks)

To change the color of the element with the corresponding risk evaluation the column ‘Evaluation number’ (FMEA interface) is linked with the column ‘Task type’ (Navisworks), see figure 21. In Navisworks the different task types can be assigned to the same evaluation colors as proposed in table 10 in the Timeliner option “configure”.

All the tasks with this task type (REN) will change to the color evaluated in the FMEA interface. In figure 23 all the columns used in Navisworks are presented. The columns ‘Task_ID’, ‘Name’, ‘Planned Start’, ‘Planned End’ and ‘Task Type’ (REN) come directly from the FMEA Interface. In the column ‘Attached’ the search sets as described above are inserted according to their corresponding tasks.

Active	Task_ID	Name	Planned Start	Planned End	Attached	Task Type
☑		⊟ **New Data Source (Root)**	16-12-2016	20-6-2017		
☑	1	Soil	16-12-2016	20-1-2017		6
☑	1.1	Preparing terrain	16-12-2016	16-12-2016	Sets->1	5
☑	1.2	Excavating foundation	19-12-2016	21-12-2016	Sets->1	5
☑	1.3	Refilling soil	20-1-2017	20-1-2017	Sets->1	6
☑	2	Footings	22-12-2016	29-12-2016		9
☑	2.1	Formwork footings	22-12-2016	23-12-2016	Sets->2	8

Figure 23 - Columns used in Navisworks (screenshot Navisworks)

In Navisworks there is a simulation option to show the model in various stages of the construction. As stated before, an element can have different tasks with different risks along the construction period. With this 4D model these different risks are made visible and for each moment in the construction process the risk involved at that time is shown in the model.

3.5. Tool guidelines

The tool is mainly designed to be used before the construction stage. This is also the phase where possible risk measures can have a bigger influence with a smaller investment. When the design and the construction schedule are finished, the tool can be used and the results can be distributed to the stakeholders involved. The guidelines for the tool to use in this phase are described in section 3.5.1. It is not uncommon that, during the construction, the design and/ or the construction schedule change. When this is the case the tool need to be updated, the steps to be taken in this situation are described in section 3.5.2.

3.5.1. Tool use before the construction phase

Several steps need to be taken to run the BIM-based risk management tool. The steps are chronologically sorted in figure 24 based on the software that is involved.

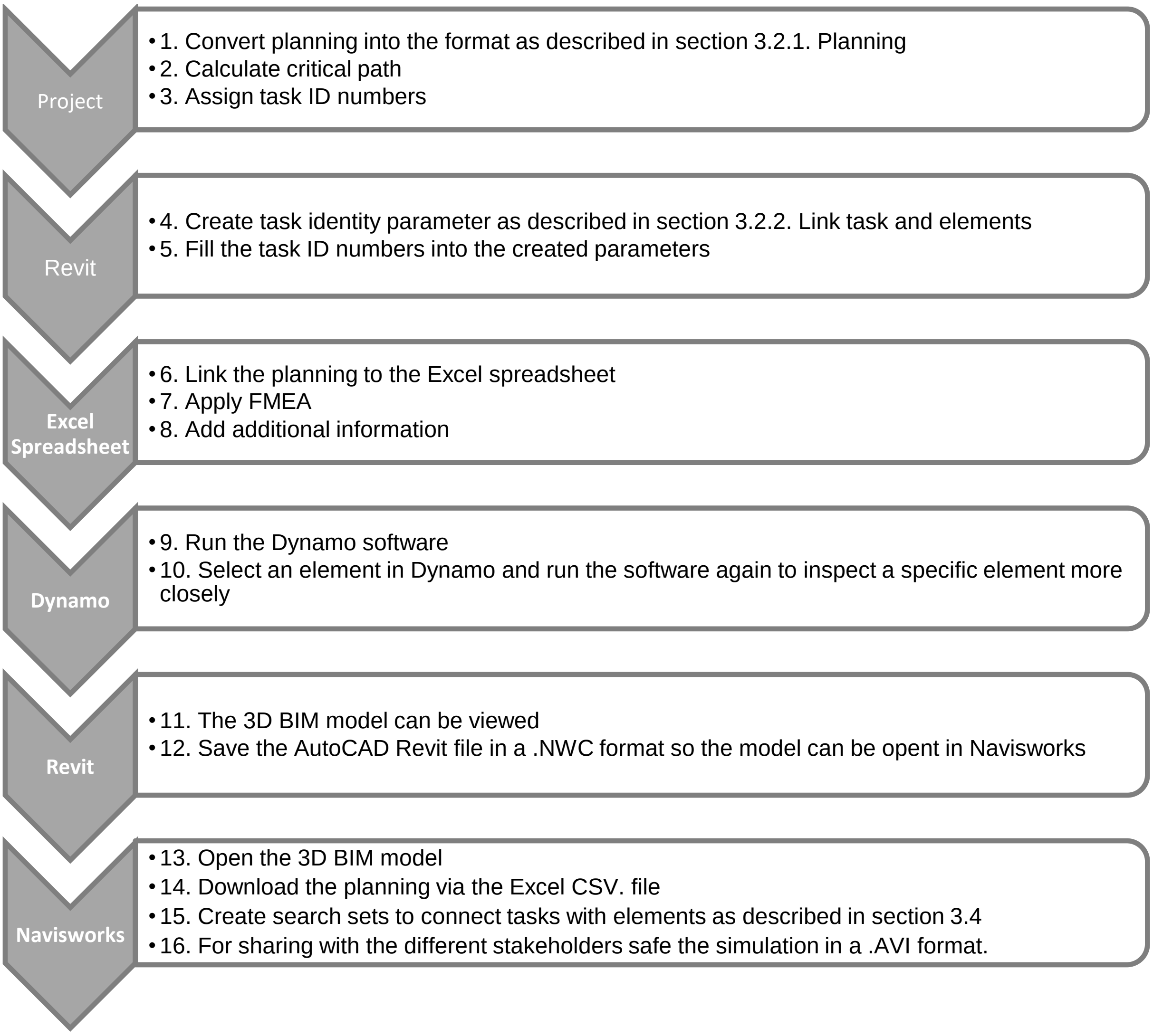


Figure 24 - Steps to take for running the BIM-based risk management tool

3.5.2. Tool use during the construction phase

During the construction phase, several things can change when compared to the initial situation. The possible changes and the steps to take accordingly are presented in table 14. With some of the changes run the software is enough, meaning running the Dynamo software, save the updated BIM model to .NWC and run the Navisworks simulation.

Table 14 - Steps to take while dealing with changes during construction

Changes	Steps to take
Changes in FMEA	• Run the software
Change in the additional information in the FMEA interface	
Evaluation in FMEA interface changes, for example risk evaluation 'low' when RPN<20	
Characteristics of elements in the design change	
Change in construction schedule while task ID numbers remains the same, for example critical path changes	• Load construction schedule again in FMEA interface • Update FMEA • Load FMEA interface into Navisworks • Run the software
Change in construction schedule with extra tasks or a change in task ID numbers	• Load construction schedule again in the FMEA interface • Link the changed task numbers to their corresponding elements in Revit and Navisworks • Update FMEA • Run the software
Change in design with the addition of already existing element types, for example an extra internal wall	• Link the added element to the existing tasks • Run the software
New elements and new tasks added	• Load construction schedule again in FMEA interface • Link the changed task numbers to their corresponding elements in Revit and Navisworks • Update FMEA • Run the software

4. Pilot case

The BIM-based risk management tool is tested in a pilot case of a BIM model plus a construction schedule of a residential house. First the construction schedule is modified into the correct format and exported to the FMEA interface where the FMEA is applied. Then the evaluation is exported to Revit and Navisworks and finally the results are discussed.

4.1. Description Pilot case

The prototype of the tool has been tested on a Revit model of a large T3 residential house. It has 2 floors and an area of 325 m2. The ground floor has a bathroom, a dining room, a kitchen and a closet. The first floor has two bedrooms including one with a suite (a bathroom and a dressing), another bathroom, an office and a weight room. A view of the pilot case is shown in figure 25. This model was created for experimental reasons.

The objective is to perform different simulations with different risk scenarios to check the efficiency of the tool and the color code system. The simulations are made based on the task identity numbers. The tool is used according to the instructions presented in the previous paragraph.

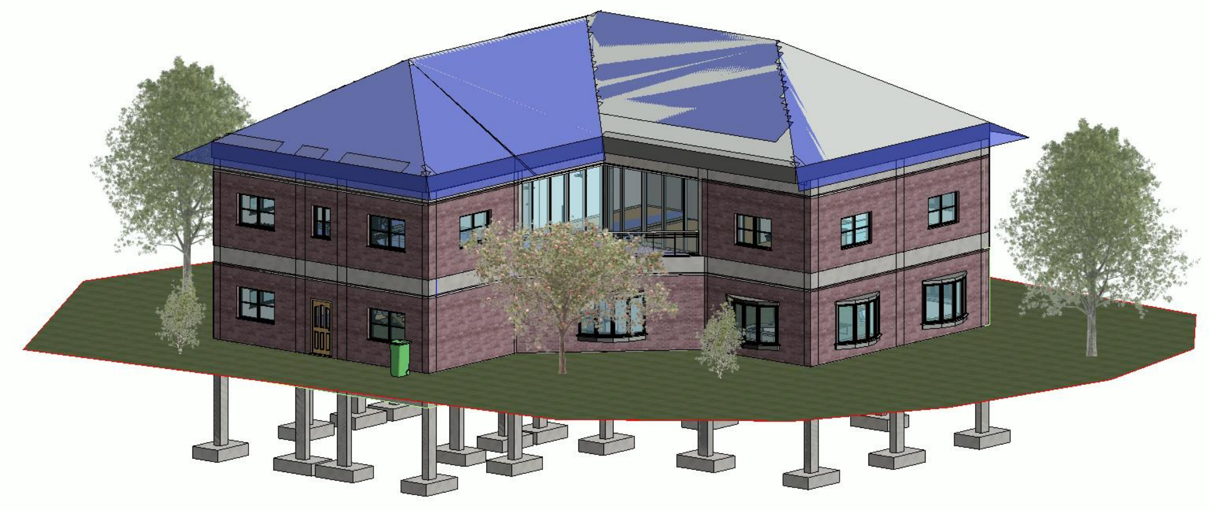
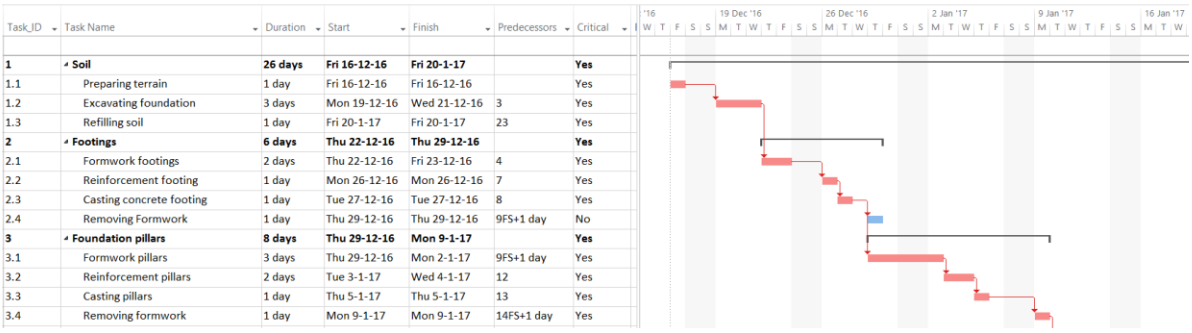


Figure 25 - View of the pilot case BIM model

4.2. Construction schedule

Before the FMEA, a fictitious simplified construction schedule was built within MS Project with for each task, a Task ID number, name, duration, start and finish date and predecessors. A screenshot of a part of the construction schedule is shown in figure 26. In the construction schedule embedded elements are not included since they won't be visible in the model. On the left of the figure several tasks and their corresponding information is presented and the right part shows a Gantt chart of these tasks. The critical path is automatically calculated within MS Project and presented in the Gantt chart with a red color. The Revit model has an element approach, which implies that all the objects are already at the finished state, therefore the construction schedule is constructed in such a way that the round numbers directly relate to an element or a specific group of elements and the numbers after the point relate to the tasks needed to construct the element.



Task_ID	Task Name	Duration	Start	Finish	Predecessors	Critical
1	**Soil**	**26 days**	**Fri 16-12-16**	**Fri 20-1-17**		**Yes**
1.1	Preparing terrain	1 day	Fri 16-12-16	Fri 16-12-16		Yes
1.2	Excavating foundation	3 days	Mon 19-12-16	Wed 21-12-16	3	Yes
1.3	Refilling soil	1 day	Fri 20-1-17	Fri 20-1-17	23	Yes
2	**Footings**	**6 days**	**Thu 22-12-16**	**Thu 29-12-16**		**Yes**
2.1	Formwork footings	2 days	Thu 22-12-16	Fri 23-12-16	4	Yes
2.2	Reinforcement footing	1 day	Mon 26-12-16	Mon 26-12-16	7	Yes
2.3	Casting concrete footing	1 day	Tue 27-12-16	Tue 27-12-16	8	Yes
2.4	Removing Formwork	1 day	Thu 29-12-16	Thu 29-12-16	9FS+1 day	No
3	**Foundation pillars**	**8 days**	**Thu 29-12-16**	**Mon 9-1-17**		**Yes**
3.1	Formwork pillars	3 days	Thu 29-12-16	Mon 2-1-17	9FS+1 day	Yes
3.2	Reinforcement pillars	2 days	Tue 3-1-17	Wed 4-1-17	12	Yes
3.3	Casting pillars	1 day	Thu 5-1-17	Thu 5-1-17	13	Yes
3.4	Removing formwork	1 day	Mon 9-1-17	Mon 9-1-17	14FS+1 day	Yes

Figure 26 - Construction schedule (screenshot MS Project)

Table 15 describes the construction schedule with all the tasks that are used in the pilot case.

Table 15 - Construction schedule

Task_ID	Name	Task_ID	Name
1	**Soil**	**7**	**Pillars first floor**
1.1	Preparing terrain	7.1	Formwork pillars
1.2	Excavating foundation	7.2	Reinforcement pillars
1.3	Refilling soil	7.3	Casting pillars
2	**Footings**	7.4	Removing Formwork
2.1	Formwork footings	**8**	**Beams first floor**
2.2	Reinforcement footing	8.1	Formwork beams
2.3	Casting concrete footing	8.2	Reinforcement beams
2.4	Removing Formwork	8.3	Casting concrete beams
3	**Foundation pillars**	8.4	Removing Formwork
3.1	Formwork pillars	**9**	**Slab second floor**
3.2	Reinforcement pillars	9.1	Formwork slab
3.3	Casting pillars	9.2	Reinforcement slab
3.4	Removing formwork	9.3	Casting concrete slab
4	**Foundation slab**	9.4	Removing formwork
4.1	Formwork foundation slab	**10**	**Pillars second floor**
4.2	Reinforcement foundation slab	10.1	Formwork pillars
4.3	Casting concrete foundation slab	10.2	Reinforcement pillars
5	**Raft foundation**	10.3	Casting pillars
5.1	Formwork raft foundation	10.4	Removing Formwork
5.2	Reinforcement raft foundation	**11**	**Beams second floor**
5.3	Casting raft foundation	11.1	Formwork beams
6	**Slab first floor**	11.2	Reinforcement beams
6.1	Formwork slab	11.3	Casting concrete beams
6.2	Reinforcement slab	11.4	Removing Formwork
6.3	Casting concrete slab		
6.4	Removing Formwork		

Task_ID	Name	Task_ID	Name
12	**Upper floor**	**17**	**Doors/ windows**
12.1	Formwork slab	17.1	Placing windows/ door exterior
12.2	Reinforcement slab	17.2	Placing doors interior
12.3	Casting concrete slab	**18**	**Stairs**
12.4	Removing Formwork	18.1	Placing stairs
13	**Roof**	**19**	**Railing**
13.1	Execution of roof	19.1	Placing railling
14	**External walls**	**20**	**Sanitary**
14.1	Laying exterior masonry	20.1	Placing sanitary
15	**Internal walls**	**21**	**Kitchen**
15.1	Laying internal masonry	21.1	Placing kitchen equipment
16	**Finishes**		
16.1	Wall finishing		
16.2	Floor finishing		
16.3	Ceilling finishing		

4.3. FMEA interface

Considering that the construction schedule and the interface are made in Microsoft software, the link between them is easily established by paste special -> Microsoft Project Document Object. Due to this link, any changes in the construction schedule are, after saving, immediately changed in the FMEA interface. In the pilot case the FMEA is filled with random values between 1 and 9. By choosing random values all the possible color outcomes can be tested. Per element an additional comment is added to check if the tool processes this information in a right way. The complete FMEA Interface as used in the pilot case is presented in Annex II.

4.4. Dynamo automation

The pilot case is a relatively small project, that is why it is possible to use a node that select all the elements in the model without the list getting too long. This node had to be programmed by a python script. A lot of elements, for example reference planes, zones, viewpoints etc. are selected by this node but do not have any use in the tool. Later these elements are filtered out of the Dynamo code since they do not have a Task ID number. Therefore, their evaluation will be “null” and will get a white color. This method of selecting all the nodes at ones is preferable because it is completely automatically regardless the model that is used. This means that it is much faster compared to selecting all the elements per category and it will reduce the chances greatly that the user will miss some elements.

4.5. Navisworks

The 3D BIM model was imported into Navisworks and the construction schedule was downloaded as a .CSV file into the Timeliner. After connecting the tasks with their respective elements, the simulation could be shown. In the simulation, only the elements are shown that are constructed at that moment in the timeline or already have been constructed. So, during the simulation the model is built up slowly as it would in reality. This process shows clearly if the elements are connected correctly to their tasks. If this is not the case, the Task ID numbers in Revit need to be adjusted and the model must be loaded again into Navisworks. Because the search sets are already created the model just need to be saved and the simulation could be performed again. The simulation proofed to be a good tool to easily check if all the connection between tasks and elements are correctly done.

4.6. Results and discussion

4.6.1. Results

In figures 27 to 30, the 3D BIM model is shown with the risk evaluation colors. The internal walls, doors/ windows, stairs railing and the kitchen received, besides their risk color, a transparency of 50% since they exist of tasks that are not critical. The model shows that the Dynamo code is functioning and that all the elements have their correct risk color and transparency. There are some elements that did not change color, for example the trees and the furniture. They were selected by Dynamo but did not receive a risk evaluation since the elements are not included in the construction schedule. Therefore, they are attributed by the color white (REN “null”, see table 10) as it is shown in the model. The test with the updated elements is proven positive as all the elements are colored as they should.

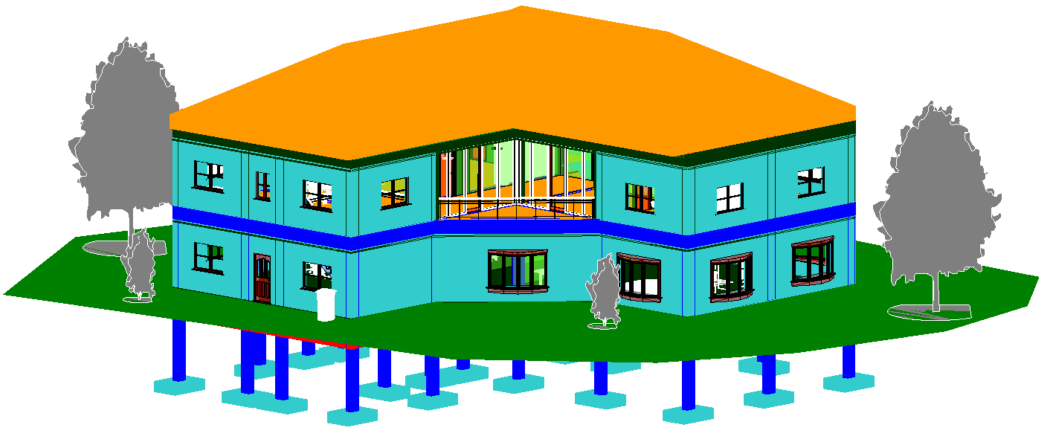


Figure 27 - 3D view of the updated 3D BIM model

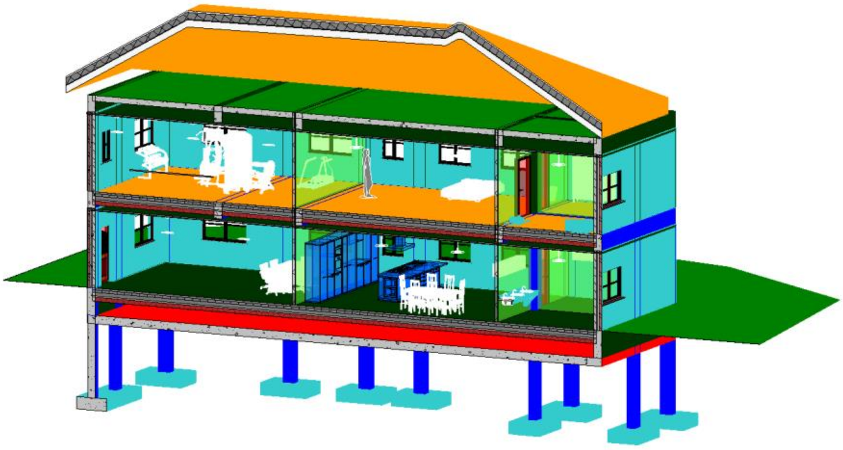


Figure 29 - Section of the updated 3D BIM model

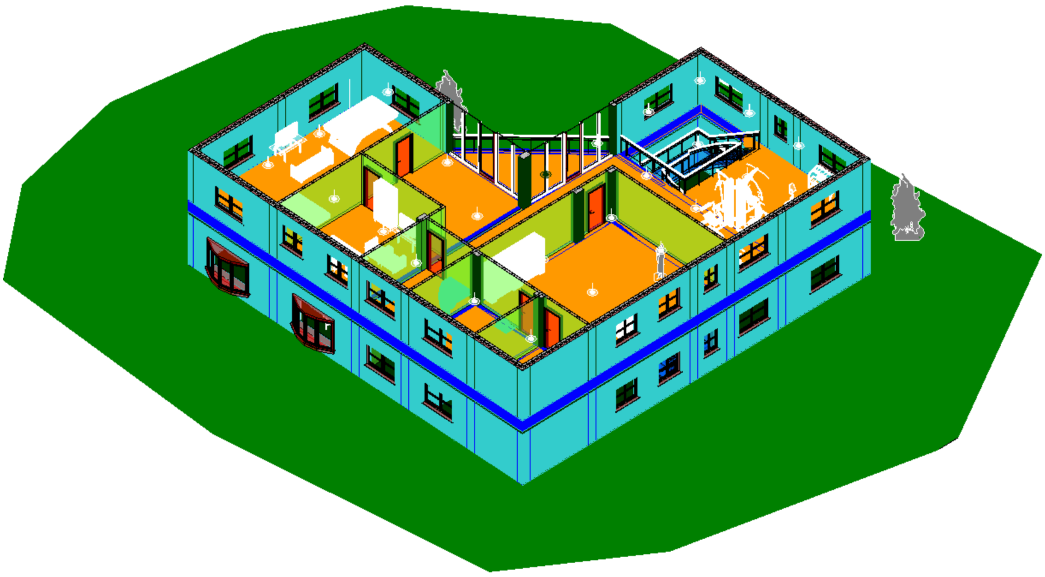


Figure 30 - Section of the updated 3D BIM model

In figure 18 a temporary view of a selected element (footing) with its additional information is shown. The information, as filled in the FMEA interface, is shown in a pop-up screen as it is intended. If the user wants even more information, it can select an element in Revit where the properties panel will show its Task ID number. By checking the FMEA interface, the user can easily identify which element corresponds to which tasks and can consult the corresponding FMEA results.

Although the colors are not the same as in the original model, the views can still be used as it was before. By selecting the 'Visual style' icon several styles can be selected to show the model. As different users/ stakeholders have different interests in the model, the views can be made accordingly to the user preferences. A great tool is the sectioning box which allows the user to watch sections of the model, see figure 29 and 30. Images of specific parts of the model can be taken and shared among stakeholders that have not the necessary software to see the model in Revit.

In Navisworks the 4D simulation shows all the elements that have a Task ID number, in the right order and with the correct color, see figure 31 and 32. The biggest advantage of the 4D part of the tool is that at the user can address the risk for any specific day or even hour see table 16. The simulation can be stopped and the Timeliner will show the date, the tasks that are performed, how far the task is completed in percentages and the model will show the specific risk colors for that moment. When an element is finished, the element will take the risk color of the last task that is performed on that element. During the simulation in Navisworks it is possible to look around the model, zoom in on specific elements and create sections for better visibility. A video can be made from the model in a .AVI format and shared among the stakeholders that have not the necessary software to view the simulation in Navisworks. A screenshot of the video from the pilot case is shown in figure 33. The exact date and time are shown in the top left corner.

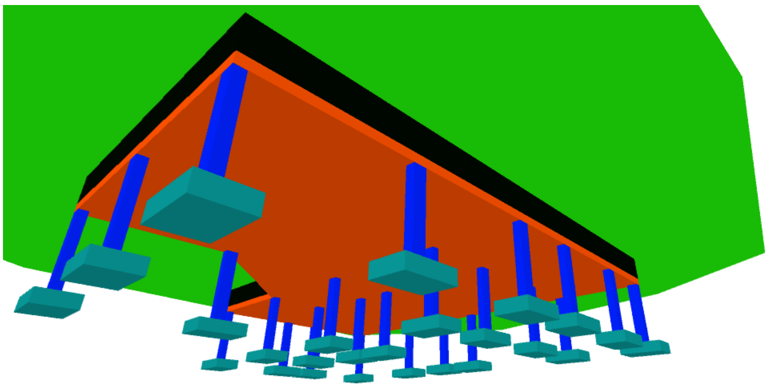


Figure 31 - Zoom of the foundation in the 4D model

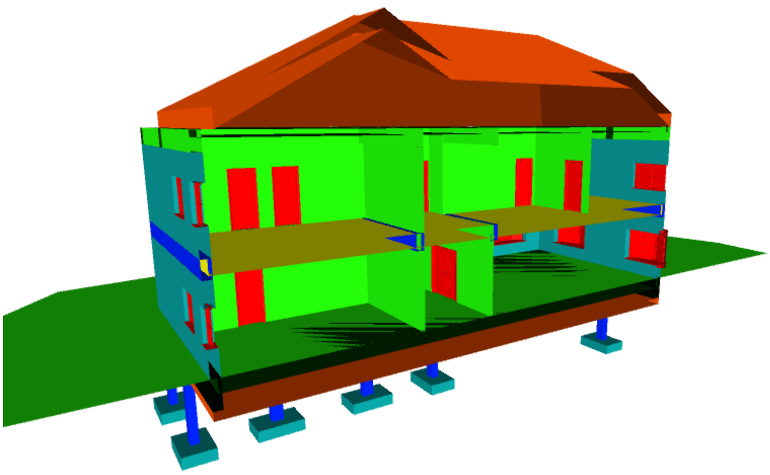
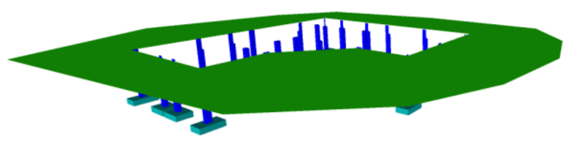
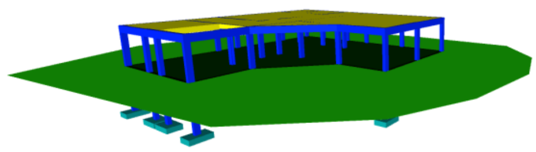
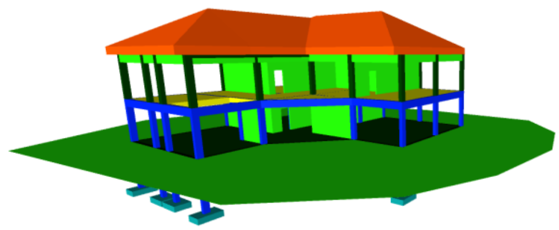
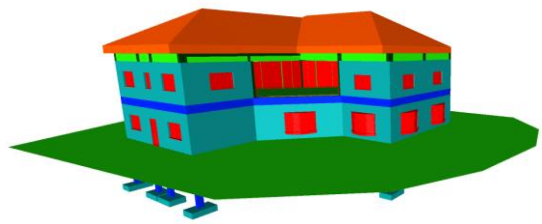


Figure 32 - Cross section of the 4D model

Table 16 - Screen shots of the 4D model

 1.	 2.
 3.	 4.

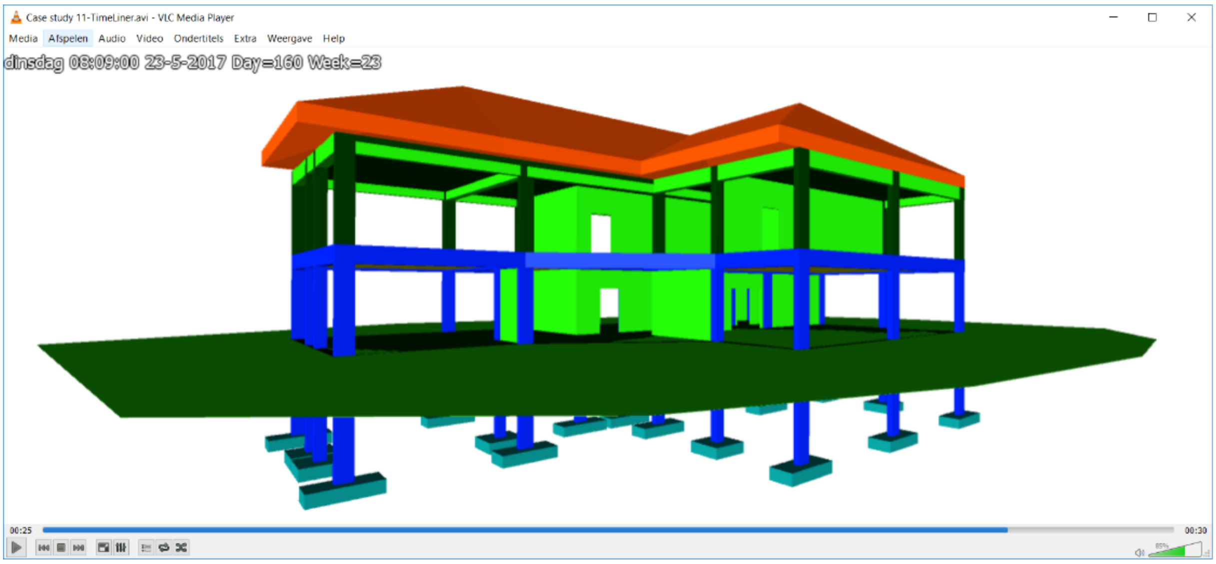


Figure 33 - Screen shot of a video from the 4D model

4.6.2. Limitations

By testing the tool with a pilot case several limitations came to the surface. The main limitation of the BIM-based risk management tool is related to the amount of tasks the user must perform to run the tool. For example, the Task ID numbers need to be filled in manually in Revit and in Navisworks. For a small project this is relatively an easy task but for complex project this can become very time consuming. Because of the non-automated connection between tasks and elements a small change in the (beginning) of the construction schedule can cause a lot of work changing all the Task ID numbers. Another point of interest is the amount of software involved in the tool which cause a few limitations. The user need to have the license for the software, knows how to use them and must perform several tasks for the software to communicate with each other. A good example is that the user need to save the construction schedule in a .CSV file, adapt it for Navisworks to read it, load it into Navisworks and correctly link the columns of the construction schedule with the default columns of Navisworks. These are various steps that can cause some time just to link two software's with each other.

For a complete overview of the risks and their consequences several software need to be consulted. An ideal scenario would be that there is one 4D model that contains all the information. The main results are now shown in the 3D BIM model with some extra information in the FMEA interface, but since multiple tasks can relate to one element and this element will take the color of the most severe risk, some essential information is lost. Within the 4D model this problem does not exist, but this software does not have the possibility to open a specific element in a separate view and show the additional information. Another example of the loss of information is the possibility to show the tasks that lay on the critical path by giving them a transparency. In the 4D model it is not possible to give the colors transparency and in the 3D BIM model multiple tasks relate to one element which can compromise the actual value of this modification.

Another limitation of the tool is the poor visibility of small or embedded objects. For example, the sewerage system is not visible in the 3D view of the model. This is partly resolved by the temporary view option, but then the user still must select the element manually which interferes with the goal of the tool to have a model with all the risks in one clear overview.

The tool focusses on the negative side of the risks. The opportunities that risks can provide are not included. Also, the link that time overruns have on the cost risks are not visualized in the tool. The influence of slacks in the construction schedule or cumulative time risks are not included in the model and if the user wants to have more information about this it must consult the schedule software. This is a limitation because it contradicts the goal of the tool to have all the information in one model.

5. Conclusions

5.1. Final considerations

The thesis aimed to provide a deeper insight on the role of BIM in managing risks in the construction industry. Based on the literature research conducted on the role of Risk management and BIM this objective is pertinent and synergies can be created between these two methodologies. This thesis focusses on the development of a tool that can be used by construction managers to have a better overview of the risks and their severity and can improve the communication between different stakeholders. This objective is fulfilled by the development of a BIM-based risk management tool using the FMEA technique to analyze the several risks and a 3D BIM model and a 4D model to show the considered risks.

The tool was tested using a pilot case and has shown that it effectively allows visualizing the risk degrees of specific elements of the construction using a color code system. During the pilot case, all the analyzed risks were shown in the 3D BIM model and a video could be produced of the construction phase with the involved risks shown at any time during the construction of the building. The established color code system proved to be efficient since it reflected “hot” areas where severe risks can occur that need some extra attention of the stakeholders. Further research is necessary to get a better insight in the real efficiency of the tool and its proposed risk colors.

The tool can be used prior to the construction phase to help managers to adapt the construction process and determine if, and where extra preventive measures are necessary. The 4D model can help visualize risks for a specific period and can improve the personnel and equipment planning to reduce and or control specific risks. It is likely that there will be some modifications to the design and construction schedule during construction. Section 3.5.2. describes the adaptations that the user need to perform to the tool to update the 3D and 4D model. Depending on the change this can be a simple or comprehensive task to do.

The BIM-based risk management tool can be an efficient communication tool. The models and the FME interface constitutes reliable information that the manager can provide to different stakeholders such as the client, subcontractors and workers. The BIM model not only can provide a 3D overview of the project but can also provide a zoom of a specific area or a section or plan view. This gives them user more flexibility to choose the appropriate view.

The tool is as much as possible automated to decrease the changes for errors and will decrease the time the user must spent on the use of the tool. The parts that are not automated are tried to be kept simple so the tool use is accessible to any manager. An example is the use of visual programming which is simpler and easier to handle than the traditional programming.

The thesis demonstrated the potential of BIM technology and how visual programming can enlarge its capabilities. It also shows that BIM can be a valuable visualization support instrument. The failure mode effect analysis is a widely-accepted risk evaluation method and can be used perfectly in combination with the proposed tool. The 3D BIM model and the 4D model provide the user an overview which can be easily analyzed, documented and discussed with all the relevant stakeholders in an efficient and clear way. Having a visual support can have a more adequate impact of the risk managers' reaction. Seeing a zone with red/ orange colors will not only give the indication that there are some potential high risks, it also provides information about the location.

As discussed in section 2.3.3, there is more research already performed on the visualization of information during construction. Some studies propose a color-based visualization to rank information such as Mushamalirwa (2016) and Kang et al. (2013). Other studies were more focused on the safety aspect of a construction project, such as Zhang & Hu, (2011), Park & Kim, (2013), Zhang et al. (2013), Zhou et al. (2013). The tool proposed in this thesis distinguishes itself by focusing on time and cost in a 3D and 4D environment using a color code system to visualize the degree of risk. In conclusion, it can be confirmed that the BIM-based risk management tool as proposed in this thesis is unique and innovative and can contribute to improve the understanding of risks in construction projects.

5.2. Challenges

One of the major challenges when facing BIM is to know how to connect the different software and explore their potential. Visual programming could be considered complex for professionals of the industry without strong programming skills. One of the most interesting features in Dynamo is that it is an open software and so, there is also an open community sharing Dynamo nodes already programmed, which can be easily imported to the application. It is relevant to refer that there is not full interoperability between the different software used, as it is the case of Dynamo and Navisworks. Dynamo cannot be used directly with Navisworks so to attribute risk colors to the elements a different solution need to be used. By importing the REN as a construction type via the .CSV file this connection is possible to be made.

Mushamalirwa (2016) proposed an EVM/BIM tool with a comparable structure of using different colors to visualize information from an Excel sheet in a BIM model. In that research work three challenges were identified, the manually linking of tasks and elements, the loss of information while linking multiple tasks to one elements, and the non-automated selection of elements in the Dynamo code. The automatic linking of the tasks with the elements remains unsolved. Still today this topic is an international issue that is debated in the research field, mainly because information is not fully organized yet which makes it difficult to link different types of information. By using Task ID numbers, an acceptable method is applied which is easy to use although the user still must fill in the parameters manually. Another challenge to solve was the loss of information while linking multiple tasks to one element. By creating a 4D model this problem was tackled because different tasks can be visualized in the same element over a period of time. The challenge of selecting all the Revit elements at ones in the Dynamo code was addressed by creating a custom node with the python script which could select all the elements at once.

5.3. Further developments

The pilot case as proposed in this thesis demonstrated that the tool is working and shows that it is possible to create a visualization tool in a straightforward manner and that it potentially can be a valuable tool for risk management in construction projects. For a definitive proof that the tool will be useful for risk managers, more research need to be performed on a real construction site with different type of projects.

One of the limitations of the tool is the poor visibility of small or embedded elements. An interesting study could be to apply this BIM-based risk management tool to more robust structures such as bridges and road overpasses. These structures often have less details and small elements which will them more suited for a risk visualization tool as proposed in this thesis.

The tool can also be used based on different risks. In the proposed tool the BIM model is updated with time and cost risks based on a FMEA. However, the following variances could be considered based on the preferences of the user

- Different types of risk;
- More risks involved in the model;
- Time and cost risks can be shown in two different models;
- Different type of analysis;
- Use for temporary structures.

These variances can all be adopted with a few changes in the FMEA interface or the Dynamo code. This can be a huge advantage since it gives the user more freedom to work with different types of construction projects and different aspects of the managing part of the construction.

Since the proposed tool is a conceptual model, it is not user friendly yet. The user needs to perform many tasks to get an outcome which compromises the value of the tool. There is a big open area that can be developed, mainly by programmers, to reduce the amount of steps the user must take. Also, the creation of one single 4D model in which all the information is stored would be a great improvement in terms of user friendliness

Another challenge that remains is the link between tasks and elements. The OmniClass system shows great potential and is already considered a valuable system in the classification of elements in construction management. If the OmniClass system could be further developed to a system where the numbers also describe the context and characteristics of the elements it could attribute to the standardization of the linking between tasks and elements in this tool.

6. References

Ahmed A., Kayis B., Amornsawadwatana S. (2007). A review of techniques for risk management in projects. *Benchmarking an International Journal*, vol. 14(1), pp. 22–36.

Aksamija, A., & Iordanova, I. (2011). Computational environments with multimodal representations of architectural design knowledge. *International journal of architectural computing*, vol. 8(4), pp. 439-460.

AUTODESK (2015). *This is Dynamo*. [online] Available from: http://dynamobim.org/download/ [Accessed: 15th March 2017]

AUTODESK (2017). *The Dynamo Primer*. [online] Available from: http://dynamoprimer.com/en/03_Anatomy-of-a-Dynamo-Definition/3-1_dynamo_nodes.html [Accessed: 15th March 2017]

Azhar, S. (2011). Building Information Modeling (BIM) - Trends, benefits, risks, and challenges for the AEC industry*. Leadership and Management in Engineering*, vol. 11(3), pp. 241-252.

Baloi, P. & Price, A. (2003). Modelling global risk factors affecting construction cost performance. *International Journal of Project Management*, vol. 21(4), pp. 261–269.

Banaitiene, N., & Banaitis, A. (2012). *Risk Management in Construction Projects*. Vilnius Gediminas Technical University, Vilnius, Lithuania.

Borrmann, A., Preidel, C. (2016). Towards code compliance checking on the basis of a visual programming language. *Journal of Information Technology in Construction,* vol. 21, pp. 402-421.

Bryde, D., Broquetas, M., Volm, J.M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management*, vol. 31, pp. 971-980.

Bryde, D., & Volm, J. (2009). Perceptions of Owners in German Construction Projects: Congruence with project risk theory. *Construction Management and Economics*, vol. 27(11), pp. 1059-1071.

Carlson, c. s. (2012), *Effective FMEAs: Achieving safe, reliable, and economical products and processes using failure mode and effect analysis*; John Wiley & Sons INC., Hoboken, New Jersey, USA.

Carmona, J., & Irwin, K. (2007). *BIM: Who, What, How and Why*, Building Operating Management. [online] Available from: http://www.facilitiesnet.com/software/article/BIMwho-what-how-and-why--7546# [Accessed: 4th August 2017]

Chapman, C., & Ward, S. (2004). Why risk efficiency is a key aspect of best practice projects. *International Journal of project management,* vol. 22(8), pp. 619-632.

Chin, K.S., Wang, Y.M., Poon, G.K.K. & Yang, B.J. (2009). Failure mode and effects analysis using a group-based evidential reasoning approach. *Computers & Operations Research*, vol. 36, pp. 1768-1779.

CRC Construction Innovation. (2007). *Adopting BIM for facilities management - Solutions for managing the Sydney Opera House*. Cooperative Research Center for Construction Innovation, Brisbane.

De Maio, A., Verganti, R. and Corso, M. (1994). A multi-project management framework for new product development. *European Journal of Operational Research*, vol. 78 (2), pp. 178-91.

De Reyck, B., Degraeve, Z., Vandenborre, R. (2008). Project options valuation with net present value and decision tree analysis. *European Journal of Operational Research*, vol. 184, pp. 341-355.

Deutsch, R. (2011). *BIM and Integrated Design: Strategies for Architectural Practice;* John Wiley & Sons INC., Hoboken, New Jersey, USA.

Dodge data & Analytics (2015). *Measuring the impact of BIM on complex building.* SmartMarket report, Bedford, England.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. (2011) *BIM Handbook, A Guide to Building Information Modeling for owners, managers, designers, engineers and contractors. Second edition*. John Wiley & Sons Inc, New Jersey, USA

El-Sayegh, S. M. (2008). Risk assessment and allocation in the UAE construction industry. *International Journal of project management,* vol. 26(4), pp. 431-438.

Eric Choen Weng Lou & Jack Steven Goulding (2008) Building and Construction Classification Systems, *Architectural Engineering and Design Management,* vol. 4:3-4, pp. 206-220.

Forbes, D., Smith, S. & Horner, M. (2008). Tools for selecting appropriate risk management techniques in the built environment. *Construction Management and Economics. vol.* 26, pp. 1241-1250.

Gehner, E. (2008). *Risicomanagement in de interne bedrijfsvoering van projectontwikkelaars*. ASRE Onderzoeksseminar, Amsterdam, the Netherlands.

Guikema, S., William, I. (2009). Managing Construction Projects Using the Advanced Programmatic Risk Analysis and Management Model, *Journal of Construction Engineering and Management,* vol. 135(8), pp. 772–781.

Halman, J. (2008). *Risicomanagement in de bouw: nieuwe ontwikkelingen bij een aantal koplopers*. Aeneas, Boxtel, the Netherlands.

Hammad, D.B., Rishi, A.G., Yahaya, M.B. (2012). Mitigating construction project risk using Building Information Modelling (BIM). *Procs 4th West Africa Built Environment Research (WABER) Conference*, 24-26 July 2012, Abuja, Nigeria, pp. 643-652.

Hartmann, T., van Meerveld, H., Vossebeld, N., Adriaanse., A. (2012). Aligning building information model tools and construction management methods. *Automation in Construction*, vol. 22, pp. 605-613.

Hogganvik I., Stølen K. (2006) A Graphical Approach to Risk Identification, Motivated by Empirical Investigations. In: Nierstrasz O., Whittle J., Harel D., Reggio G. (eds) Model Driven Engineering Languages and Systems. MODELS 2006. Lecture Notes in Computer Science, vol 4199. Springer, Berlin, Heidelberg

Howard, B. (2013). *Microsoft Project 2013 Plain & Simple.* O'Reilly Media, Inc. Sebastopol, California, USA

ISO 8402: 1994 *Quality management and quality assurance- vocabulary.* Geneva: International Organization for Standardization, 1994.

ISO 31000: 2009. *Risk management – Principles and guidelines*. Geneva: International Organization for Standardization, 2009.

Jamieson, B., & Jones, A. (2013). *Impressions from Applying ISO 31000 to an Avalanche Mitigation Project.* University of Calgary, Calgary, Canada.

Joint Technical Committee OB/7 (1999). *Risk Management AS/NZS 4360:1999*; Standards Association of Australia, Strathfield, Australia.

K. Sigalov, M. König, Recognition of process patterns for BIM-based construction schedules, *Adv. Eng. Informat.* (2017).

Kang, L.S., Kim, S., Moon, H.S., Kim, H.S. (2013). Development of a 4D object-based system for visualizing the risk information of construction projects. *Automation in Construction*, vol. 31, pp. 186-203.

Keizer, J.A., Halman, J.I.M., Song, M. (2002). From experience: applying the risk diagnosing methodology. *The journal of Product innovation management,* vol. 19, pp. 213-232.

KIM, H., ANDERSON, K., LEE, S. & HILDRETH, J. (2013) Generating construction schedules through automatic data extraction using open BIM (building information modelling) technology. *Automation in Construction, vol.* 35, pp. 285-295.

Kliem, R. L., & Ludin, I. S. (1997). *Reducing project risk.* Gower Publishing Ltd., Hampshire, England.

Kolarevic, B. (2009). Towards Integrative Design. *International journal of architectural computing*, vol. 7(3), pp. 335-344.

Lin, J.J., Golparvar-Fard, M. (2016). *Web-Based 4D Visual Production Models for Decentralized Work Tracking and Information Communication on Construction Sites*. Construction Research Congress 2016, San Juan, Puerto Rico.

Liu, H., Liu, L., Liu, N. (2013) Risk evaluation approaches in failure mode and effects analysis: A literature review. *Expert Systems with Applications,* vol. 40 (2013), pp. 828–838

Marcelino-Sádaba, S., Pérez-Ezcurdia, A., Lazcano, A. M. E., & Villanueva, P. (2014). Project risk management methodology for small firms. *International Journal of project management,* vol. 32(2), pp. 327-340.

McGraw-Hill Constructions. (2010). *The business value of BIM in Europe*. SmartMarket report, Bedford, England.

Mecca, S., Masera, M. (1999). Technical risk analysis in construction by means of FMEA methodology. *Association of Researchers in Construction Management*, vol. 2, pp. 425-434.

Mushamalirwa, A-M., N. 2016. 'A BIM-based solution to support Earned Value Management in Construction' Master thesis, Instituto Superior Técnico Lisboa

National Building Information Model Standard Project Committee (2016). *WHAT IS A BIM?,* National BIM- standard- United States, [online] Available from: https://www.nationalbimstandard.org/faqs#faq1 [Accessed: 2nd August 2016]

OMNICLASS. (2006) OmniClass™ - Introduction and User's Guide. Edition 1.0. [Online] 28th March 2006. Available from: http://www.omniclass.org/tables/OmniClass_Main_Intro_2006-03-28.pdf. [Accessed: 5th January 2017]

Park, C. & Kim, H. (2013). A framework for construction safety management and visualization system. *Automation in Construction*, vol. 33, pp. 95-103.

Peláez, J. B. (1995). Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. *Reliability Engineering and System Safety*, pp. 200-213.

Project Management Institute. (2008). *A guide to the Project Management Body of Knowledge (PMBOK® GUIDE*). PMI Book Service Center, Atlanta, USA.

Purdy, G. (2010). ISO 31000: 2009, setting a new standard for risk management. *Risk analysis, vol. 30*(6), pp. 881-886.

Sacks, R., Barak, R., Belaciano, B., Gurevich, U., Pikas, E. (2012). KanBIM Workflow Management System: Prototype implementation and field testing. *Lean Construction Journal 2013,* pp. 19-35.

Scannell, T., Curkovic, S., & Wagner, B. (2013). Integration of ISO 31000: 2009 and Supply Chain Risk Management. *American Journal of Industrial and Business Management,* vol. 3(04), pp. 367.

Schieg, M. (2006). Risk Management in Construction Project Management*. Journal of Business Economics and Management*, vol. VII (2), pp. 77-83.

Serpella, A. F., Ferrada, X., Howard, R., & Rubio, L. (2014). Risk Management in Construction Projects: A Knowledge-based Approach. *Procedia-Social and Behavioral Sciences,* vol. 119, pp. 653-662.

Singh, V., Gu, N., & Wang, X. (2011). A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction*, vol. 20, pp. 134-144.

Sousa, V., De Almeida, N. M., & Dias, L. A. (2012). Risk management framework for the construction industry according to the ISO 31000: 2009 standard. *Journal of Risk Analysis and Crisis Response,* vol. 2(4), pp. 261-274.

Tah, J. y Carr, V. (2001). Knowledge-Based Approach to Construction Project Risk Management. *Journal of Computing in Civil Engineering*, vol. 15(3), pp. 170-177.

Technische Raad van TVVL. (2011). BIM: Toren van Babel? *TVVL Magazine Ontwerpen*, vol. 5, pp. 30.

Tomek, A., Matějka, P. (2014). The impact of BIM on risk management as an argument for its implementation in a construction company*. Procedia Engineering*, vol. 85, pp. 501-509.

Uher, T. E., & Toakley, A. R. (1999). Risk management in the conceptual phase of a project. *International Journal of project management, vol. 17*(3), pp. 161-169.

Van Well-Stam, D., van Kinderen, S., & van den Bunt, B. (2013). *Risicomanagement voor projecten: de RISMAN methode toegepast.* Uitgeverij Unieboek Het Spectrum Bv, Houten- Antwerpen, Belgium.

Zhang, J.P., Hu, Z.Z. (2011). BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in Construction*, vol. 20, pp. 155-166.

Zhang, S., Teizer, J., Lee, J., Eastman, C.M., Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, vol. 29, pp. 183-195.

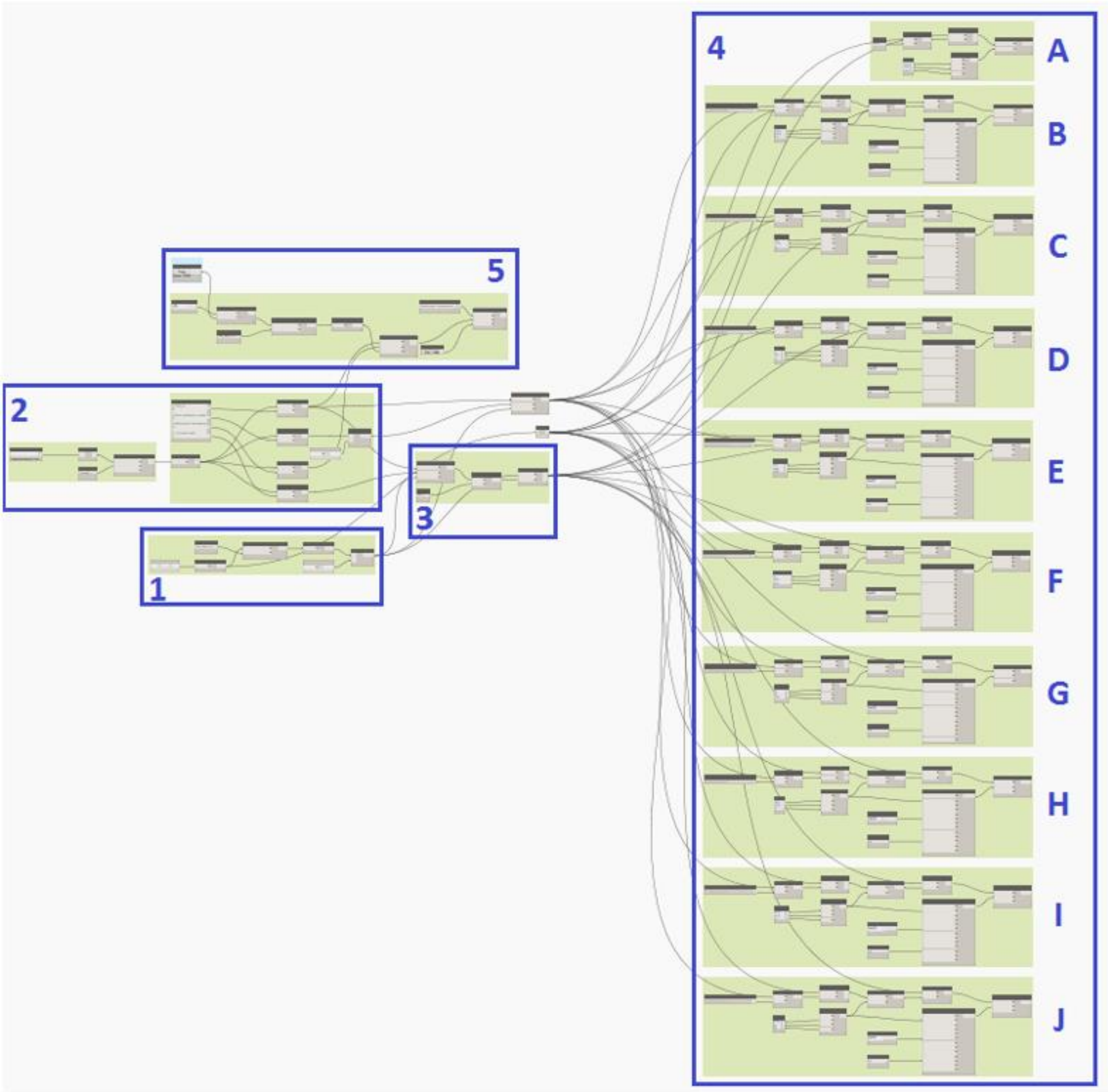
Zou, Y., Kiviniemi, A., Jones, S.W. (2016) A review of risk management through BIM and BIM-related technologies. *Safety Sci. 2016.*

Zhou, Y., Ding, L.Y., Chen, L.J. (2013). Application of 4D visualization technology for safety management in metro construction. *Automation in Construction*, vol. 34, pp. 25-36.

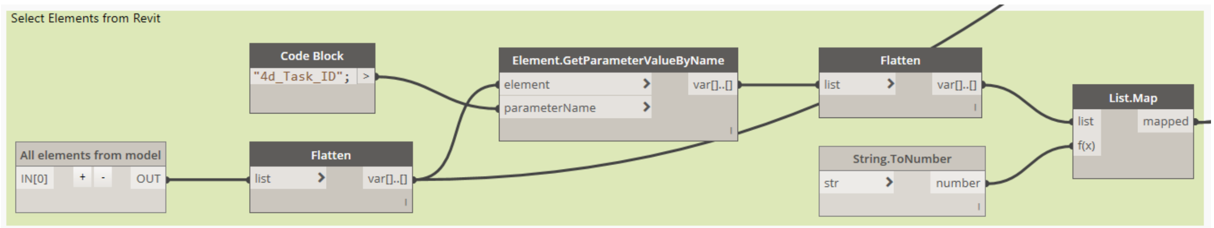
7. Annexes

Annex I: Dynamo Code

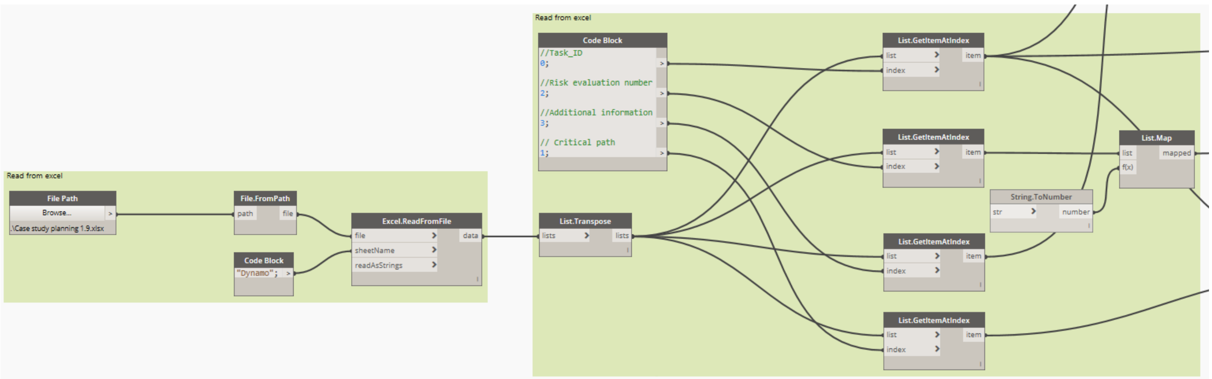
Dynamo code



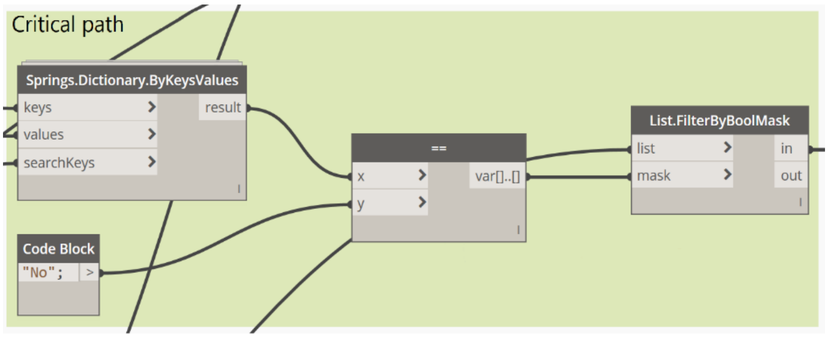
1: Read elements from Revit model



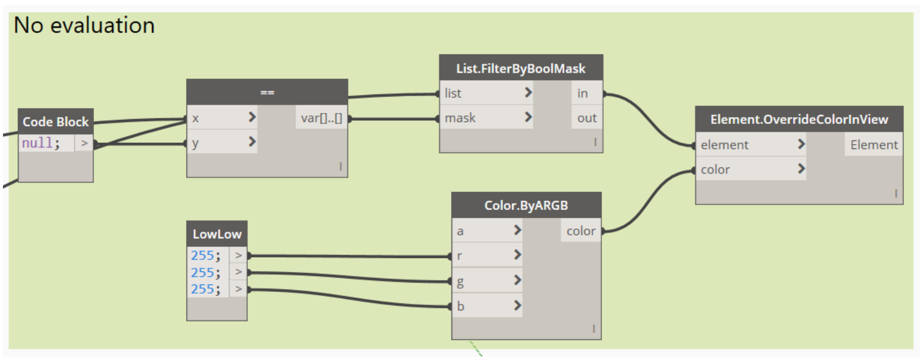
2: Read elements from Excel



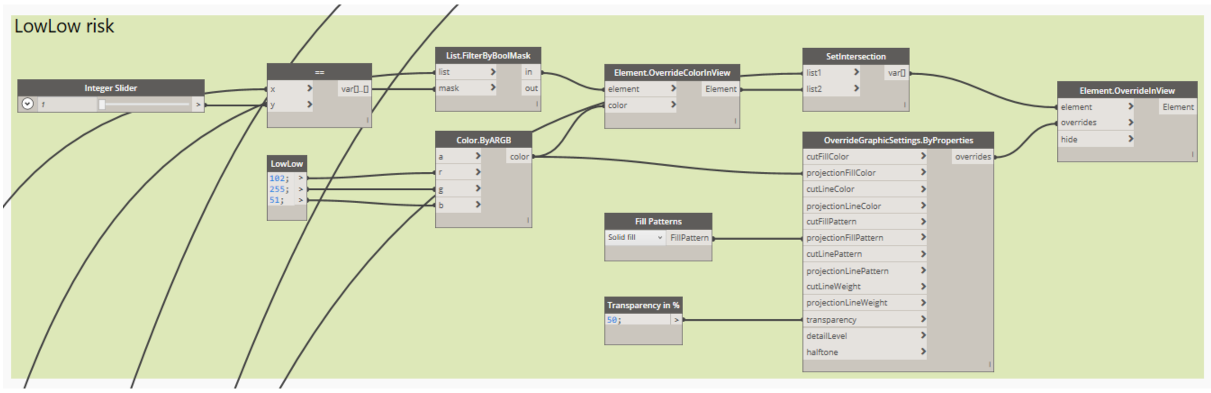
3: Filter elements with task that are not critical



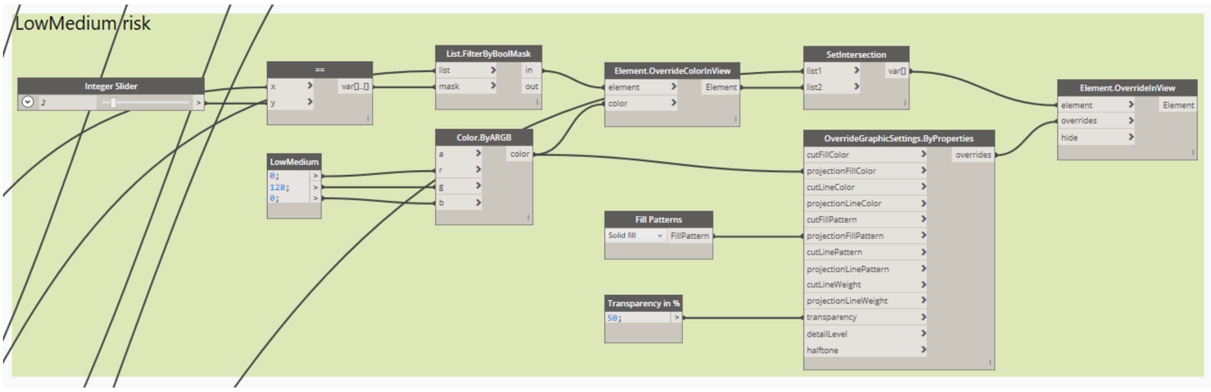
4A: Override element with risk color “no evaluation”



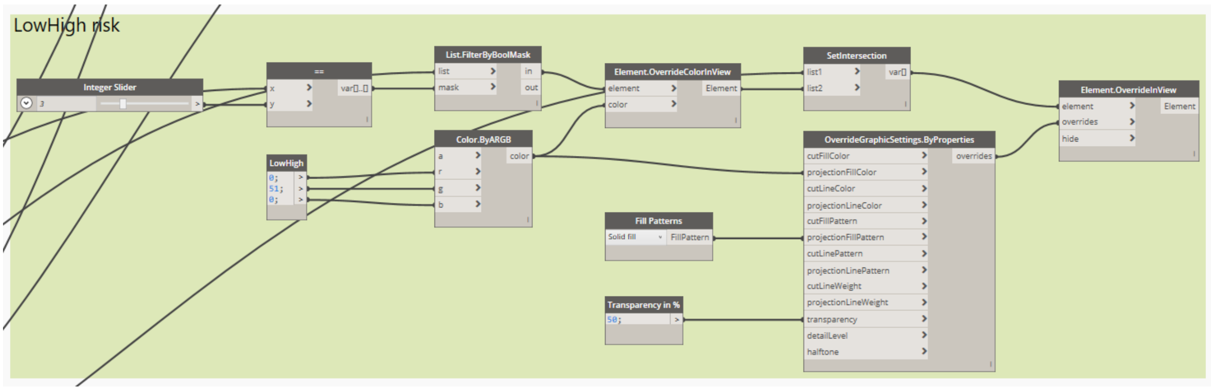
4B: Override element with risk color “LowLow”



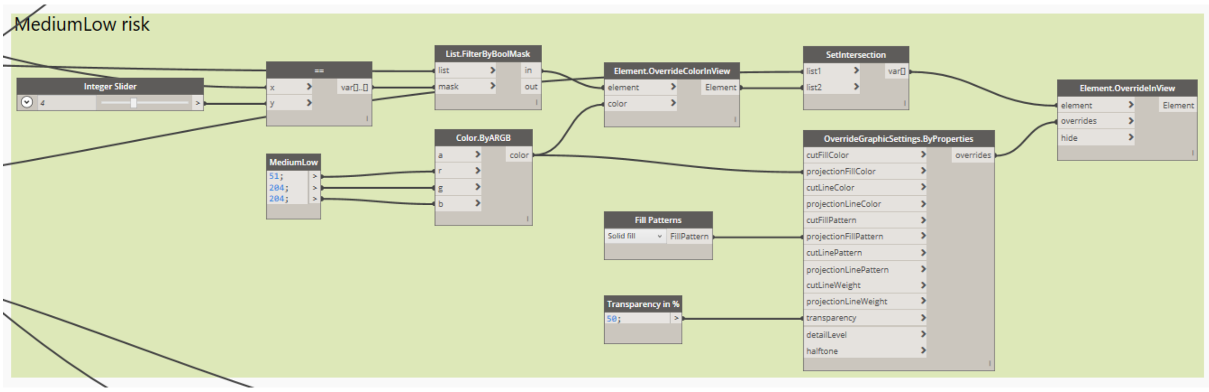
4C: Override element with risk color “LowMedium”



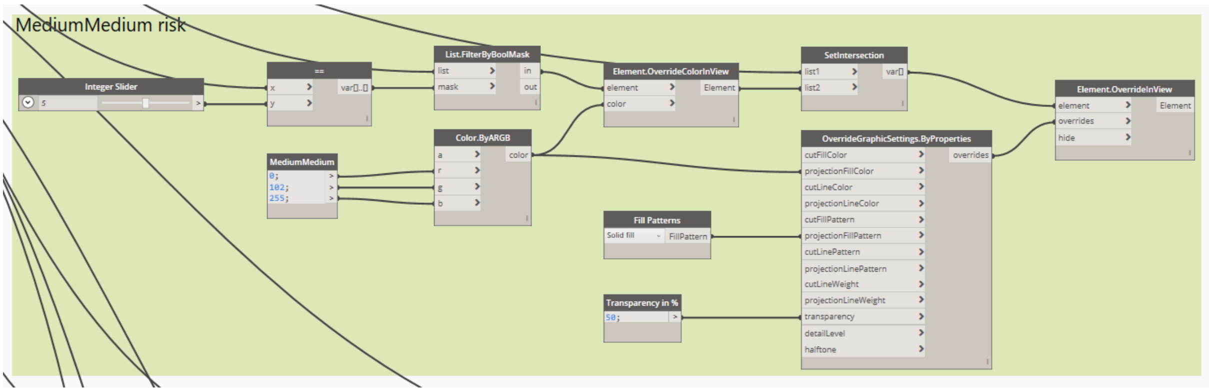
4D: Override element with risk color “LowHigh”



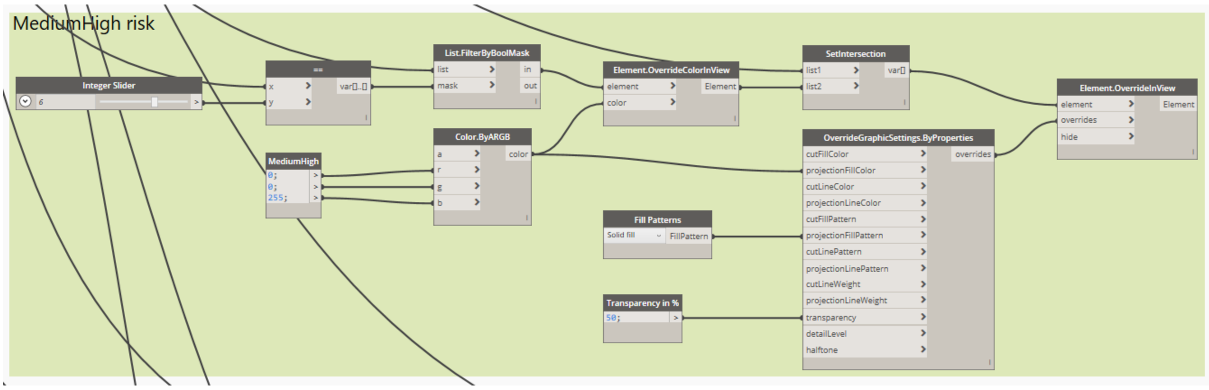
4E: Override element with risk color “MediumLow”



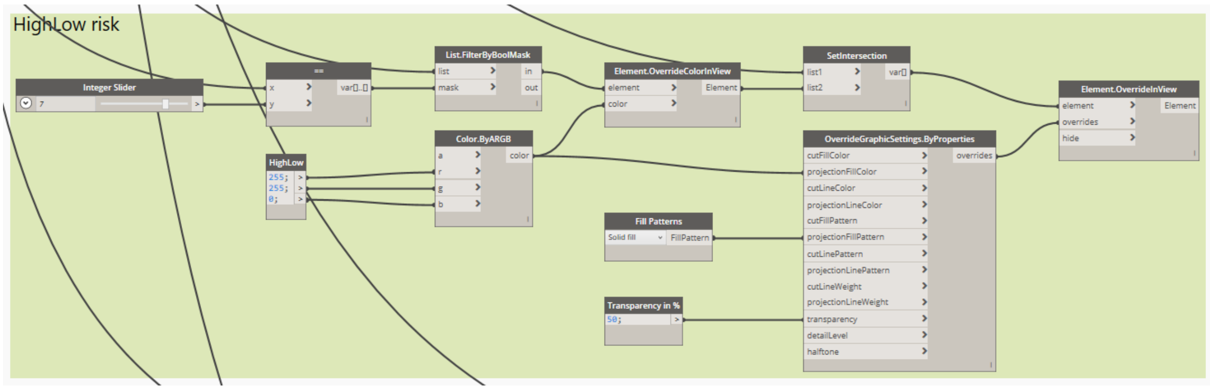
4F: Override element with risk color “MediumMedium”



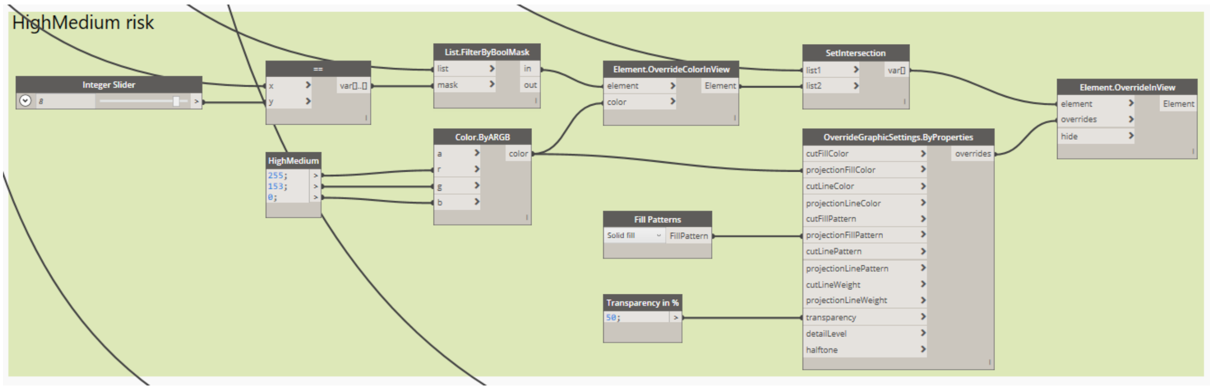
4G: Override element with risk color “MediumHigh”



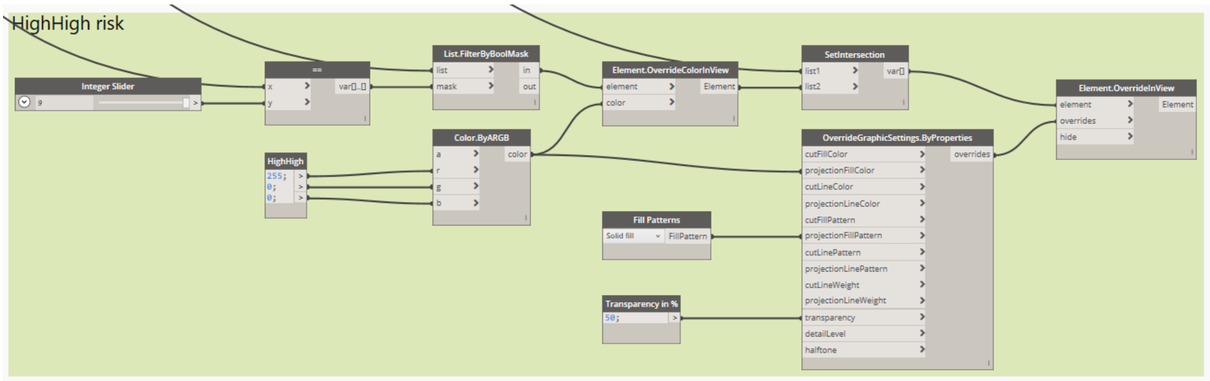
4H: Override element with risk color “HighLow”



4I: Override element with risk color “HighMedium”



4J: Override element with risk color “HighHigh”



5: Showing isolated view plus additional information

Annex II: FMEA Interface

Task_ID	Name	Duration	Start_Date	Finish_Date	Predecessors	Critical path	Occurence	Severity	Detection	RPN	Risk	Occurence	Severity	Detection	RPN	Risk	Color	Additional Information
1	**Soil**	**26 days**	**Fri 16-12-16**	**Fri 20-1-17**		**Yes**	**9**	**1**	**1**	**9**	**Low**				**81**	**Medium**	LowMedium	**Be aware of groundwater level**
1.1	Preparing terrain	1 day	Fri 16-12-16	Fri 16-12-16		Yes					Low	1	9	9	81	Medium	LowMedium	
1.2	Excavating foundation	3 days	Mon 19-12-16	Wed 21-12-16	3	Yes					Low	1	2	10	20	Low	LowLow	
1.3	Refilling soil	1 day	Fri 20-1-17	Fri 20-1-17	23	Yes					Low	7	1	1	7	Low	LowLow	
2	**Footings**	**6 days**	**Thu 22-12-16**	**Thu 29-12-16**		**Yes**	**4**	**1**	**8**	**32**	**Medium**				**14**	**Low**	**MediumLow**	**Be aware with heavy rain fall**
2.1	Formwork footings	2 days	Thu 22-12-16	Fri 23-12-16	4	Yes					Medium	4	3	1	12	Low	MediumLow	
2.2	Reinforcement footing	1 day	Mon 26-12-16	Mon 26-12-16	7	Yes					Medium	7	1	2	14	Low	MediumLow	
2.3	Casting concrete footing	1 day	Tue 27-12-16	Tue 27-12-16	8	Yes					Medium	1	1	1	1	Low	MediumLow	
2.4	Removing Formwork	1 day	Thu 29-12-16	Thu 29-12-16	9FS+1d	No					Medium	4	1	1	4	Low	MediumLow	
3	**Foundation pillars**	**8 days**	**Thu 29-12-16**	**Mon 9-1-17**		**Yes**	**7**	**1**	**5**	**35**	**Medium**				**729**	**High**	**MediumHigh**	
3.1	Formwork pillars	3 days	Thu 29-12-16	Mon 2-1-17	9FS+1d	Yes					Medium	1	1	1	1	Low	MediumLow	
3.2	Reinforcement pillars	2 days	Tue 3-1-17	Wed 4-1-17	12	Yes					Medium	4	10	10	400	High	MediumHigh	
3.3	Casting pillars	1 day	Thu 5-1-17	Thu 5-1-17	13	Yes					Medium	9	9	9	729	High	MediumHigh	
3.4	Removing formwork	1 day	Mon 9-1-17	Mon 9-1-17	14FS+1d	Yes					Medium	5	6	7	210	Medium	MediumMedium	
4	**Foundation slab**	**3 days**	**Tue 10-1-17**	**Thu 12-1-17**		**Yes**	**3**	**9**	**9**	**243**	**High**				**270**	**High**	**HighHigh**	
4.1	Formwork foundation slab	1 day	Tue 10-1-17	Tue 10-1-17	15	Yes					High	5	6	9	270	High	HighHigh	
4.2	Reinforcement foundation slab	1 day	Wed 11-1-17	Wed 11-1-17	17	Yes					High	6	1	2	12	Low	HighLow	
4.3	Casting concrete foundation slab	1 day	Thu 12-1-17	Thu 12-1-17	18	Yes					High	8	9	3	216	Medium	HighMedium	
5	**Raft foundation**	**5 days**	**Fri 13-1-17**	**Thu 19-1-17**		**Yes**	**6**	**2**	**1**	**12**	**Low**				**336**	**High**	**LowHigh**	
5.1	Formwork raft foundation	2 days	Fri 13-1-17	Mon 16-1-17	19	Yes					Low	3	9	9	243	High	LowHigh	
5.2	Reinforcement raft foundation	2 days	Tue 17-1-17	Wed 18-1-17	21	Yes					Low	9	1	9	81	Medium	LowMedium	
5.3	Casting raft foundation	1 day	Thu 19-1-17	Thu 19-1-17	22	Yes					Low	6	7	8	336	High	LowHigh	
6	**Slab first floor**	**5 days**	**Mon 23-1-17**	**Fri 27-1-17**		**Yes**	**5**	**1**	**1**	**5**	**Low**				**729**	**High**	**LowHigh**	
6.1	Formwork slab	2 days	Mon 23-1-17	Tue 24-1-17	5	Yes					Low	9	9	9	729	High	LowHigh	
6.2	Reinforcement slab	1 day	Wed 25-1-17	Wed 25-1-17	25	Yes					Low	3	2	1	6	Low	LowLow	
6.3	Casting concrete slab	1 day	Thu 26-1-17	Thu 26-1-17	26	Yes					Low	7	7	7	343	High	LowHigh	
6.4	Removing Formwork	1 day	Fri 27-1-17	Fri 27-1-17	27SS+1d	Yes					Low	6	6	6	216	Medium	LowMedium	
7	**Pillars first floor**	**7 days**	**Mon 30-1-17**	**Tue 7-2-17**		**Yes**	**9**	**1**	**9**	**81**	**Medium**				**512**	**High**	**MediumHigh**	
7.1	Formwork pillars	3 days	Mon 30-1-17	Wed 1-2-17	28	Yes					Medium	5	6	9	270	High	MediumHigh	
7.2	Reinforcement pillars	2 days	Thu 2-2-17	Fri 3-2-17	30	Yes					Medium	1	2	3	6	Low	MediumLow	
7.3	Casting pillars	1 day	Mon 6-2-17	Mon 6-2-17	31	Yes					Medium	8	8	8	512	High	MediumHigh	
7.4	Removing Formwork	1 day	Tue 7-2-17	Tue 7-2-17	32SS+1d	Yes					Medium	2	9	9	162	Medium	MediumMedium	
8	**Beams first floor**	**7 days**	**Wed 8-2-17**	**Thu 16-2-17**		**Yes**	**8**	**8**	**1**	**64**	**Medium**				**512**	**High**	**MediumHigh**	
8.1	Formwork beams	3 days	Wed 8-2-17	Fri 10-2-17	33	Yes					Medium	6	5	9	270	High	MediumHigh	
8.2	Reinforcement beams	2 days	Mon 13-2-17	Tue 14-2-17	35	Yes					Medium	3	3	3	27	Low	MediumLow	
8.3	Casting concrete beams	1 day	Wed 15-2-17	Wed 15-2-17	36	Yes					Medium	8	8	8	512	High	MediumHigh	
8.4	Removing Formwork	1 day	Thu 16-2-17	Thu 16-2-17	37SS+1d	Yes					Medium	8	2	9	144	Medium	MediumMedium	
9	**Slab second floor**	**21 days**	**Fri 17-2-17**	**Fri 17-3-17**		**Yes**	**7**	**7**	**9**	**441**	**High**				**64**	**Medium**	**HighMedium**	
9.1	Formwork slab	3 days	Fri 17-2-17	Tue 14-3-17	38	Yes					High	3	3	2	18	Low	HighLow	
9.2	Reinforcement slab	1 day	Wed 15-3-17	Wed 15-3-17	40	Yes					High	3	3	2	18	Low	HighLow	
9.3	Casting concrete slab	1 day	Thu 16-3-17	Thu 16-3-17	41	Yes					High	4	4	4	64	Medium	HighMedium	
9.4	Removing formwork	1 day	Fri 17-3-17	Fri 17-3-17	42SS+1d	Yes					High	3	3	2	18	Low	HighLow	

10	**Pillars second floor**	**23 days**	**Mon 20-3-17**	**Wed 19-4-17**		**Yes**	1	6	1	**6**	**Low**				**343**	**High**	**LowHigh**	
10.1	Formwork pillars	3 days	Mon 20-3-17	Wed 22-3-17	43	Yes					Low	2	2	2	8	Low	LowLow	
10.2	Reinforcement pillars	2 days	Thu 23-3-17	Fri 24-3-17	45	Yes					Low	3	1	1	3	Low	LowLow	
10.3	Casting pillars	2 days	Mon 27-3-17	Wed 19-4-17	46	Yes					Low	4	5	5	100	Medium	LowMedium	
10.4	Removing Formwork	1 day	Tue 28-3-17	Tue 28-3-17	47SS+1d	Yes					Low	7	7	7	343	High	LowHigh	
11	**Beams second floor**	**7 days**	**Wed 29-3-17**	**Thu 6-4-17**		**Yes**	**5**	**1**	**1**	**5**	**Low**				**512**	**High**	**LowHigh**	
11.1	Formwork beams	3 days	Wed 29-3-17	Fri 31-3-17	48	Yes					Low	2	3	1	6	Low	LowLow	
11.2	Reinforcement beams	2 days	Mon 3-4-17	Tue 4-4-17	50	Yes					Low	2	3	1	6	Low	**LowLow**	
11.3	Casting concrete beams	1 day	Wed 5-4-17	Wed 5-4-17	51	Yes					Low	8	8	8	512	High	LowHigh	
11.4	Removing Formwork	1 day	Thu 6-4-17	Thu 6-4-17	52SS+1d	Yes					Low	2	3	1	6	Low	**LowLow**	
12	**Upper floor**	**21 days**	**Fri 7-4-17**	**Fri 5-5-17**		**Yes**	1	1	1	**1**	**Low**				**135**	**Medium**	**LowMedium**	
12.1	Formwork slab	3 days	Fri 7-4-17	Tue 2-5-17	53	Yes					Low	1	1	1	1	**Low**	LowLow	
12.2	Reinforcement slab	1 day	Wed 3-5-17	Wed 3-5-17	55	Yes					Low	5	1	1	5	Low	LowLow	
12.3	Casting concrete slab	1 day	Thu 4-5-17	Thu 4-5-17	56	Yes					Low	5	3	9	135	Medium	LowMedium	
12.4	Removing Formwork	1 day	Fri 5-5-17	Fri 5-5-17	57SS+1d	Yes					Low	5	8	2	80	Medium	LowMedium	
13	**Roof**	**12 days**	**Mon 8-5-17**	**Tue 23-5-17**		**Yes**	**6**	**9**	**9**	**486**	**High**				**36**	**Medium**	**HighMedium**	
13.1	Execution of roof	12 days	Mon 8-5-17	Tue 23-5-17	58	Yes					High	1	4	9	36	Medium	HighMedium	
14	**External walls**	**10 days**	**Wed 24-5-17**	**Tue 6-6-17**		**Yes**	**8**	**5**	**1**	**40**	**Medium**				**12**	**Low**	**MediumLow**	
14.1	Laying exterior masonry	10 days	Wed 24-5-17	Tue 6-6-17	60	Yes					Medium	3	2	2	12	Low	MediumLow	
15	**Internal walls**	**7 days**	**Mon 8-5-17**	**Tue 16-5-17**		**No**	**2**	**1**	**4**	**8**	**Low**				**10**	**Low**	**LowLow**	
15.1	Laying internal masonry	7 days	Mon 8-5-17	Tue 16-5-17	58	No					Low	5	1	2	10	Low	LowLow	
16	**Finishes**	**5 days**	**Wed 7-6-17**	**Tue 13-6-17**		**Yes**	**2**	**1**	**4**	**8**	**Low**				**360**	**High**	**LowHigh**	
16.1	Wall finishing	5 days	Wed 7-6-17	Tue 13-6-17	62;64	No					Low	5	8	9	360	High	LowHigh	
16.2	Floor finishing	5 days	Wed 7-6-17	Tue 13-6-17	58;62;64	Yes					Low	5	5	4	100	Medium	LowMedium	
16.3	Ceilling finishing	3 days	Wed 7-6-17	Fri 9-6-17	58;62;64	No					Low	5	1	1	5	Low	LowLow	
17	**Doors/ windows**	**3 days**	**Wed 17-5-17**	**Fri 19-5-17**		**No**	**9**	**9**	**9**	**729**	**High**				**360**	**High**	**HighHigh**	
17.1	Placing windows/ door exterior	3 days	Wed 17-5-17	Fri 19-5-17	64	No					High	5	8	9	360	High	HighHigh	
17.2	Placing doors interior	2 days	Wed 17-5-17	Thu 18-5-17	64	No					High	5	8	3	120	Medium	HighMedium	
18	**Stairs**	**1 day**	**Mon 8-5-17**	**Mon 8-5-17**		**No**	**9**	**1**	**4**	**36**	**Medium**				**45**	**Medium**	**MediumMedium**	
18.1	Placing stairs	1 day	Mon 8-5-17	Mon 8-5-17	58	No					Medium	5	9	1	45	Medium	MediumMedium	
19	**Railing**	**1 day**	**Tue 9-5-17**	**Tue 9-5-17**		**No**	**2**	**1**	**4**	**8**	**Low**				**90**	**Medium**	**LowMedium**	
19.1	Placing railling	1 day	Tue 9-5-17	Tue 9-5-17	73	No					Low	5	2	9	90	Medium	LowMedium	
20	**Sanitary**	**2 days**	**Wed 14-6-17**	**Thu 15-6-17**		**Yes**	**6**	**7**	**1**	**42**	**Medium**				**9**	**Low**	**MediumLow**	
20.1	Placing sanitary	2 days	Wed 14-6-17	Thu 15-6-17	67	Yes					Medium	1	1	9	9	Low	MediumLow	
21	**Kitchen**	**1 day**	**Wed 14-6-17**	**Wed 14-6-17**		**No**	**2**	**5**	**4**	**40**	**Medium**				**90**	**Medium**	**MediumMedium**	
21.1	Placing kitchen equipment	1 day	Wed 14-6-17	Wed 14-6-17	67	No					Medium	5	2	9	90	Medium	MediumMedium	
#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A												
Planning							**FMEA cost**			**RPN**	**Risk**	**FMEA time**			**RPN**	**Risk**	**Evaluation**	**Additional information**

Risk evaluation	**value**
'Low' <	27
'High' >	216
'Medium'	

Guidelines	
Import schedule	
Fill in manually	