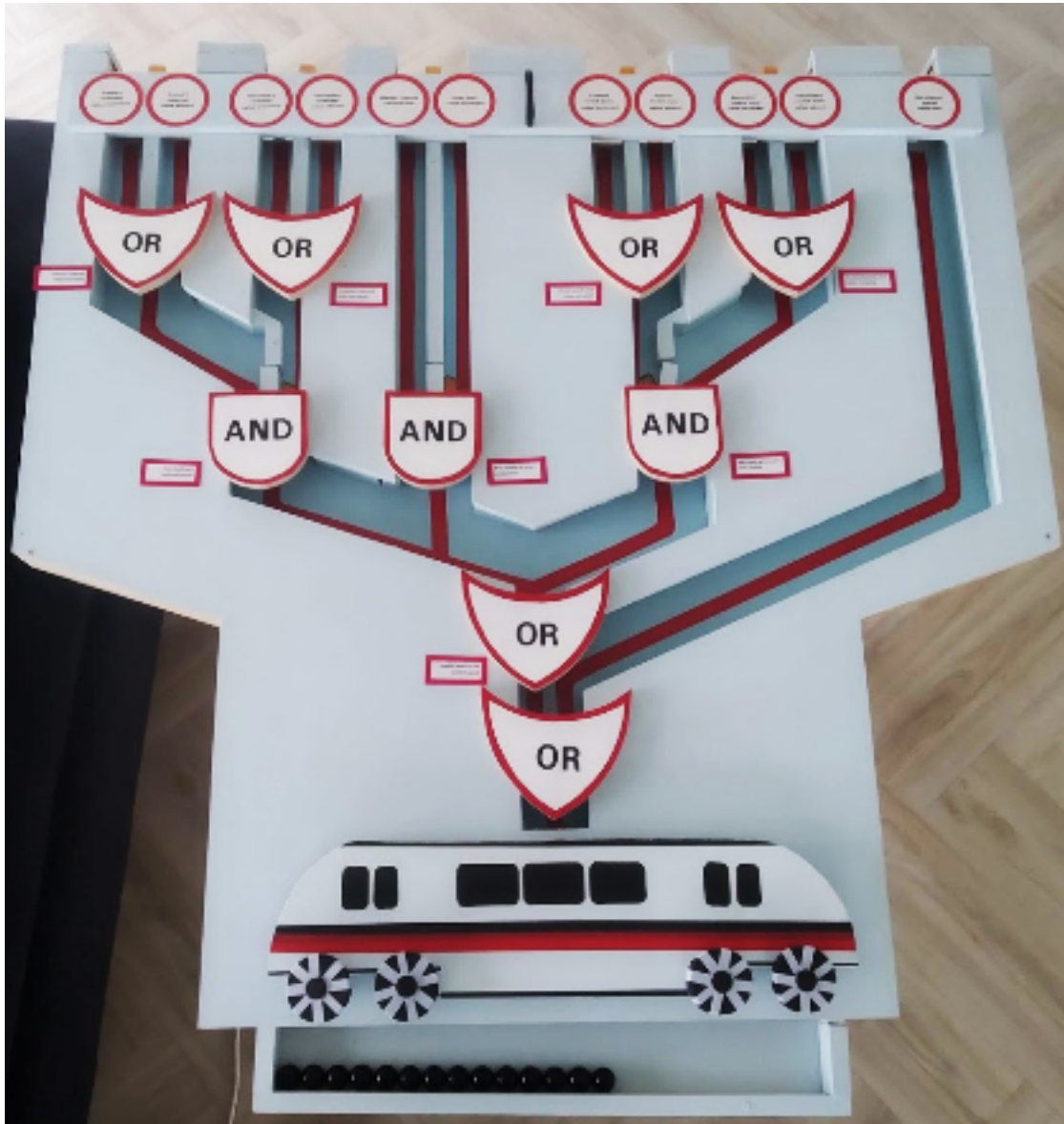


# The Physicalization of Risk Models



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# Abstract

Modern technologies can cause riskful situations. These risks are analysed by risk engineering experts through technical models such as fault trees, but these models are not always understandable for non-experts. This research aims at designing an attractive physicalization that makes fault trees more understandable to non-experts. Based on literature about problems with engineering explanations, the effectiveness of fault trees and visualization techniques, a design of an interactive marble track is created. This marble track shows the most basic features of a fault tree. Experts approve of a prototype of this design, but would also like to show more difficult fault tree concepts with it. Evaluation with non-expert through a digital survey and a video of the installation shows that a prototype of the marble track is considered to be attractive and increases confidence about understanding. However, no significant difference in understanding is found between participants being exposed to the installation and participants only reading a text about fault trees. Further research needs to be done in a physical manner and on a larger number of participants with a higher variance in backgrounds in order to obtain a more complete view on the influence of the marble track on understanding the concept of fault trees.

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# 1. Introduction

Modern technologies come with many risks in terms of for example safety, security and reliability. To analyse these risks, multiple models have been built by engineering specialists, of which the fault tree is an important one. However, these models are not always understandable for non-specialists, such as technical managers and the general public. To give them insight into the issues that come with certain technologies, risk management models should be able to give a better understanding to individuals other than just the developers.

Lack of well explained risk models can have great impact on engineering processes, but also on society as a whole. Giving clear explanations has been confirmed to be difficult in the past, due to experts and non-experts having different perspectives [1] and the focus of engineers on formal rather than informal communication [4]. Even in extensive projects, such as NASA's Space Shuttle Challenger, a lack of sufficient communication has led to dire consequences, including death. Moreover, more day-to-day technologies, such as trains, traffic lights or even mobile phones, can suffer from a lack of sufficient risk management communication. Since these technologies have become a big part of our lives, system failures caused by miscommunication can have great impact. This was confirmed when the failure of the Dutch KPN phone network in 2019 made contacting emergency services impossible.

Visualization techniques are often used for improving the ease of communication regarding complicated data or models, which has been proven to be effective [25]. This gives an interesting perspective on decreasing miscommunication in risk management. However, literature states that physical representations of data are in some cases more engaging and encourage the user to explore more than visualizations [15], in spite of the limited amount of research that has been completed about physicalization. A physicalization can be described as "a physical artifact whose geometry or material properties encode data" [26]. As can be derived from this definition, most of the physicalizations that have been made in the past regard data rather than models and are passive instead of interactive, decreasing their appeal to engage the user. This opens a door towards researching the possibility of designing an interactive physicalization of a risk model, to increase the attractiveness and accessibility of such a technical model.

The main goal of this project is to build a working physicalization of a fault tree to improve the insight of non-experts into the risks of technical systems. Besides being technically correct, the physicalization should be attractive for experts as well as non-experts to use as a communication method. Furthermore, the installation should be as innovative as possible, meaning it should differ from current solutions.

In order to design such a physicalization, this research first explains the background of fault tree analysis and physicalization. Then, we take a closer look at literature about aspects of effective engineering explanations, which mainly tells us that miscommunication is caused by (1) different perspectives and background knowledge of engineers and non-experts, (2) the reluctance to communicate and receive bad news and (3) the lack of proficiency of informal communication by engineers. Another literature study summarizes the aspects that make fault trees more understandable: the categorization and more extensive explanation of basic events. In order to have the tools to design an attractive physicalization, we then look at different visualization techniques and come to the conclusion that complexity should be reduced by using colours and shapes that are associated with the context of the installation. After doing case studies of existing risk visualizations and interactive physicalizations, I start the designing process, which leads to the idea of using a marble track for the explanation of qualitative fault trees. Using the prototype that is built based on this design, experts are asked to evaluate it in interviews. According to these experts, the idea has a lot of potential, but the complexity of fault tree features in the marble track could be increased. Furthermore, a user test with non-experts is executed, in which we find out that they rate the prototype high on being attractive, but there are no significant results that prove their understanding is increased.

## 2. Background

### 2.1. Fault Tree Analysis

When analysing the risks of failures occurring in technology, fault trees are often used as a graphical tool [5]. They can give a quick insight into the most important causes of a system's failure, as to display if a technology is safe and reliable. Furthermore, with the help of fault trees the weak points in a system can be pinpointed, which can be used to reduce failure risks.

For this research, we are only focussing on *qualitative fault trees*. These mainly illustrate the components and causal failure paths of a system, while *quantitative fault trees* also focus on dependability metrics.

Fault trees demonstrate how the failure of individual components (also known as *basic events*) can lead to the failure of greater parts of the system, or even the whole system. This analysis is shown step by step by means of *tree gates*, which display how failures of certain components combine into higher level faults. The path through these gates leads from the *top level undesired event* to the basic failure that causes the undesired event, as can be seen in the example in figure 1.

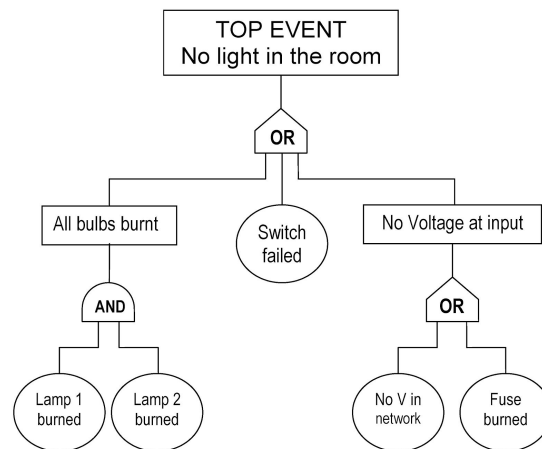


Figure 1: Example of a static fault tree [6]

This is an example of a *static fault tree*, which only consists of boolean gates, like the AND and OR gates that define the path of the tree in figure 1. An AND gate outputs failure if and only if all children fail; an OR gate outputs failure when one or more of its children fail.

When looking at the fault tree in figure 1, it can be seen that not all basic events will lead to the system's failure. For example, the failure "All bulbs burnt" can only be true when both lamp 1 and lamp 2 are burnt. When looking at the right side of the tree, either "No V in network" or



“Fuse burnt” can be true in order to make “No Voltage at input” true. The same accounts for the first layer of failures under the top event: only one of the three premises (“All bulbs burnt”, “Switch failed”, “No Voltage at input”) has to be true in order for a lack of light in the room.

Fault tree analysis can have multiple types of goals:

- Understand failure propagation and root causes of a system’s failure. This can be used when the top undesired event is observed and the cause leading to its occurrence has to be identified. By starting at the top of the fault tree and slowly moving downwards with the observations of the failing system, the leaf causing the failure can be found.
- Improve the system design to be more reliable, e.g. by comparing multiple alternatives. When two fault trees are compared, the weak points of the system can be identified for multiple designs. This way, more informed decisions can be made on how to design a system without the most hazardous weak points.
- Keep track of risks while a system is active. While the system is functioning and a root failure occurs, someone who is tracking the system can determine what other failures this leaf can cause and whether the top undesired event will arise.

Fault trees play an important role in risk management. However, they are not always understandable for those who know little about the system they describe [7]. This is why this research aims at designing a more understandable and attractive structure for fault trees, by using physicalization, of which an explanation can be found in the next paragraph.

## 2.2. Physicalization

Just like visualization, physicalization aims at making abstract information more understandable through easily perceivable representations. In the past few years, the question why simple data representations should be limited by 2D pixels has arisen. That is why recent research has been focussing on how visualizations can be moved into the physical 3D space. However, physical data and models have been around much longer, while the creators were unaware of the field of physicalization as a research topic. An example of this is the Galton board, which demonstrates the central limit theorem, stating that binomial distribution approximates a normal distribution when enough samples are taken (figure 2) [27].

With new technologies, physicalizations can be produced and changed fast. Techniques such as laser cutting and 3D printing can accelerate the production of specific parts. Furthermore, technological features like sensors and motors can make the physicalization easily adaptable to multiple sets of data. Although digital visualizations are still more flexible, multiple researchers have suggested that the use of physical rather than (2D) visual representation can make data more memorable [28]. This is the reason why this research aims at designing a physicalization

rather than a visualization. However, research on physicalization is still limited and should be extended in the future to increase clarity about its applications and effectiveness.



*Figure 2: Galton board displaying the central limit theorem*

### 3. Research Questions

The goal of this project is to design an interactive physicalization of a fault tree that is attractive, accessible and innovative. Therefore, the main question of this research is:

**How can an attractive physicalization of a fault tree be designed to improve the explanation of risks?**

This question is leading during the project, in order to reach the intended goal. Since this question is difficult to answer as a whole by doing research, it has to be split into sub-questions. In order to be able to answer the main question, several more specific questions can be asked:

- How can the explanation of risks be improved?
- What factors increase the effectiveness of conventional fault trees in risk explanation?
- How can a physicalization be made to be attractive?

To answer these questions, the research first focuses on a state of the art literature study. In this section, we see examples on how researchers have tried to answer these questions before and how these can still be improved. The analysis of the state of the art review can help with optimizing the ideation process, which leads to the design of the final physicalization. The evaluation of this design contributes to formulating an answer to the research questions.

## 4. State of the art

In this chapter I give a review of the research that has been conducted before, related to the sub questions. In the research into engineering explanations, we can find that risk explanations by engineers are often misinterpreted because of (1) different perspectives and background knowledge of engineers and non-experts, (2) the reluctance to communicate and receive bad news and (3) the lack of proficiency of informal communication by engineers. When looking at the effectiveness of fault trees, research shows that non-experts have more difficulty in understanding fault trees than experts and that a more complete explanation and the categorization of basic events improves this understanding. The third part of the state of the art summarizes the most important visualization techniques, which mainly tell us that the complexity of visualizations should be reduced by using recognizable visual clues. These techniques are then used for analysing existing risk visualization, interactive physicalization and logic gate physicalization projects, in which it becomes clear that shapes and positions are often used well, while there is a lack of use of associative colours. All these conclusions can be used for the specification of the physicalization design in the next chapter.

### 4.1. Engineering Explanations

#### 4.1.1. The importance of communication

Technological failures can often be traced back to a lack of communication [1][2]. Investigation points out that in most cases, failures could have been predicted and prevented by individuals within a team, while this knowledge was not shared with the rest. This can mainly be explained by two factors: (1) managers and engineers view facts from different perspectives, and (2) individuals are reluctant to share or receive bad news. Windsor [1] found this while doing a case study of the failed Challenger Space Shuttle project by NASA and this was supported by Marsen [2], who conducted a literature study about the avoidance of crises through communication.

From factor (1) Windsor concluded that communication is not always about sharing information, but about sharing interpretation of facts. Furthermore, he pointed out that bad news, which is often involved in risk management for technological systems, travels slowly upward inside an organisation or is not passed on at all. What is more, when this information is shared with superiors, it is not likely to be listened to or believed. This was observed in the process of building the Space Shuttle Challenger which led to a disaster in 1986, when seven crew members were killed due to the failure of the shuttle, despite technical reports stating the unreliability of certain parts of the orbiter. Marsen observed that multiple other software projects and studies also showed the reluctance of sharing negative messages.

From the Challenger disaster, multiple lessons regarding precautions can be learnt, according to Windsor. Managers should create an open atmosphere in which engineers feel comfortable with speaking up about the risks of their systems. Moreover, both managers and engineers should anticipate the tendency of optimism while interpreting disadvantageous data. Finally, any team member should be aware of the possibility of misinterpretation while communicating and try to empathise with different views on certain subject matters.

#### 4.1.2. Reasons for miscommunication

To analyse the problems that occur when transferring information between multiple specialist groups (which requires explanations), Martin J. Eppler [3] conducted interviews with managers as well as experts (like engineers and IT specialists). From these interviews, he identified five different communication problems:

1. Expert-caused difficulties, such as overly technical jargon or starting with details instead of overviews. This causes a lack of insight in the subject matter for the decision maker, which in turn makes it difficult for them to explain their constraints and priorities to the expert.
2. Manager-caused problems often occur, in which expectations are not clearly communicated to specialists. When these types of issues arise, managers can not fully profit from experts, due to their reluctance to discuss the details of their problems. This causes a lack of concentration of certain expertises while tackling tasks.
3. A combination of (1) and (2): on both sides a lack of role understanding and feedback causes a project to move forward at a slow pace or fail entirely. Moreover, both managers and experts are sometimes reluctant to let go of their view or compromise, which causes conscious sabotage of projects.
4. Situation of communication. This can involve time constraints or external distraction.
5. The organisation of a project: the involved team members can for example also be involved in other projects, or have different interests or priorities from each other.

When all involved team members become aware of these types of problems, they can work on them together and create an open environment in which miscommunication can be pointed out. This could avoid the risks of project failures due to explanation problems between experts and decision makers.

#### 4.1.3. Importance vs. proficiency in types of communication

Studies have shown large differences between professionals' communication skills and the demands of their jobs. To understand this gap between the proficiency and importance of

communication, a team of researchers at the Rose-Hulman Institute of Technology [4] conducted several interviews with engineers and technical managers with an engineering degree.

The results of these interviews showed that these professionals had been academically prepared for formal written documents and presentations, while they lacked the skill of communicating more informally, as can be seen in Table 1. When ranking communication skills on importance (1 = most important, 5 = least important) in their jobs, a huge mismatch could be observed.

*Table 1: Communication types by proficiency and importance*

Communication Type	Rank (proficiency)	Rank (importance)
Formal written	1	4
Formal presentation	2	5
Informal correspondence	3	2
Face-to-face meetings	4	1
Informal face-to-face	5	3

The lack of skill to communicate informally rather than formally can be traced back to engineering education. However, the interviewees also pointed out that the field of engineering is often identified with stereotypes of introversion and awkwardness. Both truthful occurrences and prejudices of this statement cause informal communication to be difficult. Furthermore, engineers tend to share too much information, especially when email is used as the communication medium.

From these results Housem et al [4] concluded that engineers should find a way to learn how to communicate informally and focus more on face-to-face instead of written communication. This could also result in a decrease of information dumps, making communication more effective. Important to note is that formal writing is still very crucial for engineering professions, for example for the sake of technical reports.

## 4.2. The effectiveness of fault trees

It is also important to evaluate fault trees' effectiveness as a modelling and graphical tool. In 2018, a group of researchers tested both Attack Graphs and Fault Trees about cyber-attacks on participants with computer-science and non-computer-science backgrounds to research their

effectiveness [7]. They asked the participants to use both visual means to understand the process of cyber attacks. This experiment pointed out that non-computer-scientists preferred Attack Graphs over Fault Trees on average, but the result was not statistically significant enough to draw any conclusions. However, there was a very significant difference in the understanding of both graphs between computer-scientist and non-computer-scientists, meaning that the participants with a non-computer-science background had difficulty understanding the graphical models (AG and FT). This could mean that Fault Trees mainly work well for experts in the subjected area of expertise, while non-experts still struggle with understanding them. Chen et al. [8] claim that Fault Trees are easy to understand for those who are not involved in the system design, but this is not supported by any evidence.

Researchers at the University of Sao Paulo conducted research on FTA as a tool for deriving safety functional requirements [9], which might be an important task for technical managers. When doing a case study with a fault tree for insulin pumps, they found that FTA is not always enough for deriving safety functional requirements. Interviews with software engineers pointed out that FTA offers a good overview of the most important risks, but that important details of safety requirements can easily be missed, due to the lack of explanation of each leaf in the fault tree. This means that FTA is sufficient for finding the most important risks, but should be combined with extra information to understand the details surrounding the basic events which are depicted as leaves in a fault tree.

The same study pointed out that the classification of each basic event can greatly help to derive safety functional requirements. When the leaves were not labeled with a specific department, the requirements engineer did not know whom to approach during occurrence of certain failures. Therefore, each leaf in the used fault tree was labeled as a software, electronic or mechanical failure, which helped the requirements engineer ask the right experts for advice when dealing with the failures in the fault tree.

### 4.3. Techniques for Attractive Visualization

The attractiveness of visualizations is determined by multiple visual factors, like shapes and colours. It is important to reduce the complexity of visualizations by using these factors well, so that the visualization is understandable at a glance. One of the most important ways of reducing complexity is using visual associations, like colours (e.g. red for failure and green for success). Since research about physicalization is limited, this section describes techniques meant for visualization but which can also be applied in case of physicalization. Techniques that are not relevant for the design of the physicalization of a fault tree are left out. During the design process I will consider the techniques below to make the physicalization more attractive.

#### 4.3.1. Contrast

The brain is better at relative than absolute processing, which makes contrasting images quickly and easily understandable. This can be done by large contrasts in form, size or for example by using complementary colours [19]. To clearly see the contrast between certain objects, contrasting objects should be put close to each other, so they are easily comparable. When two graphs need to be compared, it is hard to see the difference in their dimensions if they are far apart. For making comparisons between two situations, the objects representing their data should be in close proximity to each other [24]. For example, the population of two countries can be compared through bars with lengths that represent the population's size. In order to clearly distinguish their difference in length, and thus population size, the bars need to be placed closely to each other.

#### 4.3.2. Colour

Colour is very important when making visualizations or physicalizations, because they are easily recognizable and can cause distinguishable contrasts. They can also be used for drawing attention to certain objects. For example, small objects should have highly saturated colours. This way, they stand out more and are easier to distinguish from each other, which makes sure that no details are missed by the viewer [19]. In contrast, large objects should not have too strong colours. If bright colours are used, the viewer will not feel tempted to look at large objects. Furthermore, large objects should not draw too much attention by using strong colours, since the viewer might miss information conveyed by other objects [19]. Overall, the viewer should not be overwhelmed by the colours, so that the focus of a visualization can be easily found. A limited number of colours should be used, in order to lead the eyes of the viewer to the right focussing points. With too many colours, the viewer can be overwhelmed because of the seemingly large amount of information [19].

Contrasting colours are a good way to distinguish certain categories. Complementary colours are most easily distinguishable from each other, but combinations that cannot be distinguished by colourblind people (green-red) should be avoided [24]. The colours used should not be too similar, since they should be easily differentiable. If five shades of blue are used, it might be hard to see the difference between categories or objects [24]. However, contrasting colours are not always the best application for differentiating between groups. For scales or other types of ordering, it is better to use brightness or saturation instead of difference in hue. Only specific cases (like temperature) allow viewers to easily understand hue scales, while saturation or brightness scales are logical enough for the brain to adapt to fast [24].

Moreover, colours can be used for recognition of certain contexts. To achieve this, colours should be used consistently (they should have similar meanings in different applications). If a visualization is used for example for data about browsers, it is not wise to use red for Microsoft Edge and blue for Opera. The colours in the visualization should correspond to the colours that



are associated with those categories. Moreover, if multiple visualizations are made about the same topic, the colours representing each category should stay the same [20]. For making contexts clear, some colours are more recognizable when paired (pink-blue for girls-boys, red-blue for republicans and democrats, red-green for traffic lights) [24]. Associations with colours can be used for a faster and easier understanding of the viewer. The most well-known associations are [24]:

- Red: danger, passion, blood
- Green: nature, renewal, clearance
- Yellow: happiness, caution
- Blue: water, calm, religion, military
- Black: mourning, death, sophistication, luxury
- White: purity, weddings, sympathy, the afterlife
- Pink: affection, imagination, childishness
- Grey: neutrality, conservatism, modesty, maturity
- Orange: fire, energy
- Brown: dirt, leather, stone, earthiness, animal waste
- Purple: royalty, magic

#### 4.3.3. Shapes

The recognition of shapes is quite easy for humans, since this forms an important part of day-to-day observations. However, still simple shapes are easier to recognize and stimulate the detection of minor shape changes. It is sometimes better to represent certain objects by squares or circles than by actual visualizations (like drawings or photos) [23]. Furthermore, the areas of simple shapes are easier to distinguish: rectangles are most easily understandable when they vary in size [24]. Another way to make shapes and deformations easily recognizable, is the use of symmetry. The brain is good at seeing and remembering symmetry, which is why it is wise to use as many symmetric shapes as possible [23].

Most icons have easily distinguishable shapes. They can greatly differ in complexity, for example by their number of dimensions. 2D icons should be used if only simple representations are needed; 3D icons can also be used, but should only be applied if this is logic in the environment (like 3D maps) [20]. In general, the shape of icons should be kept as simple as possible, unless the visualization as a whole asks for more complexity.

Finally, the visualization should be large enough to see all information clearly, but not much larger. Each shape should have an appropriate size: circles and squares might be easy to distinguish when they are smaller, but more complicated shapes should be made large enough to distinguish their details [23].

#### 4.3.4. Position

Visualizations can be a lot more logical for a viewer when position is used well. Central positions can draw more attention, but the reading direction should be taken into account as well (left to right and top to bottom in the West). If objects should be read in a certain order, the reading direction of the intended viewer should determine the position of each object [24]. Similarly, sorting makes it easier to see similarities and differences between data. So objects should be placed in order of for example size for the viewer to be able to compare them more easily [23]. In conclusion, for ordering it is best to use the reading direction of the target group by placing objects next to each other.

As stated before, the brain is good at seeing and remembering symmetry. It is therefore wise to place objects as symmetric as possible in a large visualization, to make the amount of information not too overwhelming [23]. When there is a large number of objects and symmetry is not enough to keep it manageable, frames can be used for separation, but these should only be used when needed. When certain objects should be separated from each other, a frame can be placed around them. However, it is in most cases better to position them further away from each other for separation, to avoid clutter [23].

#### 4.3.5. Annotations

Text should be used sparingly in visualization, but can highlight certain aspects. It can attract the viewer's attention or can give explanation when needed. When too much text is used, a clutter of overwhelming information is created, making it hard to focus on the most important aspects [23]. In visualizations, as much as visual aspects should be used for clarifying the point, but in more complex subjects, text can be a good addition to make the visualization more understandable.

When using text, caps should be avoided, since the letters have similar shapes and are hard to differentiate. Research has pointed out that people often only need the length and the first and last letter of a word to understand it, but it is harder to distinguish those letters when only caps are used [24].

#### 4.3.6. Complexity

As stated in many of the categories above, too much information should be avoided, since it obscures the message and makes extracting information more difficult. A visualization should have a clear goal and message which should be communicated with a minimum number of clues. Otherwise, the viewer will be overwhelmed by the information and will have a hard time understanding and remembering the point of the visualization [24].

When a visualization does need to be complex, it explained by showing an analogy of a more simple visualization. This can be accomplished by comparing the visualization that can convey the needed amount of information to a more simple and recognizable one (e.g. a bar or pie chart)

first and then adding the full dataset to the complex visualization once the viewer understands how it works [22].

Context is another way of decreasing the amount of information in a complex visualization. A visualization should fit in with related materials, both in content and in style, to make a visualization easier to understand. The context should be easily derived from the visualization, for example by using associative colours or shapes [23].

#### 4.3.7. Graph layout

Since a fault tree is a type of graph with gates that can be seen as nodes and connections that can be seen as edges, some techniques for making graphs are summarized here.

Nodes and edges should be evenly distributed. If they are too close to each other, this can cause a clutter and increase difficulty to differentiate elements from each other. Furthermore, even distribution will make sure that all elements are considered to be important. To accomplish this, it helps for edges to have similar lengths. Another way of keeping a graph orderly, is avoiding too many edge crossings. When edges cross too often, it is hard to track which elements are connected to each other [23].

### 4.4. Visualization of risks

Previous research has used different types of visualizations to show risks. These projects show that the types of visualizations depend on the target audience and user situations. Visualizations for patients should be kept simple, while those for engineers can and need to be more complex. Furthermore, when someone is in a stressful situation, it can be beneficial to minimize information by using a limited number of objects. Technical texts can also be simplified by using recognizable images. With these projects, it is possible to see the use of context to simplify visualizations applied. This overview of risk visualization projects can both be used for inspiration and for learning about what works and what does not in terms of visualization techniques used for the explanation of risks.

#### 4.4.1. Prostate Cancer Health Risk Communication

For most prostate cancer patients, the optimal treatment is unclear, since multiple treatment options result in similar prognoses. However, each treatment comes with different risks, such as erectile dysfunction and incontinence. Medical research has pointed out that the most important reason for most men choosing surgery as a treatment is a lack of tools that communicate the risks of each treatment effectively. Therefore, a group of researchers designed a tool for personalized health risk communication for localized prostate cancer patients [10].

In order to design an appropriate tool, two requirements were formulated: (1) making the prognoses of clinical prediction models (CPMs) easy to understand for patients and (2)

developing a narrative structure that is best suited for doctor-patient communication. Based on previous research and contact with experts, four interactive visualizations were designed to comply with these requirements (figure 3). To use this tool, the patient has to input their age, biopsy scores, cancer stage and tumor tissue differentiation. Based on this data, the survival rate and treatment effectiveness for the specific patient are visualized. In general, test patients reacted positively to the usability and accessibility of these visualizations.

Furthermore, three guidelines that are specific for health risk visualization and are not as important in other risk communication were formed: (1) the user's emotional state should be taken into account as explicitly as possible, (2) the complexity of the visualizations should be minimized and (3) the design process should be iterative and include as much user testing as possible.

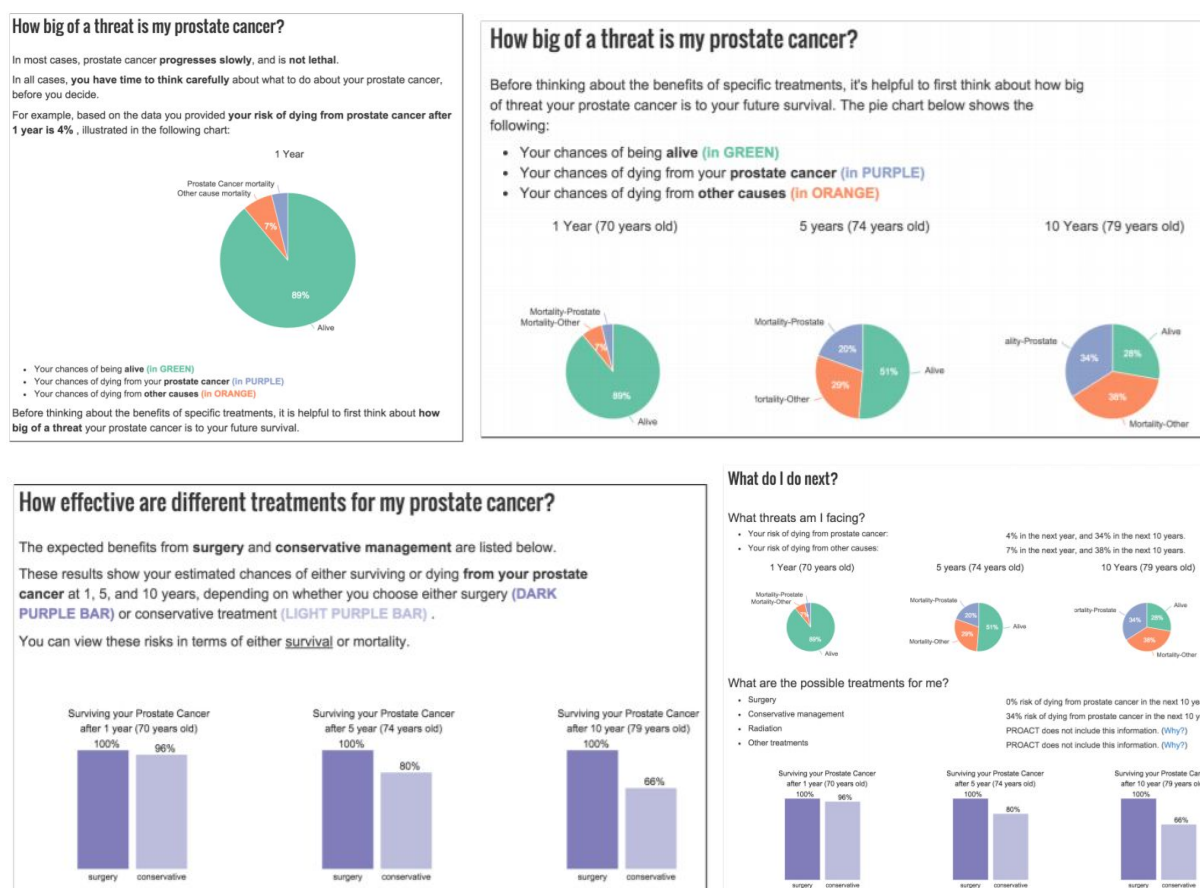


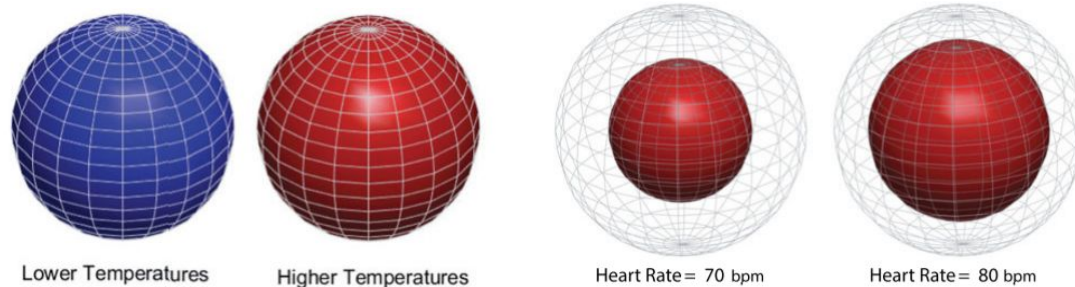
Figure 3: a) 1 year survival rate, b) mortality rate for several time frames and diseases, c) comparison of survival rates after surgery or conservative treatment, d) summary of all data, for a patient to take home.

**What can be learnt:** making innovative visualizations does not always benefit the user; sometimes it is better to use recognizable visualizations to make data more easily understandable.

#### 4.4.2. Real-Time Risk Situation Awareness

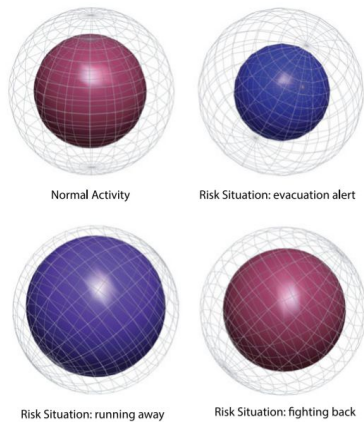
Riskful situations, such as health problems or natural disasters, often call for a prompt response. However, individuals in hazardous positions lack the awareness to ask for assistance as quickly as needed, resulting in dire consequences. To tackle this problem, a group of researchers introduced Fitness to Visualization ( FiToViz) [11], in which wearable sensors are used to create a visualization of an individual's state. The system provides feedback on a user's activity in order to trigger them to take the needed actions to minimize consequences of riskful situations.

A Personal Risk Detection (PRIDE) dataset is used to visualize the risks of a user, by monitoring their heart rate, skin temperature, acceleration and other behavioural data. A sphere is used to visualize the measured data in an intuitive manner, with attributes such as color and diameter. For example, the sphere's surface colour is dependent on the user's skin temperature, ranging from blue to red, while the diameter of the sphere rhythmically varies in correspondence with their heart rate (figure 4).



*Figure 4: a) colour variation of the sphere based on skin temperature and b) diameter variation based on heart rate*

Using the PRIDE data, the FiToViz application creates a new spherical visualization, which informs the user on the advisable action to take (figure 5). This can mainly be used by a person monitoring several individuals' data to make decisions in riskful situations. The psychological validity of this method has not been tested yet.



*Figure 5: Visualized activities used for decision making*

**What can be learnt:** one (visual) object can convey a lot of information by using its many aspects, such as size and colour.

#### 4.4.3. Risk Assessment in Military Shipbuilding

Military shipbuilding projects often face problems related to delivery delays and increased costs, due to insufficient risk management. This risk management is difficult to improve because of the classification of information within the military and the fast development of technologies used for shipbuilding. To make risk assessment models more accessible for all employees working in shipbuilding, information from all layers in the military was gathered anonymously and comprised into visual models [12]. The two most important visualizations were created to help identifying risks (figure 6a) and analysing risks (figure 6b).

In figure 6a the most important causes for failures and their causal relations (arrows) are displayed. Figure 6b identifies eight groups of risks and twenty causes leading up to these. Furthermore, a colour scheme was added to display the frequency of occurring risks and their causes. These visual models were accepted by military experts because it was appropriate to use even in unique cases, easy to understand and usable throughout the entire process of projects. However, the model is still flawed, since it does not include the possible dependency between causes. Furthermore, not enough data has been collected to validate the visual models in different kinds of projects and contexts.

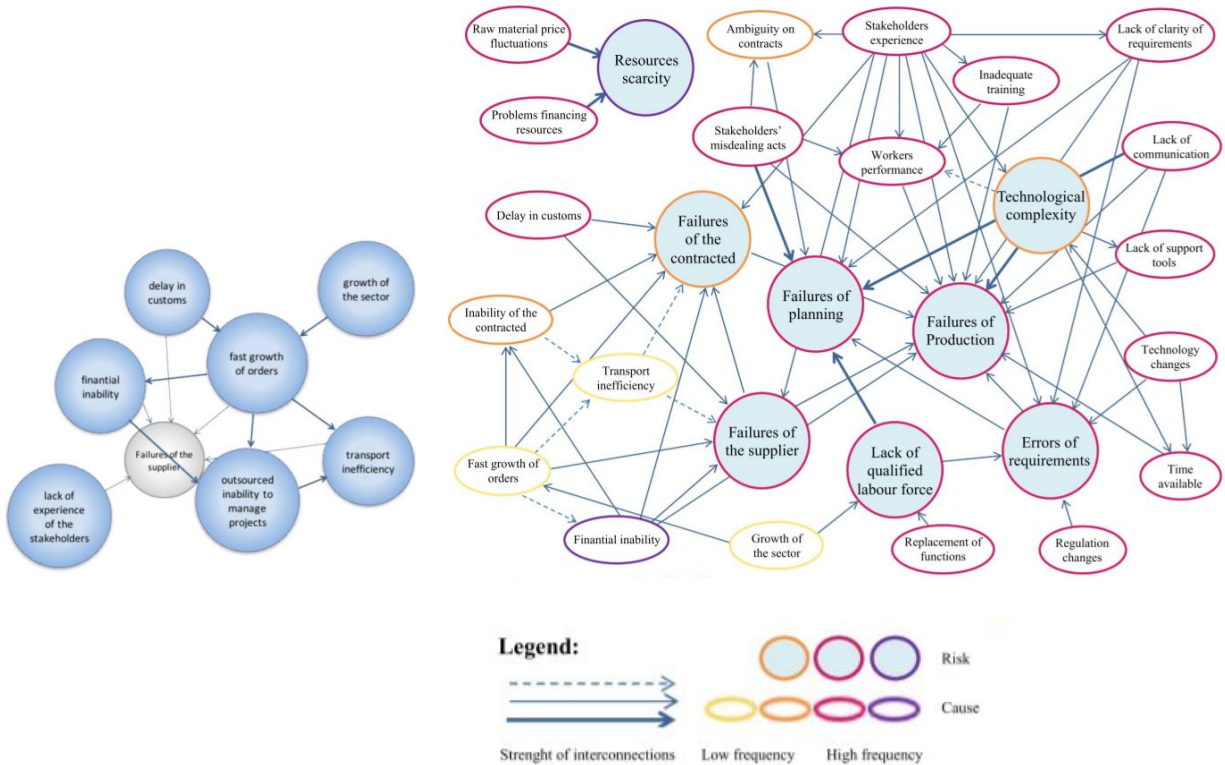


Figure 6: a) causes to help identify risks in shipbuilding, b) most important risks and their causes, with colour indications of their frequency

**What can be learnt:** more complex visualizations can be beneficial in some cases, since they contain a lot of information that can be used in a variety of situations.

#### 4.4.4. Hazard Impacts of Urban Flooding on Critical Infrastructures

Critical Infrastructures (CIs), such as energy generators and water supply systems, commonly have high quality standards to withstand environmental damage. However, climate change might increase the risk of failures within these systems. Because of the large impact of the failures of CIs, visualizations were made to increase the resilience of stakeholders to natural hazards [13].

A more literal visualization was created for civilians to more easily understand what kind of impact the flooding of their city would have (figure 7). It shows the process of flooding for four days from high tide, which would bring large populated areas and the buildings in the town centre at great risk. In the same figure the damage in financial terms is indicated with red and orange. Participants in the study showed that this visualization was easy to understand.



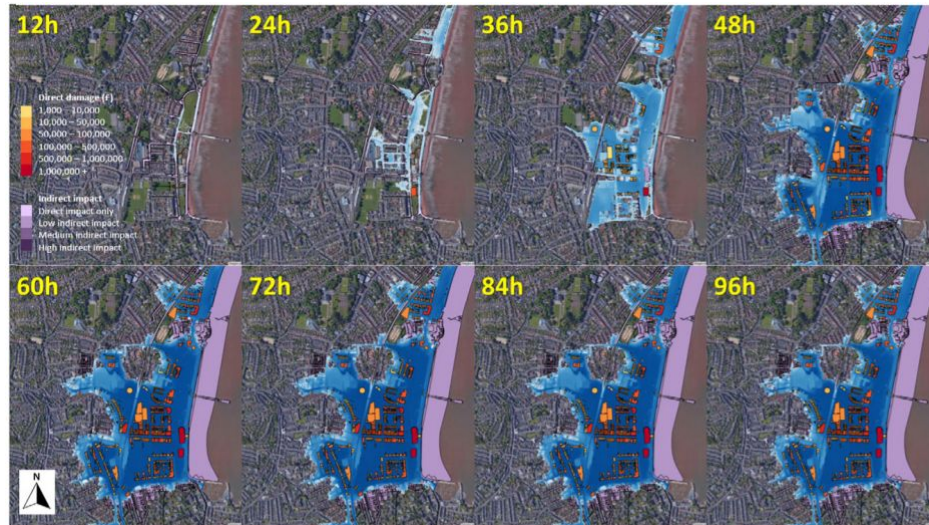


Figure 7: Flood process in Paignton. The red and orange parts indicate financial damage

**What can be learnt:** more literal visualizations can increase the understandability of models for non-experts.

#### 4.4.5. Privacy Policy Risks

Privacy policies are the main mechanism to inform users on the management of their personal information. Literature suggests that users have difficulties with understanding privacy policies, due to the large amount of text and technical and legal jargon. Therefore, AppWare was created to give users a visualized report of privacy policies by using icons (figure 8) [14].

The creators of AppWare used the twenty most popular apps in 2017 to evaluate their application using surveys. Their findings show that the app scores well in usability and that users prefer visualized reports over actual privacy policies.

**What can be learnt:** complicated texts can be made to be more understandable and graspable when visual explanations are added.



Permission : Directly call phone numbers  
Threat : Overcharge



Description : Allows the app to call any phone number including emergency numbers without your intervention. Malicious apps may place unnecessary and illegal calls to emergency services

Permission : Precise location GPS and network\_based  
Threat : Location



Description : Allows the app to get your precise location using the Global Positioning System GPS or network location sources such as cell towers and Wi-Fi. These location services must be turned on and available to your device for the app to use them. Apps may use thi

*Figure 8: Images with description from an AppWare visualized report*

## 4.5. Dynamic Data Physicalization

Physicalizations are attractive to interact with and can be easily adapted by hand. However, due to the extended information that can be shown through physicalization, they can be overwhelming and can lose their accuracy. Two projects that show this are described below.

### 4.5.1. Wheeled Micro Robots

Physically promoted data can increase engagement, encourage the exploration of data and be beneficial for the visually impaired as compared to visual data. However, most data physicalizations are passive and lack interaction. Therefore, researchers introduced composite (consisting of multiple pieces) dynamic data physicalization, using Zooids [15]. These microrobots can represent data by moving around on a table towards different magnets, for example by each representing a student and moving to a location showing the student's grade in certain subjects (figure 9).



figure 9: a) Zooids distributing themselves between two magnets representing science and maths grades and b) Zooids creating a scatter plot, following magnets that represent the axes

Based on user scenarios the research came up with several benefits and limitations to their systems, which are described below.

### Benefits

- Manipulability: due to the flexibility of the robots, they can be used for many different applications of data physicalization;
- Degree of actuation: due to their dynamics, the Zooids are easy to update as soon as data changes, which is a benefit as compared to passive data physicalization;
- Level of granularity: the robots are relatively small, making it very practical to use them for small datasets, such as personal data analysis.

### Limitations

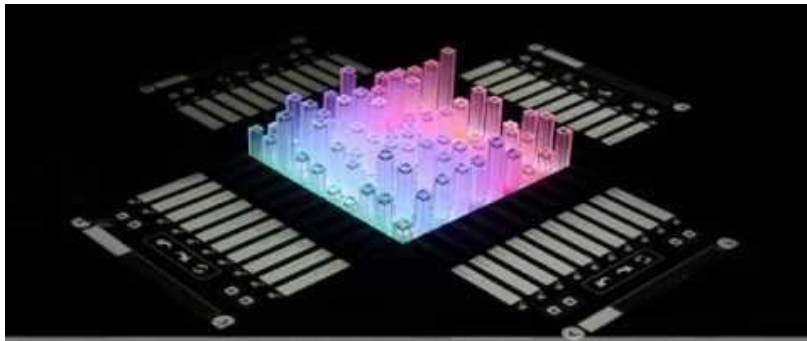
- Axes, text and legends: the Zooids can be used on any table top, but lack dynamic axes, text and legends, which makes it hard to interpret the data without other media;
- Other data representations: in their current form the robots can only be used for scatter plots and proximity based encoding, while other types of graphs still have to be implemented;
- Other visual variables: currently the Zooids can only change position and LED-colour, while data could also be represented by variables such as size and shape;
- Overlapping data cases: data points can overlap, but two robots cannot be in the same position at once;
- Data scalability and cost: the data sets that can currently be physicalized by the Zooids are limited in size and the cost of the entire setup is still high;
- Other synthetic interactions: right now the information of each robot has to be uploaded one-by-one, due to the focus on physical interaction, but this could be made more efficient if computer systems are connected to the Zooids;

- **Evaluation:** user tests and comparisons to other physical data systems still need to be thoroughly researched.

**What can be learnt:** the flexibility of a physicalization can result in a wide variety of applications, but can also result in limitations, like loss of accuracy, increase of reset time and rising costs.

#### 4.5.2. Use of a Physical Bar Chart

Even though dynamic data physicalizations seem promising, knowledge about user interactions with such installations are limited. Therefore, researchers did a user study with a physical barchart (figure 10) to study behaviour around data physicalizations [16].



*figure 10: EMERGE physical barchart which was used for user studies*

During the research, it was found that all participants successfully gained insight by exploring the unknown dataset. The participants moved around the installation frequently to get a better overview of the data and extensively used hand gestures (such as pointing) for inspection. Even though the participants recurrently used physical interactions such as pulling and pressing the bars and were confident in doing so, none of them managed to explore the entire dataset.

Overall, the findings confirm that physicalization of data engages users in exploring and thinking about data. However, participants were overwhelmed by the amount of data that was conveyed in the physicalization.

**What can be learnt:** physicalizations are engaging, but their many dimensions can cause an overwhelming amount of information.

## 4.6. Logic Gate Physicalization

Even though only few physicalizations have been subject to scientific research, multiple non-scientific attempts have been made to physicalize logic gates, which are also included in

fault trees. These physicalizations can be made with day-to-day objects, like toys, but can get complex soon. The physical logic gates below confirm this, but can still be used as an inspiration for the ideation phase.

#### 4.6.1. Dominos

In a video by Michael Littman [17], it is explained how dominos could be used for the physicalization of logic gates, as can be seen in figure 11. In this case an OR-gate is physicalized: if the input of both leaves is zero, the output is zero as well, while if either one of them has an input of one, the output is also one.



*figure 11: an OR-gate physicalized with dominos*

**What can be learnt:** simple toys like dominos can be used to show the propagation of risks, but take time to reset.

#### 4.6.2. Marbles

Michael Littman [17] also proposes physicalizing logic gates through marble tracks, of which an example is displayed in figure 12. This too represents an OR-gate, only giving an output if zero when both marbles are rolled down from the zero state.

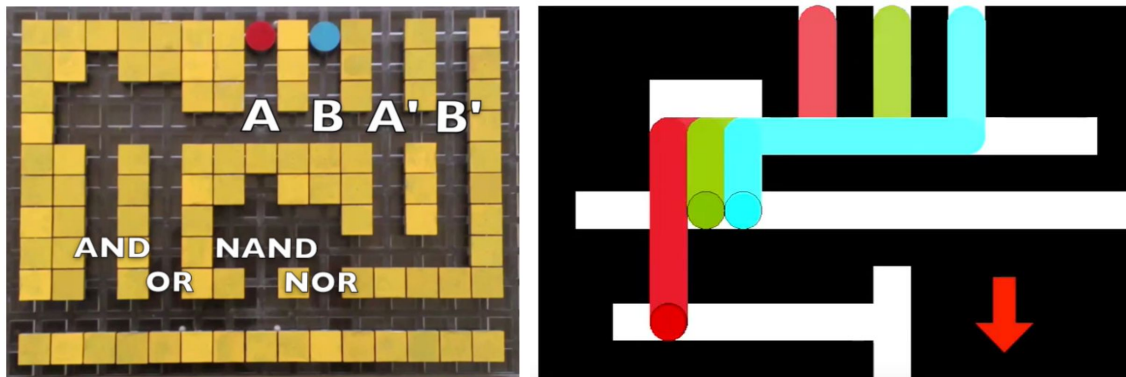
**What can be learnt:** simple toys, such as marble tracks, can be used to physicalize logic gates, but these physicalizations can get complex soon (figure 12).



*figure 12: an OR-gate physicalized as a marble track*

#### 4.6.3. Tilt

To physicalize decision trees which should give insight in complex problems, Tilt was created [18]. It consists of a board with entries enclosed by blocks, through which multiple discs can travel (figure 13). The user can tilt the board around in order to make the discs move through the entries. Depending on both the number of discs that are put into the system and the movements the user makes with the board, a certain output is given.



*figure 13: a) logic gates physicalized with the Tilt system and b) the process of the pucks sliding through the board*

A more complex decision tree made out of a model for Tilt is displayed in figure 14. When all twelve discs are put into the system, the outcome (“True” when one ends up in the grey box on the left and “False” if it all end up in the large box on the right) is dependent on the sequence of movements that is made by the user, of which a more detailed description is displayed in figure

15. With this system complex decision trees can be physicalized in an interactive way, although the user has to be informed about the meaning of each movement.

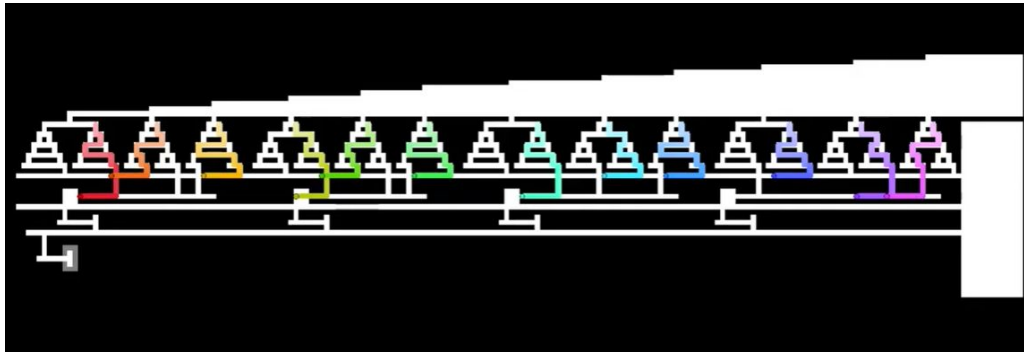


figure 14: decision tree with twelve inputs visualized as it would work on a Tilt board

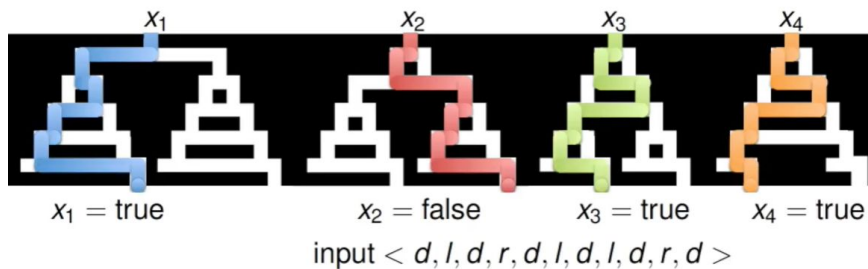


figure 15: detailed description of how a certain movement can lead to a certain output

**What can be learnt:** even complicated decision trees can be physicalized, but their complexity makes it hard to use and understand the physicalization.

## 4.7. Visualization Techniques in State of the Art

All projects in the previous sections use visualization or physicalization. Some of them use certain visualization techniques well, while others lack these techniques. To classify the uses of techniques, Table 2 shows whether the techniques have been used well or should have been used better. Table 3 motivates these classifications. When looking at Table 2, it is remarkable that visualizations and physicalizations often fail to use the right colours, while shapes and positions are used well more often. This can be taken into account during the design phase.

Table 2: Visualization techniques in state of the art projects

Project	Contrast	Colour	Shape	Position	Anno- tations	Com- plexity	Graph layout
Legend	Used well			Should have been used better		Not applicable in this visualization	

Prostate Cancer Visualization [10]							
Riskful Situation Advice [11]							
Risks in Shipbuilding [12]							
Flood models [13]							
AppWare [14]							
Zooids [15]							
Physical bar charts [16]							
Logic gate dominos [17]							
Logic gate marble track [17]							
Tilt [18]							

Table 3: Motivation for the categorization in Table 2.

Project	Motivation
Prostate Cancer Visualization [10]	The use of simple shapes, colours and proximity makes the different visualizations easy to understand [23][24]. Improvement points are the quantity of text (should be decreased) [23] and the use of orange and green in one pie chart (hard to distinguish for colourblind people) [24].
Riskful Situation Advice [11]	Contrast between different situations is used well, just as part of the colour associations (red and blue for temperatures for example) [24]. However, since the different visualizations are displayed separately, it is hard to identify the difference between some situations [24]. Furthermore, the



	volume of a sphere might be hard to perceive for humans, so it is not the best option for visualizing data [24].
Risks in Shipbuilding [12]	The contrast of simple shapes is used well for distinguishing causes from risks [19]. However, the colours of the nodes seem to have no meaning and use ordering of frequencies with hue instead of brightness or saturation [24]. Moreover, due to the number of crossing edges the visualization becomes quite complex [23].
Flood models [13]	The flooding visualization is easily understandable, due to the use of context [23], associative colours (such as blue for water) and saturation colour scales [24]. The different situations in figure 9 are also easy to compare due to their proximity, although they might contain too much information that cannot be easily processed by a viewer [24].
AppWare [14]	Since these visualizations are quite literal, they are easy to understand, although the lack of associative colour use might not trigger the right response from a user [24]. Furthermore, the use of photos might give more information than needed, while simple icons with appropriate colours would have given off a clearer message [23].
Zooids [15]	Using simple shapes and proximity improves the accessibility of this physicalization [23]. However, the lack of information about the data points on the physicalization itself (legends, axes etc.) makes it impossible to understand what is being physicalized without looking at the settings on an accompanying tablet.
Physical bar charts [16]	By placing the bars for each country and year close to each other, it is easy to see their contrast and compare them [24]. Even though the colours might not be that associative, they make sure that it is easy to differentiate between each category. The simple shapes that only vary in height are easy to understand [23] and the axes give the appropriate amount of information. However, the number of bars makes the visualization complex by supplying too much information, so a user is not able to understand the whole dataset without looking at all parts separately [24].
Logic gate dominos [17]	The zeros and ones (annotations) make the physicalization understandable, but the lack of other visual clues might not make it that intuitive. If colours were added to indicate the input and output, it would take less effort and time for a user to see what is meant with the physicalization. The use of



	recognizable shapes (dominos) does decrease the complexity of the physicalization [23]. Furthermore, the reading direction (left to right) makes the propagation process logical [24].
Logic gate marble track [17]	The zeros and ones (annotations) make the physicalization understandable, but the lack of other visual clues might not make it that intuitive. Currently the random colours are quite distracting, but if colours were used to indicate propagation process from the input towards the output, it would take less effort and time for a user to see what is meant with the physicalization. The reading direction (top to bottom) does make the propagation process logical [24].
Tilt [18]	The process of using the Tilt board (figure 13.a) is complex due to multiple factors. No visual explanation is given to indicate the meaning of the pathways and the movements that need to be made to use it. The only visual aspect to make it more understandable, is the use of different colours for different inputs (red and blue discs). Maybe (illuminating) colours could be used to indicate the sub-paths that have to be taken by each disc and illuminating arrows (possibly with an attractive flicker) for indicating the movement that has to be made for asking a certain “question”. Furthermore, the two different outcomes (True or False) should be indicated with clues such as annotations, shapes or colours. The shapes used do slightly resemble trees, so the subject can be recognized through shapes.

## 4.8. Conclusions

### 4.8.1 Improvement of the Explanation of Risks

Faulty explanation of risks often cause miscommunications in engineering projects. This can be avoided in multiple ways. One of these is making an explanation unambiguous enough to evade multiple possible interpretations when different perspectives occur, for example by avoiding technical jargon. Secondly, the communication of bad news should be made easier and more explicit, averting the slow spread of this type of news. Not only the people involved in giving or receiving the explanation should be taken into account, but the situation as well: this should give people the chance to communicate clearly, without being pressed by other issues or distractions. Finally, engineers should be able to use a more informal way of explaining risks, instead of only using formal presentations and e-mails; they should find a way to give a clear face-to-face explanation of their work.

#### 4.8.2. Increasing the Effectiveness of Fault Trees

Generally, non-experts in the field of risk management or engineering have more difficulty in understanding fault trees than experts. A fault tree can give a good general overview of the risks, but the knowledge is often too limited to make informed decisions based on fault trees. For decision makers, the leaves should contain more detailed information about the events and safety requirements. Another way of making more informed decisions based on fault trees, is placing each leaf inside a category. This way, it is more explicit what kind of fault is described by each leaf and specific experts can be asked for more information based on the category.

#### 4.8.3. Attractive Factors for Physicalization

Many factors can make a physicalization (or visualization) attractive. However, a general remark for almost all factors is to focus on the important aspects, minimize the rest and keep it simple. Examples of this are basic shapes, using a minimum number of colours and avoiding to supply too much information. Another important way of making a physicalization more understandable, is using the association viewers have with the subject matter, like colour combinations or certain shapes. In the projects in the state of the art it became clear that shape and position are often used well in visualizations and physicalizations, while there is a lack of associative colours.

## 5. Specification

After formulating partial conclusions to the subquestions, the design phase started. The goal of this project is to build an attractive installation with fun interaction that clearly explains how a fault tree works to non-expert. Based on this goal and literature, we found multiple requirements, which are described in part 5.1. The most important ones are that (1) no background knowledge must be needed to understand the installation, (2) a fault tree layout must be recognizable in the installation and (3) the visualization techniques must be used, like associative colours and shapes. These design requirements can serve as a framework for designing an application that is supported by literature, to increase the effectiveness of the installation. From the generated ideas with this framework in mind, I chose the idea of using a marble track to explain a fault tree of the HVAC system in trains (section 5.2). The main functionalities and mechanisms of this marble track are described in section 5.3. Based on these, the functional requirements of the physicalization are listed, which focus on the prioritization of the mechanisms that make the marble track work as an interactive fault tree. The most important ones include (1) an AND-gate mechanism that only allows an output marble when there are two input marbles, (2) a train of which the wheels stop spinning when the top event is reached and (3) marble slots that allow users to select basic events themselves. With these requirements and the designed mechanism, it is possible to start building the installation, as described in chapter 6.

### 5.1. Design requirements

Based on the goal of this research and the state of the art, seven requirements were found. Each requirement is prioritized using the MoSCoW model (Must, Should, Could, Won't). In general, the goal of this project is to build an attractive installation that explains how a fault tree works to non-experts. To do so, I want to show one of the most important and basic features of the fault tree: the propagation from a leaf towards the top event. The target audience consists of all non-experts in risk management engineering, which is why this basic part of the fault tree was chosen. Since explaining fault trees as a risk model is the goal, the installation must include the most important features of a fault tree lay-out. Making the installation attractive must be done by using the visualization techniques found in the state of the art.

#### 5.1.1. Requirements to increase understanding

- **Background knowledge - Must**

Literature stated that miscommunication often occurs due to a variation of background knowledge [3]. Therefore, to understand the installation, no deep background knowledge in risk engineering must be needed [7]. This is an important requirement, because the goal of the installation is to explain risks to non-experts. To keep it simple, the most basic feature of the fault tree must be shown by the installation: the propagation from a basic

event to the top event through the fault tree. This means the physicalization must contain a moving element that travels from a basic event to the top event.

- **Bad news - Should**

The literature research also pointed out that risks explanations suffer when people are not open to receiving bad news [1]. To avoid such reluctance, the installation should have a light-hearted impression. This is not essential, but still important for optimizing the impact of the installation. To keep the installation the interaction with the installation should be playful.

- **Informality - Should**

Engineers lack training in informal communication [4], which makes it harder for them to explain themselves in informal face-to-face meetings. The installation should therefore give an informal impression (meaning relaxed, friendly and unofficial [29]), in order to assist them during these types of explanations. This way, it is easier for engineers to explain fault trees in an informal way. Informality is an important requirement, since the lack of skill in informal communication is an important factor in faulty risk explanation. However, informality is not crucial for explaining fault tree models, which is why this is a Should requirement. For informality the interaction with the installation should be playful and colours like black (sophistication) and grey (maturity) should be avoided.

- **Fault tree design - Must**

The goal of the installation is to explain how fault trees work. Therefore, it is important that the fault tree is easily recognizable in the installation. To achieve this, the installation must contain indications of basic events that are connected through OR and AND-gates with the top event in a tree-like shape.

- **Leaf categorization - Could**

Each leaf of the fault tree could be divided into a category that is visible in the installation, since Martins and Oliveira [9] state that this makes informed decision making easier. Since the target audience is not only decision makers, but non-experts in general, this requirement is not as important as others.

- **Leaf explanation - Could**

Each leaf could contain an explanation of its basic event, as proposed by Martins Oliveira [9]. Again, this requirement focuses mainly on decision makers, while the target audience is broader than that.

### 5.1.2. Requirements for attractiveness

- **Association with trains - must**

To reduce complexity by showing context, the installation must have a theme associated with trains, since an train fault tree is used for the installation (figure 16). In order to do this intuitively, the shape of an actual train must be used.

- **Association with failure - must**

For the association with failure, the shape of the fault tree must be displayed in red.

- **Using colours for focus - should**

To focus attention on the important parts of the installation, the basic events, fault tree path, gates and top event should use highly saturated colours, while the larger surfaces should have a lower saturation.

- **Minimizing annotations - should**

The use of annotations should be kept to a minimum in order to decrease complexity, meaning only the crucial text has to be used (such as the basic events), while other indications should be shown by means of visual elements. An example of this is the failure of the top event, which must be clearly indicated with visual clues, such as the aforementioned shape of a train.

- **Reading direction - should**

To keep the installation logical for users, their reading direction should be taken into account. Elements that need to be interacted with first, should be at the top and/or left of the physicalization, working downwards / to the right from there.

- **Fun interaction - must**

In order to make the installation attractive for people to use, the interaction must be fun. This can be done by using playful and easy to understand interaction elements. As can be seen in the state of the art, logic gates can be physicalized by recognizable objects like toys, which are fun and easy to interact with.

## 5.2. Ideation

Brainstorming techniques are used to come up with multiple ideas to create a physical installation according to the requirements listed above. These ideas can be found in the Appendix. When looking at the requirements, multiple ideas from the ideation are options for reaching the goal. However, using a marble track feels most intuitive. In this idea, a marble is used to show the path through the fault tree from a basic event to the top event. This feels intuitive, due to the causal relationship between gravity, the selected leaf and the path followed from the leaf to the top event, which represents the propagation from a basic event to a system failure well.

## 5.3. Design

To make a marble track work as a fault tree, certain mechanisms have to be used, for example a mechanical switch that only has a marble as output if it has two marbles as inputs (like an AND-gate). Furthermore, I chose to show the occurrence of the top event by using a train figure of which the wheels stop rotating. In order to implement colour association, the fault tree is shown with red lines in the installation. These mechanisms and design choices are described in

this section. Understanding these is essential to create an effective prototype. The installation uses the train fault tree in figure 16.

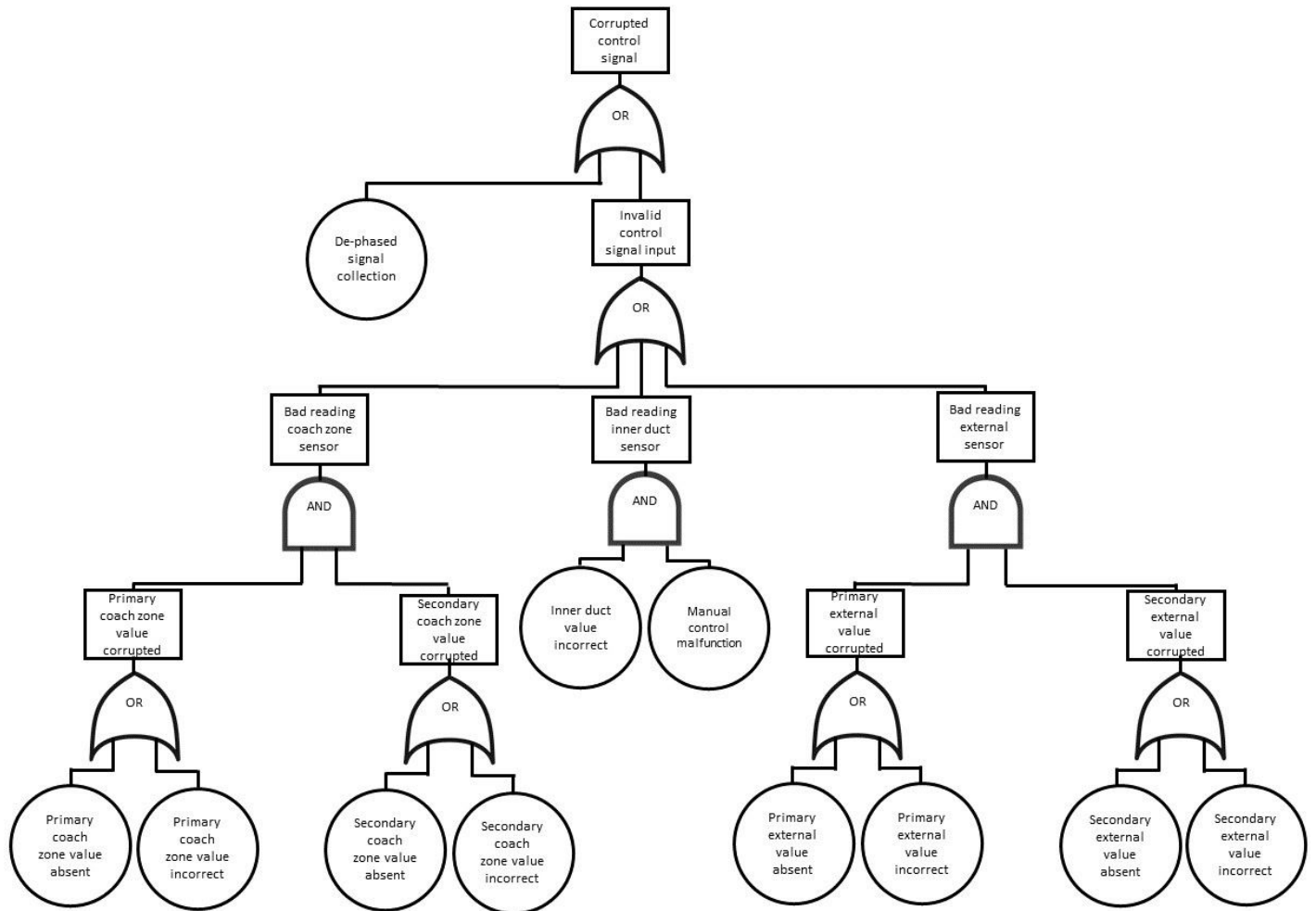


figure 16: train fault tree that is used for the physicalization

### 5.3.1 Overall process

figure 17 shows the sketch of a marble track representing a fault tree used for Dutch trains. The physicalization shows the propagation inside a fault tree from a basic event to the top undesired event, which is on the bottom of the installation.

1. At the top of the installation eleven marble slots are located. Each slot is positioned above a basic event: the user can choose basic events by placing a marble in their slots.
2. If someone wants to see what happens when a basic event (represented by the white circles in figure 18) occurs, they can pull on the drawer under the marble slots. A slit in the shelf on which the marbles were resting is moved underneath the marbles, through which the marbles roll into the track (section 5.3.2.). In most cases, the marbles roll

towards an AND-gate. Only if marbles roll in both of the input paths of the AND-gate, the AND-gate outputs a marble.

3. After rolling over the remaining OR-gates, the marble ends up at the train with spinning wheels. A sensor sees the marble has reached the top event and sends a signal to the motors that make the wheels spin, after which the wheels stop spinning for 10 seconds (section 5.3.4.). This way, the user knows that the chosen basic events cause the train to stop.

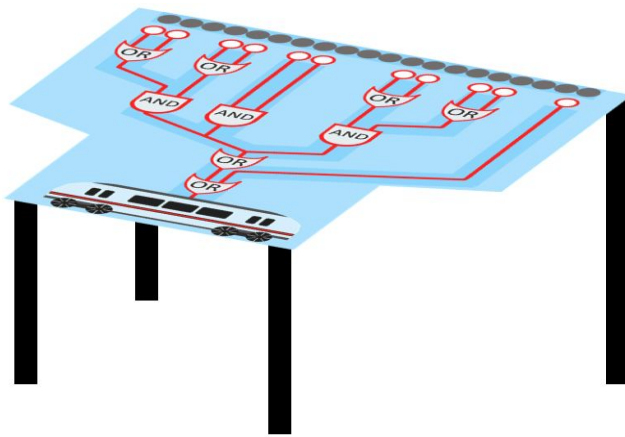


figure 17: Sketch of train fault tree marble track

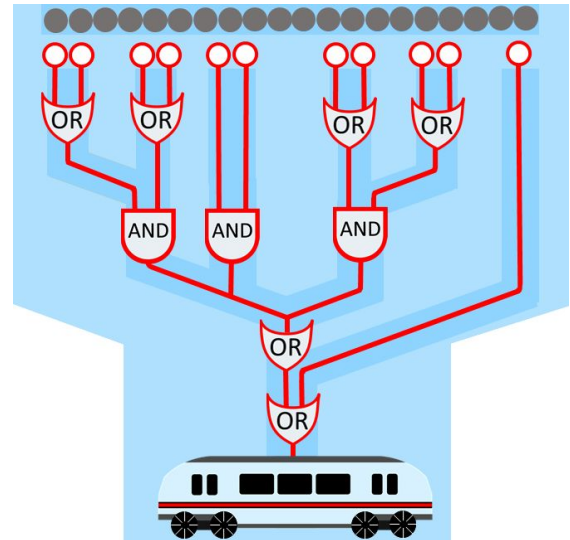
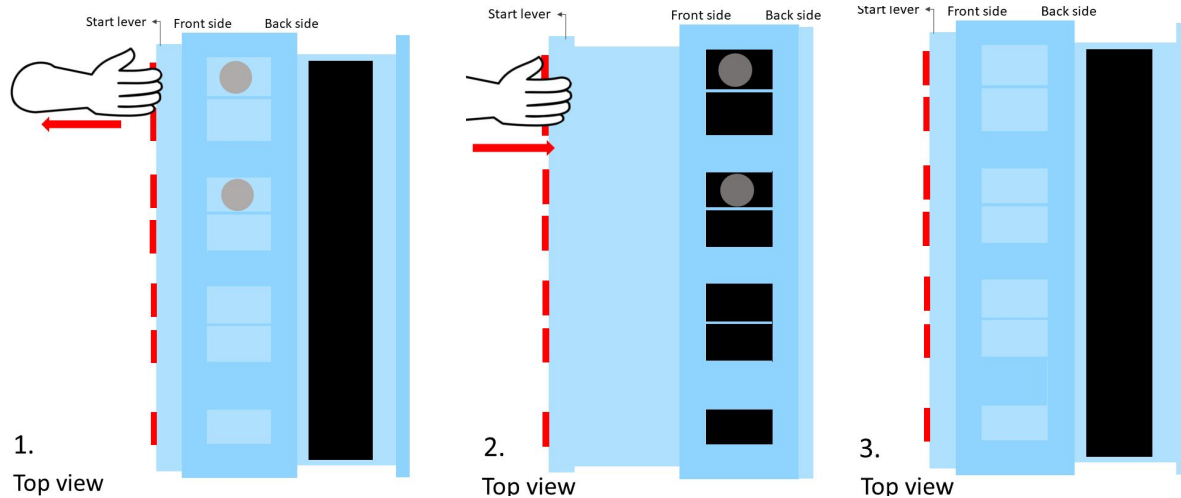


figure 18: Top view of marble track

### 5.3.2. Basic events

A user can activate the installation by placing marbles in the basic event slots and pulling on the handle attached to the drawer underneath the marble slots. At the backside of the drawer is a hole/slit which is slightly larger than the diameter of the marble. When the drawer is pulled towards the user, a barrier stops the drawer from moving further, which places the hole right underneath the marbles that were first supported by the other side of the board (figure 19). This causes the marble to fall through into the track leading to the tree gates, allowing users to see the propagation from a basic event into the rest of the fault tree. When a new session with the marble track starts, the drawer should be placed into its original position again.



*figure 19: If a basic event is pulled, a hole is moved under the marble lying on top of it, causing the marble to fall through it into the fault tree track*

### 5.3.3. AND-gate

On its way from a basic event towards the top event, the marble meets an AND-gate in most cases. Therefore, a mechanism should be used that only allows a marble to roll further downwards if it has two marbles as input, which is displayed in figure 20. A diagonal beam blocks the path of one marble (right), stopping it from rolling further downwards. Only if a second marble rolls down the second path (left), the beam is flipped over in an upright position, allowing the first marble (right) to roll further downwards. The second marble (left) strands after flipping the board over and rolls to a marble reservoir at the bottom of the installation. This mechanism only allows a marble to roll further downwards when both marbles serve their tasks, which means it acts as an AND-gate.

After one user session with the installation, the beam should be placed back to its diagonal position. To indicate that this has to be done, a sticker is placed underneath the board (the yellow block in figure 20). This sticker has the diagonal position the board should be in. This way, it is only visible when the board is in the wrong position and immediately indicates how the board should be placed.



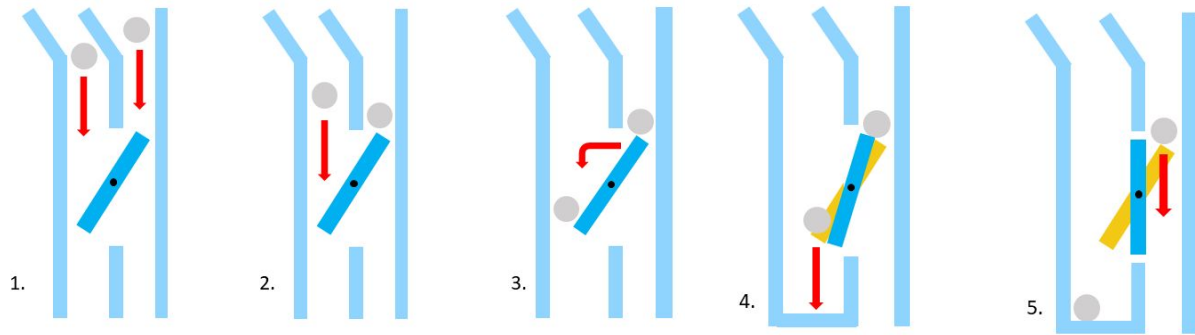


figure 20: The AND-gate mechanism. One marble (right) falls onto the orange board, which blocks its path from rolling further down. The second marble (left) falls onto the board, pushing it in an upright position, allowing the first marble to roll further down again.

#### 5.3.4. Train

A figure of a train is present at the bottom side of the installation, under the last OR-gate. This train has four wheels, which rotate (using DC-motors) when the installation is in default mode (figure 21). If the selection of a basic event causes the marble to end up at the last OR-gate, meaning the top event is reached, these wheels stop rotating for an interval of 10 seconds. This is done by connecting a motion sensor to the same Arduino as the DC motors. After the marble has passed the sensor, it disappears to the reservoir at the bottom of the installation.

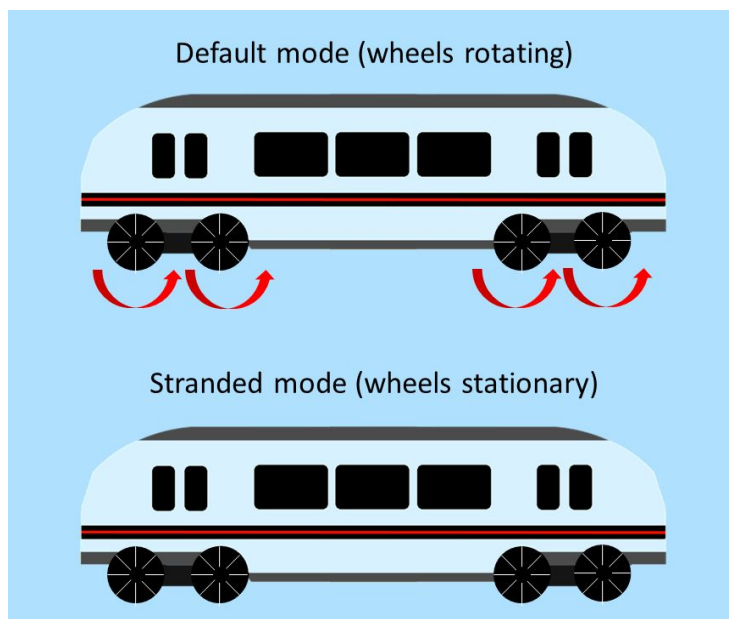


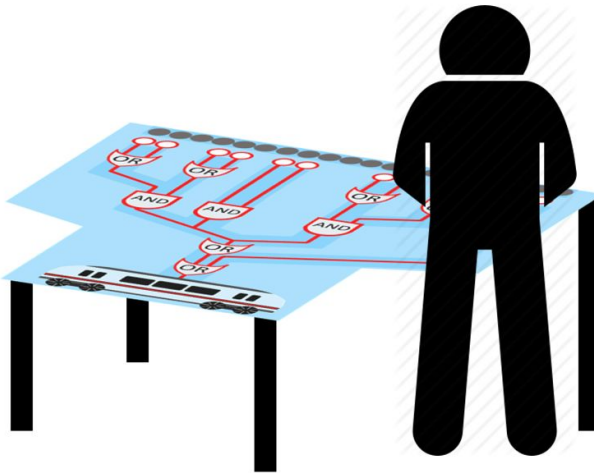
figure 21: When a marble reaches the top event, the wheels of the train stop spinning.

## 5.4 Storyboard

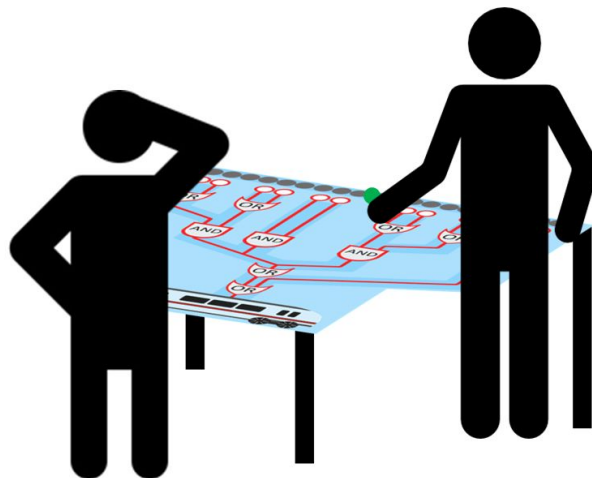
The description of the design above mainly focuses on the technical aspects of the design. In order to see how a user would interact with the product, I created a storyboard (figure 22). The storyboard shows how a risk engineer can use the physicalization to explain fault trees to his manager, which is one of the most important user scenarios.

**This is Pete. He is a risk engineer who analysed a train system. However, he has difficulty explaining the risks of this system to his manager. To clear it up, he uses the physicalization of a fault tree.**

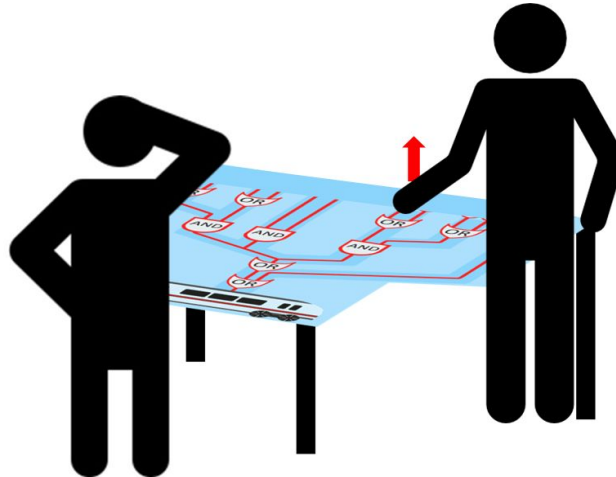
**Pete wants to show how a combination of two failures leads to the train system failing completely.**



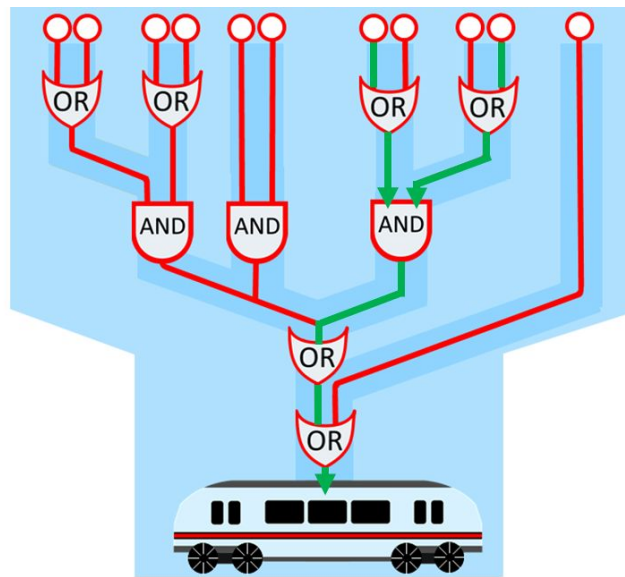
**Pete puts marbles above the two failures he wants to explain to his manager.**



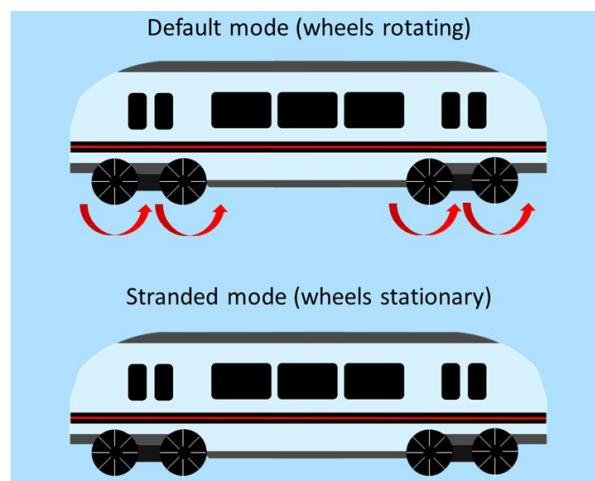
Pete pulls the start lever, causing the two marbles to roll into the marbletrack.



Pete and his manager observe the marbles rolling through the installation. After rolling through separate OR-gates, both enter the same AND-gate. Only one marble exits the AND-gate and follows the path through the last two OR-gates, after which it disappears behind the train.



When the marble has reached the bottom, Pete and his manager observe that the wheels of the train stop rotating for 10 seconds.



Now Pete can explain easily how two failures of the system can cause the whole train system to fail. His manager understands and can make informed decisions about the system.



figure 22: Storyboard showing a possible use of the installation

## 5.5 Functional requirements

A design was made to include the most important design requirements. This design in turn leads to functional requirements. All functional requirements of the installation are listed in Table 4, according to MoSCoW priorities. These are important to keep in mind while building the installation, since the Must functionalities should be implemented first, after which the Should features are included. If possible, the Could features can be implemented as extra functionalities, but these are not important for the main goals of the installation.

Table 4: Functional requirements sorted into MoSCoW priorities

Must	Should	Could
A marble only rolls out of an AND-gate when two marbles roll into it	One start lever allows marbles from all basic events to roll into the track at once	Resetting the AND-gate is automated
The wheels of the train stop rotating when a marble reaches the top event	A marking on the track shows how the AND-gate should be placed before using the installation	
Marble slots above each basic event allow users to select basic events themselves	The track should be supported by legs so it does not need the support of another table	

## 6. Realisation

With the theoretical design in mind, an installation was built. I managed to implement all functional requirements, except for automating the resetting of the AND-gates. When looking at the sketches in the specification chapter, two things were added: a marble reservoir underneath the train representing the top event and a handle in the middle of the basic event drawer.

By building the installation, it is possible to test whether the design of this marble track actually helps to solve the listed problems and achieves its goals. In this chapter, the building process is captured in photos and the implementation choices are motivated. Please note that this installation was built during the home isolation in the corona crisis, meaning certain professional equipment (like laser cutters) was not available.

### 6.1 The building process

#### 6.1.1. Back plate

The building process started with making a back plate for the track. The part of the wooden plate that serves as the marble track was painted, after which I installed beams that can guide marbles through the installation (figure 23).



*figure 23: The back plate of the installation, including beams which guide marbles over it*

#### 6.1.2. AND-gates

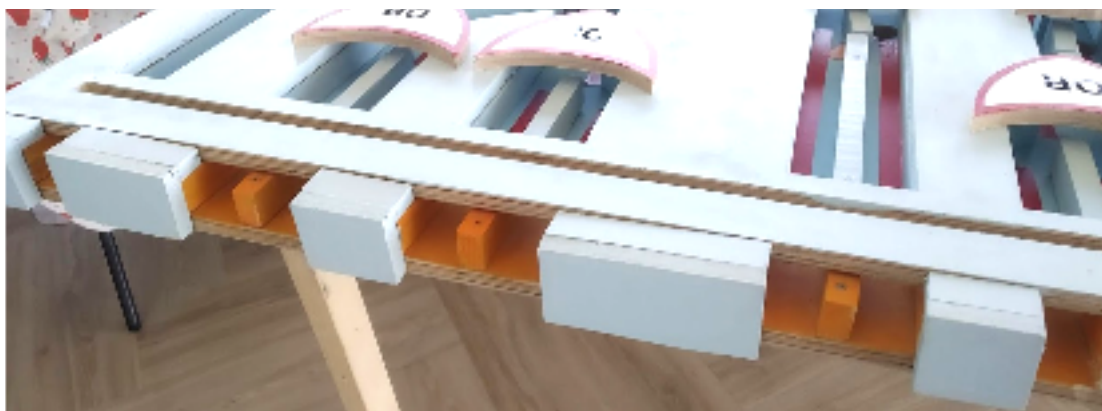
When attaching the guiding beams to the back plate, the AND-gates were also implemented. I placed a separate beam with iron wire as a rotational axis in between two guiding beams, at the locations of the AND-gates. One marble (right path) can rest on this rotational beam, another (left path) can flip it upright (figure 24) and roll into a hole. This way, the right marble rolls

further to the top event when the left marble flips it upright, but the marbles cannot separately roll to the top event.

The “shadow” of the default position of the rotational beam was painted orange on the back plate (figure 24), to show how it should be placed before using the installation. Later, I chose to make the marble slots the same colour (figure 25), to colour code the parts of the installation that require interaction.



*figure 24: a) The AND-gate in its default position and b) the AND-gate after it was flipped upright by a marble in the left path.*

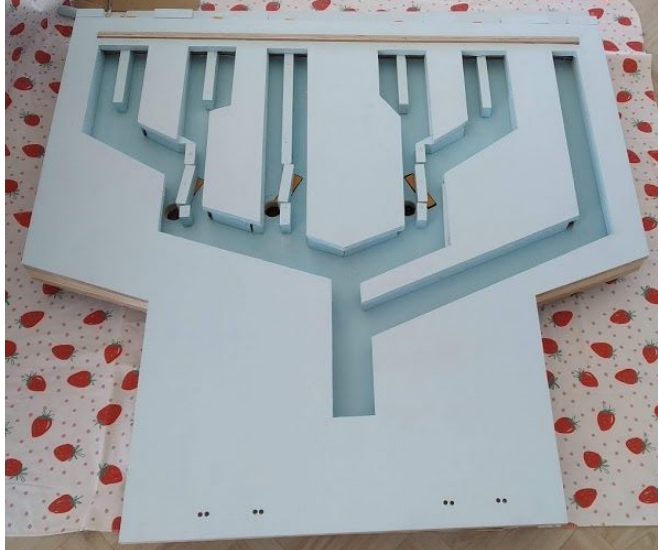


*figure 25: The marble slots are orange to show this part of the installation requires action*



### 6.1.3. Front plate

After I made sure the track on the back plate worked (including AND-gates), a front plate was made with a circular saw (figure 26). This focuses attention on the paths of the marble track and gives it a cleaner look.



*figure 26: The front plate lying on top of the backplate, focusing attention on the fault tree paths*

### 6.1.4. Train

A train shape and four wheels were sawn out of wood, painted and finished off with tape (black, red and white stripes), as displayed in figure 27. Then I attached the wheels to the axes of four DC-motors and placed the motors on the front plate. A reflective TCRT5000 sensor was placed at the end of the path under the train and was connected to the same Arduino as the motors (full schematic and code can be found in the appendix). Since the sensor sometimes has a random value as output, a switch-case mechanism was implemented in the code, that checks if there are multiple “marble” values close to each other. This way, it knows when there is a marble and when the value is just random noise.



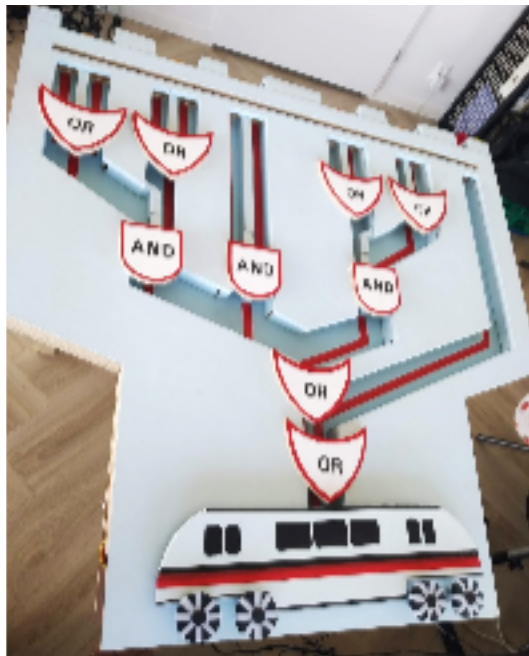
*figure 27: The train wheels are attached to DC-motors and the train coach to the front plate.*

### 6.1.5. Fault tree features

The Must functional requirements were applied in the sections above, but the Must design requirement of the installation having a fault tree formatting not yet completely. To achieve this, OR and AND-gates were sawn and painted by hand (since a laser cutter was not available in time) and finished with letter stickers (figure 28 and 29). I also connected the gates with red lines (tape) to apply more focus to the fault tree paths (figure 29).



*figure 28: The OR and AND-gates were a) sawn out and b) painted by hand*



*figure 29: The installation including gates and red paths*



### 6.1.6. Legs

To make sure the installation can be used without the need of anything else but electricity, four legs were attached to the lower side of the back plate (figure 30). I attached them with screws, so they are easily removable for transportation.



*figure 30: Four legs support the marble track*

### 6.1.7. Marble reservoir

Even though this was not included in the sketch, a marble reservoir was attached at the bottom of the installation (figure 31). Both marbles falling through the AND-gate holes and rolling to the top event end up in this reservoir. This way, users can easily grab marbles to put into the basic event marble slots and all marbles end up at the same place again after using the installation.



*figure 31: After falling through an AND-gate hole or rolling to the top event, marbles end up in a reservoir at the bottom of the installation.*

### 6.1.8. Drawer and start handle

The drawer for distributing the marbles from the marble slots into the track was made out of three parts. A board with a slit was sawn, which blocks the marbles in default mode, but lets the marbles roll through the slit when the start handle is pulled (figure 32). I attached a second perpendicular board to it. This board lies on top of the front plate (figure 33), and is also used for displaying the basic events and using the start handle. I placed the start handle in the middle of the board, so that a user only has to grab onto one handle to have all marbles roll into the track (figure 33). On the lower side of the board with the slit, two smaller boards were attached to block users from pulling out the drawer further than necessary.



*figure 32: a) The board with the slit blocks marbles when the drawer is in default mode and b) allows the marbles to roll through when the start handle / drawer is pulled.*



*figure 33: The start handle is placed in the middle of the basic event board, so only one hand is needed to make the marbles roll into the track*

### 6.1.9. (Basic) Events

After the previous steps, all Must and Should functional requirements were met. The only thing missing at this stage, were the events. With the use of stickers, I applied the circles with the basic events to the upper board of the activation drawer (figure 34). The intermediate events were placed in the same letter size after each gate with photographic paper. I chose not to place a label of the top event after the last OR-gate, since the top event is already represented by the train. With the implementation of the events, the installation was finished (figure 35).

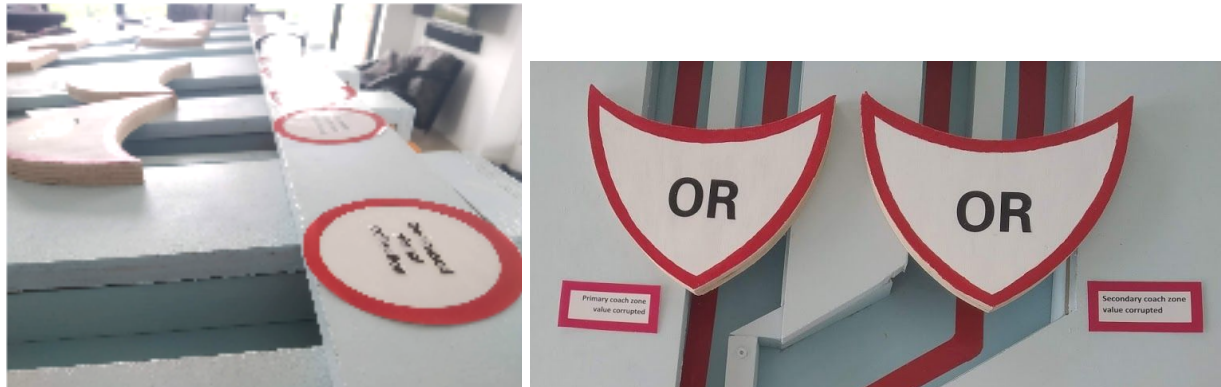


figure 34: a) The basic events are stuck on the activation drawer and b) the intermediate event after each gate

## 6.2 Compliance with functional requirements

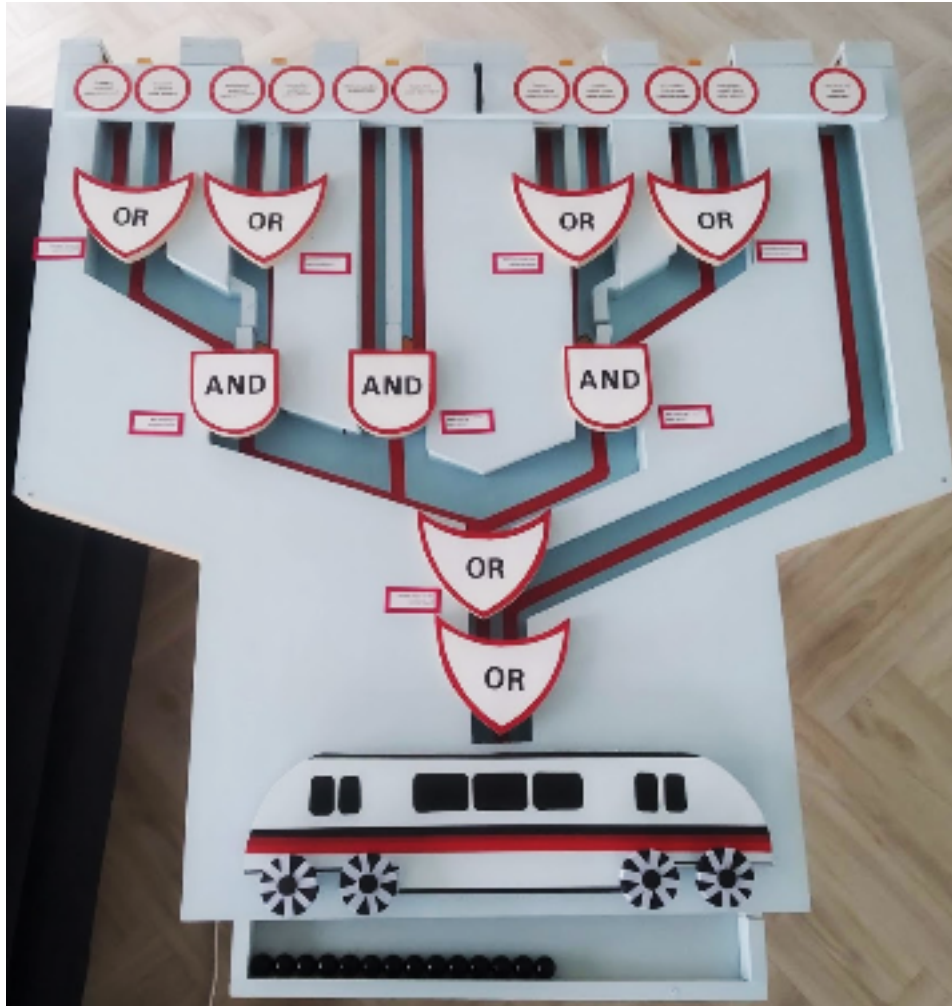
All Must and Should functional requirements have been met (Table 5). Only the Could requirement of making the AND-gates to reset automatically was not met. I brainstormed about ways in which the gates could be reset with one action (a button or a lever for example), but all of these were too technically complicated to fit into the scope of this research. It was therefore decided that the orange marking of the default setting of the AND-gate is used as a communication tool to tell users the beam has to be placed in this position before use. This way, users do have to reset them manually, but are told to do so by visual clues.

Table 5: Functional requirements sorted into MoSCoW priorities. Green = met, Red = not met

Must	Should	Could
A marble only rolls out of an AND-gate when two marbles roll into it	One start lever allows marbles from all basic events to roll into the track at once	Resetting the AND-gate is automated
The wheels of the train stop rotating when a marble reaches the top event	A marking on the track shows how the AND-gate should be placed before using the installation	

Marble slots above each basic event allow users to select basic events themselves

The track should be supported by legs so it does not need the support of another table



*figure 35: Top view of the installation*

## 6.3 Conclusion

A prototype of the marble track fault tree was built, including the most important functional requirements. It was designed to clearly explain fault trees to non-experts in an attractive way, including fun interaction. After building the prototype it was possible to evaluate with users whether these goals have been reached. We discuss this evaluation in the next chapter.

## 7. Evaluation

After building a prototype, the marble track was evaluated. The evaluation consisted of two parts: semi-structured interviews with experts and a survey among non-experts. The experts confirmed the relevance of better fault tree explanations and thought the installation can be used in a variety of contexts. To make the explanation deeper and more realistic, they advise to also add more complex fault tree features, such as other logic gates and probabilities. The surveys amongst non-experts showed that the installation is considered attractive and it increases confidence in understanding fault trees. However, when checking this understanding, no significant evidence was found that proved that the installation increases understanding indeed.

### 7.1 Interviews with experts

To evaluate the installation with experts, 3 risk consultants in engineering departments of different companies were interviewed. They all confirmed the relevance of better risk model explanations and argued that the installation can be used well for introducing students or employees to fault trees. To give a deeper and more realistic explanation, more complex fault tree features could also be added in the future according to the experts. The interview questions and answers can be found in the appendix.

#### 7.1.1. Relevance of the installation

When talking to the risk experts, they confirmed that communication involving fault trees can be difficult. The engineers who design constructions often find it hard to think in terms of risks, while less technical employees do not always understand logic gates. Another misunderstanding is that safety (being protected from danger) and reliability (performing consistently well) are not related, while they are often correlated: the reliability of a warning system also causes safety. Even though decision makers often base their decisions on the advice of risk engineers, they do sometimes ask for an explanation, making it important for them to also understand risk models. Factors such as redundancy can also be more easily discussed with an understandable fault tree.

#### 7.1.2. Usage in other contexts

According to the experts, the marble coaster could be used in multiple contexts. Since the specific fault tree in this installation is relatively simple, it would mainly be used as an introduction to fault trees. This might for example be useful in educational courses or company training and when presenting to colleagues or managers of other companies. Another possible application of the installation is business fairs: the installation can be used as an eye-catcher for recruiting people or to show what a risk department does. To make it applicable for different companies, the basic events and top event could be made to be easily adaptable, for example by making it easy to replace the train with a bridge.

When using the installation, it should be critically considered if the receiver of the explanation really needs and likes it. Experts mentioned that some might experience the marble track as childlike, although toys like model trains are already in use in some companies for technical explanations.

### 7.1.3. Recommendations

The experts argued that the installation serves as an excellent introduction about fault trees. Even though qualitative fault trees are important to get a good overview of a system and AND and OR-gates are often enough, the experts recommend to also add more complex fault tree features. Examples of this are the concepts of redundancy and common cause in basic events. Moreover, more complex logic gates (like voting or XOR-gates) could be added for a more complete explanation of fault trees. In order to make the explanation of the fault trees more realistic and complex, it could also include probabilities, for example by automating the marbles to roll into the track with a certain frequency (in this scenario the AND-gates should also be reset automatically). Finally, sometimes parts of the fault tree are not important or active in certain contexts, so deactivating part of the marble track could be added to show this.

## 7.2 User tests

The most important goal of this research is to design an attractive installation with fun interaction that makes fault trees more understandable to non-experts. By executing surveys with 38 participants, this goal and the other design requirements were evaluated. The participants of the user test assessed the installation to be attractive and fun to interact with, while being generally neutral about it being informal. For testing the participants' understanding, they were put into two groups: 19 participants answered questions based on a video of the installation, the other 19 were in a control group that answered the same questions based on a textual explanation. They understood the concept of fault trees well based on the installation, but did not score significantly higher on understanding than the participants who only read a text explaining fault trees. Participants did feel more confident about their understanding after watching an explanation video with the installation, when comparing it to only reading a text.

### 7.2.1. Survey

The survey is used for two evaluations: an evaluation on the attractiveness of the installation and an evaluation of the understanding of the users. The participants of the user test are randomly put into two groups, one of which is a control group that has to show their understanding based on a textual explanation. The other group is asked to show their understanding after being exposed to the installation. They are asked the same questions about whether certain combinations of basic



events lead to the top event to check if they understand the fault tree. Furthermore, all participants are asked how much they feel like they understand fault trees: the video group based on the video, the control group based on the text and later also based on the video. Both groups have to answer questions about the attractiveness of the installation: they are asked whether it is visually pleasing, informal, too childlike and fun to interact with. The structure of the survey is displayed in Table 6, where the steps that are only asked to one of the groups are displayed in blue. The whole survey can be found in the appendix, accompanied by the raw results.

*Table 6: Structure of the two different surveys, in which the blue steps are particular for one of the groups*

	<b>Video group</b>	<b>Control group</b>
1	General questions about the participants are asked, like their age group, gender and educational level.	General questions about the participants are asked, like their age group, gender and educational level.
2	The participants are asked to watch a video in which fault trees are explained, based on the installation (YouTube link: [30]).	The participants are asked to read a text explaining fault trees, which is almost the same as the voice-over in the installation video. The text is accompanied by the image of the used fault tree (figure 16).
3	The participants are asked how much they feel like they understand fault trees.	The participants are asked how much they feel like they understand fault trees.
4	Questions about the attractiveness of the installation are asked: the participants are asked whether it is visually pleasing, too childlike, informal and fun to interact with.	Five combinations of basic events are given to the participants and they are asked to answer whether these combinations lead to the top event. These are used to check if the user understands how the fault tree works.
5	Another video shows the participants three cases in which marbles are put into basic event marble slots and roll through the installation. In two cases a marble reaches the top event and the wheels of the train stop rotating, the other one shows a case in which the top event is not reached.	The participants are led to a new page on which they can view the explanation video with the installation [30]. They are asked again how much they feel like they understand how fault trees work (the same as step 3 of the video group).

6	Five combinations of basic events are given to the participants and they are asked to answer whether these combinations lead to the top event. These are used to check if the user understands how the fault tree works (the same as step 4 of the control group).	Questions about the attractiveness of the installation are asked: the participants are asked whether it is visually pleasing, too childlike, informal and fun to interact with (the same as step 4 of the video group).
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### 7.2.2. Attractiveness results

There were 38 participants who took part in the user test, of which 19 in the textual group and 19 in the video group. They were both given likert scales to evaluate the attractiveness aspects of the installation. The average scores (1 = strongly disagree, 5 = strongly agree) are displayed in Table 7 and coloured in a shade of red to green based on the score. The colour for category “too childlike” is inverted, since in this case low scores are positive. The boxplots in figure 36 show the division of the ratings.

Table 7: Average scores for the general categories about the installation

Category	Visually pleasing	Too childlike	Fun interaction
Average score	4.5	2.2	4.1

According to the participants, the installation scores well on being visually pleasing and being fun to interact with (although they could only experience this through a video). The combination of these two tells us that the installation generally scores high on attractiveness. A majority of the participants also said that they did not think the installation was too childlike.

Multiple participants commented that they liked the visual clue of the stopping train wheels when the top event occurs. One participant proposed to also add lights to the train, to clarify even more that it was about a system shutting down (trains also stop at stations) and another proposed making the top event clue mechanical to keep everything in the same style.

Most participants said they liked the simplicity of the explanation when using the marble track, although one of them argued they would have understood the fault tree even without the installation. The main part of the explanation through the marble track that was evaluated positively, were the logic gates. The participants commented that the marble mechanism is a good way to explain logic gates in general, since they are part of all technological systems.



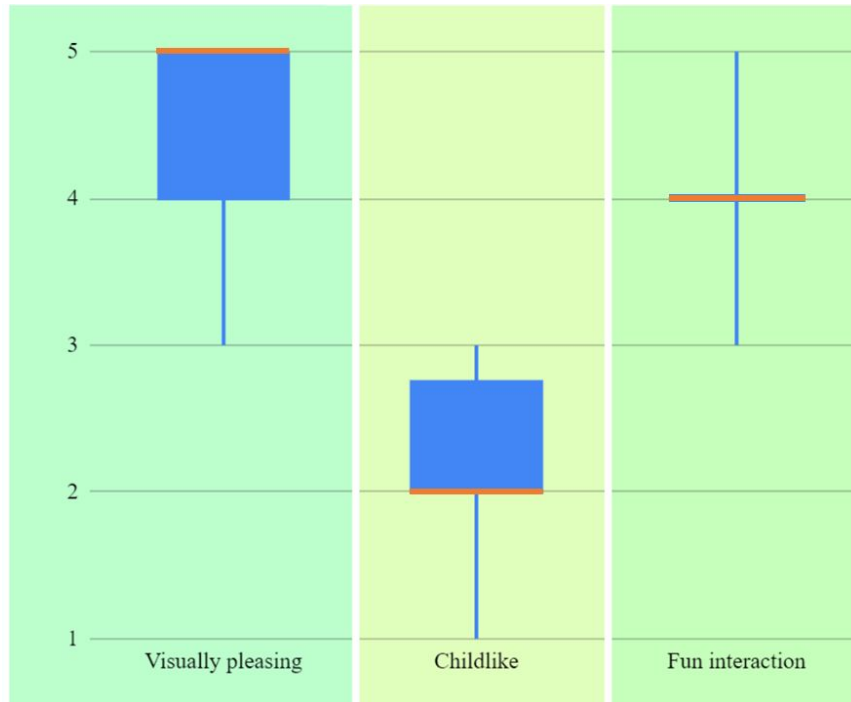


Figure 36: Boxplots of the attractiveness factors

### 7.2.3. Concept understanding results

One group was asked to analyse what combinations of basic events lead to the top event based on a textual explanation, the other based on a video with a similar explanation in the voice-over. However, they were first asked if they felt they understood fault trees after reading the text or seeing the video. Both groups had approximately the same amount of confidence (4.3/5, figure 37). The text group was asked to also watch the video after answering the basic events questions and was asked again about their confidence in understanding the concept. This time, however, they showed a significantly (tested with a Mann Whitney test) higher level of confidence: 4.7/5. It therefore seems like the explanation with the installation does not give more confidence in understanding in itself, while it does when people compare it to a mere textual explanation.

The understanding of the fault tree concept was also tested by asking all participants about 5 combinations of basic events and whether they lead to the top event. Both the textual group and the installation group scored high on average, although the installation group had a slightly higher average (textual: 4.4 and installation: 4.7, figure 38). A Shapiro-Wilk test tells us that the distribution of the results is highly skewed to the left [31], which means that the difference between the results cannot be tested with a t-test (for this a normal distribution would be needed). Therefore, a Mann-Whitney U test is used to see if the difference between the two groups is significant. The p-value when using this test is 0.2 [32], meaning there is no significant difference between the results of the two groups at a 0.05 significance level.

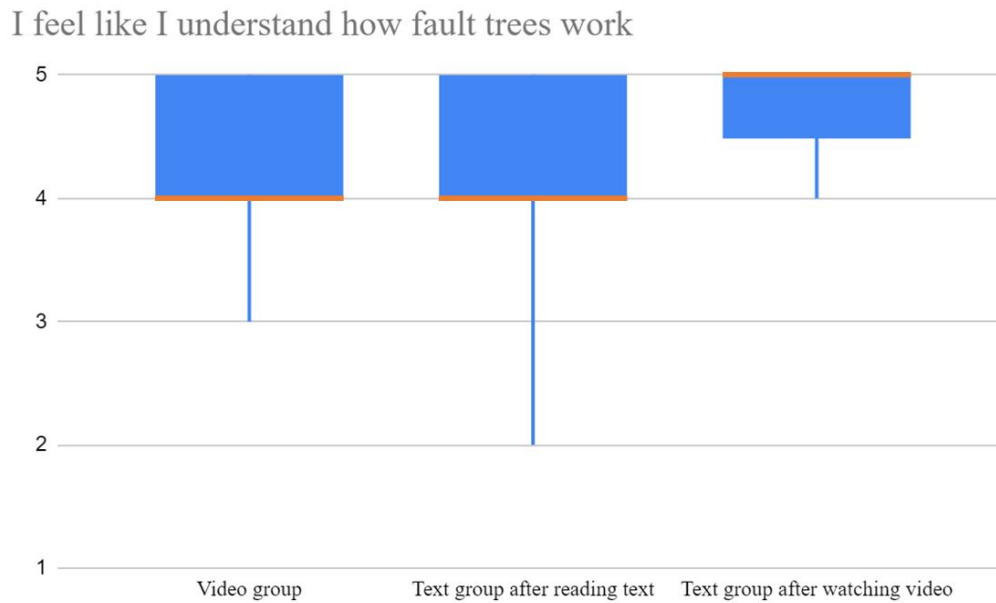


Figure 37: The two groups rating their understanding based on a video of the installation and reading a text about fault trees

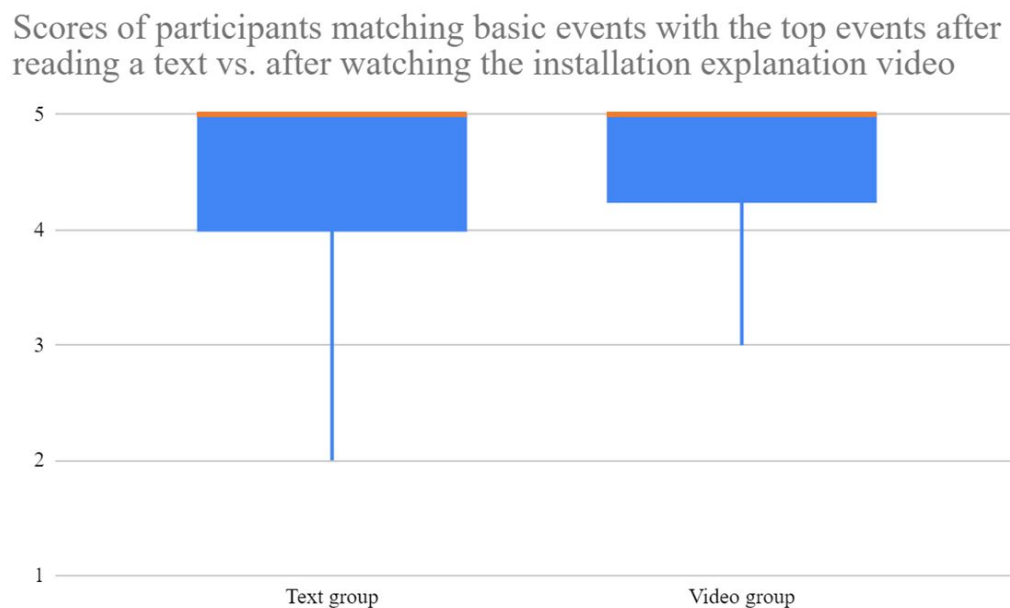


Figure 38: Boxplots of the scores of participants matching the combinations of basic events to the occurrence of the top event after reading a text vs. after watching the explanation video

One of the requirements for making the installation more understandable, was to give it an informal (meaning relaxed, friendly and unofficial) look. When asking the participants whether

the installation looked informal rather than formal, they were considerably neutral with a slight inclination to it being informal (an average of 3.1, the division is shown in figure 39).



Figure 39: Boxplot of participants' rating of the informality of the installation

#### 7.2.4. Discussion

Even though the installation can be used as an explanation tool for experts to non-experts, simulating real use through a video still might have influenced the results of the user test. Seeing details of the installation and following the path of marbles can be easier when standing next to the installation instead of watching it through a camera feed. Furthermore, when there is real interaction between a user and the installation, they can choose the complexity of cases themselves. Similarly, when using the marble track as an explanation tool while being face-to-face with someone, it is easier to see if someone gets it and needs no further explanation, or needs extra examples and information to understand the concept. Filling in the survey took more effort digitally as well: the participants had to look at images of the fault tree next to the questions, which meant they had to use a second tab and zoom in or strain their eyes. Asking the participants to match combinations of basic events with the top event physically might have been easier and more practical for most participants, which could have influenced their need for concentration.

Another discussion point is the variety in participants. A majority (87%) of the participants were aged between 18 and 30. Moreover, almost all participants were (being) highly educated (figure 40). This is not representative of the average population, but comes close to being representative of the target group.

What is your highest educational level (graduated or currently a student)?

38 responses

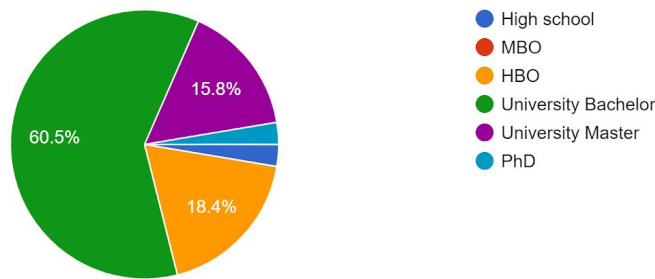


figure 40: division of educational levels of the participants

### 7.3. Compliance with design requirements

Table 8: Design requirements coloured with a scale from red to green on their compliance in the marble coaster, categorized with their MoSCoW priority and an explanation of their presence

Requirement	Priority	Explanation
<b>Understanding</b>		
<b>Background knowledge</b>	Must	The marble track explains a fault tree by showing the path from a basic event to the top event with a rolling marble. This is the most basic feature of the fault tree, explained by something everyone understands: a rolling marble. When matching combinations of basic events to the top event, the non-expert participants of the user test scored high on average, meaning they understood the concept well based on an explanation with the installation. However, when only reading a text explaining fault trees, non-experts scored high as well. They did feel more confident about their understanding after watching the installation explanation in comparison to a textual one.
<b>Bad news</b>	Should	The interaction with the installation is playful, since it acts as a marble track that is mainly associated with children's play. The light-hearted impression avoids association with bad news, which makes it easier to use it as an explanation tool for engineers to decision makers.

<b>Informality</b>	Should	The interaction with the installation was designed to be playful and create the association with children's toys to give the installation an informal impression. When asking participants whether they found the installation informal rather than formal, they were neutral with a slight inclination towards it being informal.
<b>Fault tree design</b>	Must	The installation shows the form of a fault tree, including AND and OR-gates. However, it is flipped upside down if compared to the usual form of fault trees.
<b>Leaf categorization</b>	Could	The basic events do not show categorization. This could be included by writing these specifications on the drawer that is pulled out of the installation when it is activated. However, this is only needed for decision makers, while the target audience is broader than that.
<b>Leaf explanation</b>	Could	The basic events do not show deeper explanations. This could be included by writing these specifications on the drawer that is pulled out of the installation when it is activated. However, this is also only needed for decision makers, while the target audience is broader than that.
<b>Attractiveness</b>		
<b>Association with trains</b>	Must	A figure of a train with spinning wheels was used to show the top event.
<b>Association with failure</b>	Must	The shape of the fault tree is red in the installation.
<b>Using colours for focus</b>	Should	All important parts of the installation (basic events, tree shape, gates and top event / train) include bright red colours that draw attention, while the larger surfaces are desaturated blue.
<b>Minimizing annotations</b>	Should	The top event is displayed with a visual clue, while the basic and intermediate events are displayed by means of annotations. In the future, research could be conducted about visualizing the basic and intermediate events as well.

<b>Reading direction</b>	Should	The basic event marble slots are the first place interaction should occur in the process of using the installation, which are positioned at the top. The process leads to the final visual clue of the top event, which is placed at the bottom. This is logical with the standard reading direction in mind. However, the AND-gates have to be reset manually in the prototype, meaning an interaction is needed in the middle of the installation before or after each user interaction.
<b>Fun interaction</b>	Must	The interaction with the installation was designed to be playful, by using marbles. Participants confirmed the interaction to be considerably fun, with an average of 4.1 out of 5.

## 7.4 Conclusion

The evaluation consisted of two parts: semi-structured interviews with experts and a survey among non-experts. The experts were positive about the installation being used in multiple contexts to increase understanding. To make the explanation deeper and more realistic, they advised to also add more complex fault tree features. Non-experts considered the installation to be attractive and showed it increases confidence in understanding fault trees. However, when checking this understanding, no significant results were found that proved that the installation increases understanding.

## 8. Conclusion

The main outcome of this design study is an attractive marble coaster that is meant to make fault trees more understandable. Experts in risk engineering confirmed that increasing insight in risks can help in a variety of contexts. To find an effective way to do so, I conducted a literature research to find out (1) how engineering explanations could be more effective, (2) how fault trees could be more effective and (3) what kind of visualization techniques help to make a physicalization more attractive. Based on this, the following sub-conclusions were drawn:

- **To create effective engineering explanations:**
  - Different interpretations because of a variation of perspectives should be avoided;
  - A situation in which bad news is received and communicated openly should be created;
  - The situation should not allow distractions or conflicting interests;
  - Engineers have to find a way to communicate in informal face-to-face meetings.
- **To create effective fault trees (for decision makers):**
  - Each basic event should include a thorough explanation;
  - The basic events should be categorized, for example in different departments.
- **To create an attractive physicalization:**
  - Complexity should be minimized as much as possible (e.g. using simple shapes and using a logical reading direction);
  - Colours and shapes should be used to create association with the context of the physicalization.

Based on these conclusions, I designed an interactive marble track to explain the propagation from a basic event to the top event of a fault tree. Visualization techniques were used to make the marble track look more attractive, like the associative colour red for displaying the failure path and displaying the top event by means of the shape of a train with spinning wheels. I designed the interaction with the installation to be playful and fun, to make the explanation by means of the marble track more accessible. When testing the installation with non-expert users, they rated it high on being visually pleasing and fun to interact with. The users also said they were more confident about their understanding of fault trees after being exposed to the installation as compared to only reading a text about it. However, when checking their understanding based on questions about different cases, there was no significant difference between users only reading a text and users who watched a video about the installation. Therefore, no evidence was found that the physicalization improves the understanding of fault trees.

## 9. Future work

Even though I was able to draw conclusions on the questions that are at the base of this research, there were still limitations. Therefore, I propose two main additions for future research: (1) carrying out user tests more realistically and with a larger and more diverse population and (2) adding more complex fault tree features to the physicalization.

### 9.1 Extended user tests

To test the installation, I carried out user tests with questions on attractiveness and user understanding. Even though the users clearly evaluated the installation to be attractive, no significant results were found that the physicalization improved their understanding of fault trees. However, the user test had its limitations. Due to the corona crisis, I was unable to test the installation in a realistic scenario in which users could physically interact with the installation. Future research should therefore be carried out to evaluate the physicalization in a more realistic use-situation, instead of a video. Secondly, the background of the participant population included little variety: both age group and educational level were largely the same. In order to get a better view on the influence of the installation, user tests should be conducted on a larger and more diverse population.

### 9.2 Increasing complexity

When talking to experts, they said the basic fault tree in the installation could be used for a good introduction on the subject matter. However, they argued that more complex features of fault trees could be added for deeper explanation and to make the fault tree more realistic. Even though AND and OR-gates form an important basis for logic gates, more complex logic gates could be added (such as voting and XOR-gates). Furthermore, concepts that are not understood by everyone are redundancy and common cause, which could be highlighted in the installation. Another important feature of fault trees is probability: without showing that certain basic events have a very small probability, people might get a wrong or very simplified view of fault trees. This could for example be shown by automating the marbles rolling into the installation with a certain frequency. In this case, the AND-gate mechanisms would have to be reset automatically as well. The possibility of deactivating part of the marble track could also be added to show that parts of a fault tree can be unimportant in some contexts.



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# Appendix

## A1: Ideation

### Marble Coaster Fault Tree

In figure A1, a digital sketch of idea 1 is presented. The idea is similar to a marble coaster in which the path of the marble or ball is determined by the faults chosen by the user of the installation. The user interacts with the installation by choosing the faults they would like to test and putting them in the compartment in the middle. These faults are represented by blocks with a white dot and the name of the fault. After choosing the fault(s) they would like to test, the user should insert a ball to each side of the installation, which causes them to roll through the orange path. If one (OR) or multiple (AND) blocks are removed from a certain position, the ball will start following the brown path, leading them to the compartment that represents the disfunction of the train. If both balls end up in the orange compartment, this means the train stays operational. The presence of the balls in the different compartments can be sensed through (motion) sensors, which can make sure that the text in the corresponding compartment is lit up. This way, the user can see if the train keeps working when their chosen faults occur.

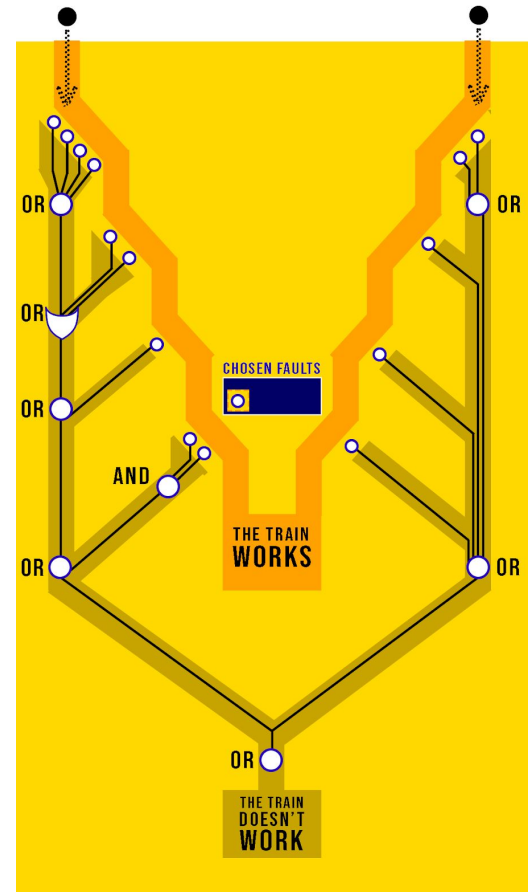


Figure A1: sketch of idea 1

### Pinball Machine Fault Tree

Since a fault tree is mainly read with the top level undesired event on top and its branches under it, an idea was also created including the tree in its traditional form. Since gravity works against a marble when it has to move in an upward direction, marbles would have to be launched in some way if the previous ideas of a marble coaster are still included. To implement this, the design in figure A2 was made. In this, the minor faults work as launchers which can be pulled back in order to test them. When the user lets go of them, a marble is launched on an upwards slope and travels to the top event, where it disappears into a hole. After this, two red lights will start blinking to indicate the system's failure.

An advantage of this design is that it explicitly shows the path from a minor fault to the top level undesired event. However, it might be difficult to build reliably in a short amount of time, since

the launcher systems might easily fail. Moreover, each fault would need its own marble, which has to be put back into the system after launching somehow.

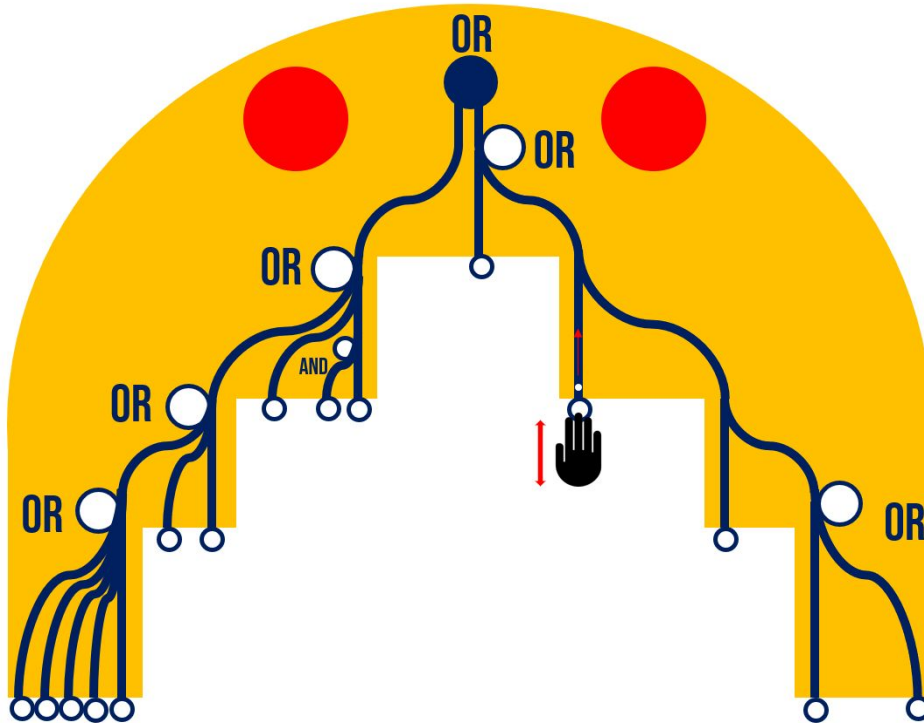


Figure A2: Sketch of idea 2 and 3

### Domino Fault Tree

When looking at the sketch for idea 2, a similar scheme could be used to build a domino track. In this case, the yellow plate would be in a horizontal position instead of an upward slope and dominos would be arranged to follow the dark blue path. When the first domino of a minor fault is pushed, the rest falls until it reaches the undesired top event. To be able to reset the board easily, the dominos should be attached to it with an axis. This way, the board can be tilted to set the dominos in an upward position again.

### Water Track with Hydrochromic Paint

Instead of using marbles for the track in figure A1, water could be used. The paint colouring the path from the leaves to the top event could be hydrochromic, so that it is green when no water is touching it and red when water is running through it. This would mean the path that causes the top failure would slowly colour red when a certain minor fault is chosen. The disadvantage is that working with water requires special pumps or the installation should be filled after a certain period of time. The same thing could be accomplished by using sand with movement sensors and lights which colour the sand red or green. However, both water and sand can cause quite a big mess.



## A2: Circuitry and code

### Component list

- Arduino Uno
- L298N Motor driver x2
- DC motor x4
- TCRT5000 reflective sensor
- 6V power supply
- 10k $\Omega$  resistor x2
- 100 $\Omega$  resistor

### Connection schematic

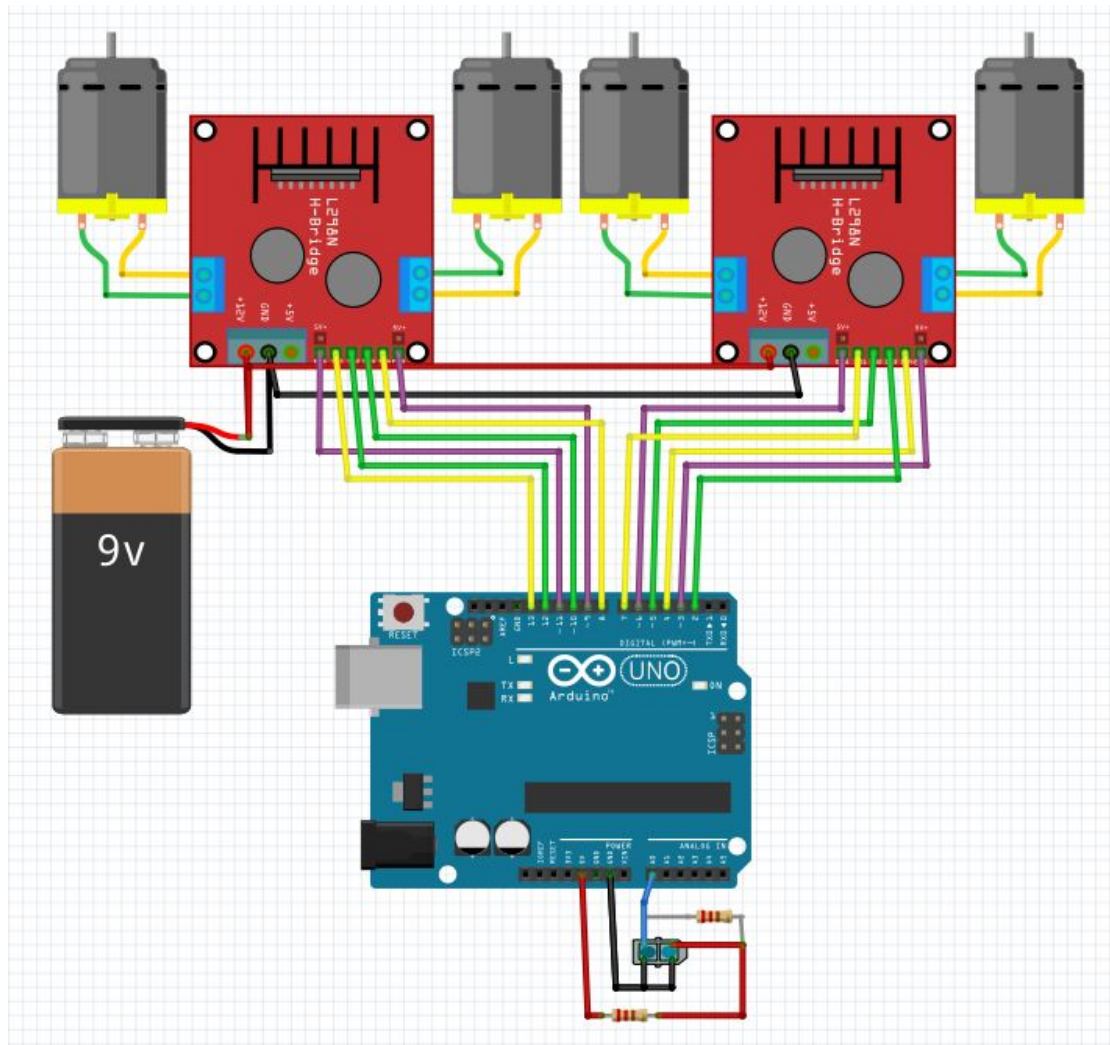


Figure A3: Connection schematic train circuitry



## Code

```
//source for motor code: surtrtech.blogspot.com for more information
int in1 = 9; //Declaring the pins where in1 in2 from the driver are wired
int in2 = 8; //here they are wired with D9 and D8 from Arduino
int in3 = 7;
int in4 = 6;
int in12 = 13;
int in22 = 12;
int in32 = 4;
int in42 = 2;
int ConA = 10; //And we add the pin to control the speed after we remove its jumper
int ConB = 5;
int ConC = 11;
int ConD = 3;
int tmp = 0;

int sensorData = 940; // data from reflective sensor

void setup() {
  pinMode(in1, OUTPUT); //Declaring the pin modes, obviously they're outputs
  pinMode(in2, OUTPUT);
  pinMode(in3, OUTPUT); //Declaring the pin modes, obviously they're outputs
  pinMode(in4, OUTPUT);
  pinMode(ConA, OUTPUT);
  pinMode(ConB, OUTPUT);

  pinMode(in12, OUTPUT); //Declaring the pin modes, obviously they're outputs
  pinMode(in22, OUTPUT);
  pinMode(in32, OUTPUT); //Declaring the pin modes, obviously they're outputs
  pinMode(in42, OUTPUT);
  pinMode(ConC, OUTPUT);
  pinMode(ConD, OUTPUT);

  Serial.begin(9600);
}

void TurnMotorA() {
  digitalWrite(in1, LOW);
```

```
digitalWrite(in2, HIGH);
digitalWrite(in3, LOW);
digitalWrite(in4, HIGH);
analogWrite(ConA, 80);
analogWrite(ConB, 80);

digitalWrite(in12, LOW);
digitalWrite(in22, HIGH);
digitalWrite(in32, LOW);
digitalWrite(in42, HIGH);
analogWrite(ConC, 100);
analogWrite(ConD, 100);
// Different motors were used: they needed different speeds for starting up
}

void TurnOFFA() {
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);
  digitalWrite(in3, LOW);
  digitalWrite(in4, LOW);
  analogWrite(ConA, 0);
  analogWrite(ConB, 0);

  digitalWrite(in12, LOW);
  digitalWrite(in22, LOW);
  digitalWrite(in32, LOW);
  digitalWrite(in42, LOW);
  analogWrite(ConC, 0);
  analogWrite(ConD, 0);
}

void loop() {
  sensorData = analogRead(A0);
  Serial.println(sensorData);
  TurnMotorA();

  // Sometimes the sensor outputs a random value.
  // To avoid the motors stopping when no marble is sensed,
  // a switch-case construction is used, since multiple high
```

// values in a row are caused by a marble.

```
switch (tmp) {
  case 0:
    if (sensorData > 989 && sensorData < 1000) {
      tmp = 1;
      Serial.println("case0");
    }
    else {
      tmp = 0;
    }
    break;
  case 1:
    if (sensorData > 989 && sensorData < 1005) {
      tmp = 2;
      Serial.println("case1");
    }
    else {
      tmp = 0;
    }
    break;
  case 2:
    if (sensorData > 989 && sensorData < 1005) {
      Serial.println("OFF");
      TurnOFFA();
      delay(10000);
      tmp = 0;
    }
    break;
  default:
    TurnMotorA();
    break;
}

}
```

### A3: Consent form expert interviews

## Informed consent form for interviews about the physicalization of risk models

---

This research is meant to design an installation that explains the propagation within fault trees. Participants in this research are asked to give feedback on the design and can help make the design of this installation more effective.

This research has been approved by the EWI ethics committee. Please note you can withdraw from this study at any time before June 22 2020, by informing the researcher(s) you do not want to take part in the study or your answers cannot be taken into account. Your personal information will not be included in the study; only the answers to the interview questions will be used and published.

### Consent Form for The physicalization of risk models

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

*Please tick the appropriate boxes*

**Yes No**

#### **Taking part in the study**

I have read and understood the study information dated [.../.../...], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

☐ ☐

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

☐ ☐

I understand that taking part in the study involves answering feedback question in a semi-structured interview, of notes will be taken by the researcher.

☐ ☐

#### **Use of the information in the study**

I understand that information I provide will be used for the design of a physical installation explaining fault trees and the accompanying bachelor thesis.

☐ ☐

I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.

☐ ☐

**Signatures**

\_\_\_\_\_  
Name of participant

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

\_\_\_\_\_  
Researcher name

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

**Study contact details for further information: Karlijn Wiggers,  
k.m.wiggers@student.utwente.nl**

**Contact Information for Questions about Your Rights as a Research Participant**

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by [ethicscommittee-bms@utwente.nl](mailto:ethicscommittee-bms@utwente.nl)

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## A4: Interviews with experts

### Semi-structured interview 1 (30 minutes)

Question	Time (minutes)
Welcoming the interviewee	3
Could you tell me something about your work in risk management? (How) Do you work with FTA?	5
In what way do you think a physical installation could help to explain fault trees to non-experts?	5
The idea is to use a marble track to show the propagation from a basic event to a top event (show and explain sketch). Do you like this idea? What can still be improved?	15
Thanking the interviewee	2

### Work with risk management and FTA

The work of the interviewee is about infrastructural systems and their risks, safety and reliability. Risk management, and FTA with that, is used in each life cycle of projects by the company: from design to implementation. For example, fault trees are used to show the requirements for constructions, to assess and improve a construction design and to analyse the risks of the system while it is active.

### How fault tree explanations could be improved

Many employees find it hard to think in terms of risks: for example the engineers making calculations and designing systems just focus on the technical aspects, not the risks of their system. Less technical colleagues do not know a lot about logic gates, so they have difficulty thinking in terms of AND and OR, just like certain clients.

### Feedback on the idea

The first impression is that some people within a company could think a marble track is a childlike way to display fault trees. However, it might be a good way to introduce fault trees in for example educational courses, or to some specific colleagues. The interviewee would even use it themselves for teaching or introducing colleagues to the concept, depending on who they are talking to. It should be noted that the fault tree is upside down, so people do not get confused when they encounter a real fault tree. Furthermore, real fault trees are often more complicated,

with more complicated logic gates for example, so it should just be used as an introduction. People also have difficulty understanding the concepts of common cause and redundancy, so those could be highlighted in future versions of the marble track.

Semi-structured interview 2 (30 minutes)

Question	Time (minutes)
Welcoming the interviewee	3
Could you tell me something about your work in risk management? (How) Do you work with FTA?	5
In what way do you experience difficulty when explaining fault trees to others?	5
Watch the video. <ul style="list-style-type: none"><li>- In what way do you think this installation can help in explaining fault trees?</li><li>- Do you think the installation looks attractive and do you think interacting with it is fun?</li><li>- Do you think the installation is informal? Too childlike?</li><li>- Future additions?</li></ul>	15
Thanking the interviewee	2

### **Work with risk management and FTA and difficulty explaining**

The interviewee does not use FTA directly, but knows about the concept. In their company, technical experts make assessments and choices about a system and they know what they are doing. Managers often take the advice of those technical experts, but it depends on their position within a project. Furthermore, they sometimes ask for an explanation of the technical expert's advice, in which making fault trees more understandable could be relevant.

### **Feedback on the idea**

It depends on the people you are talking to whether such a marble track is needed to explain fault trees. The interviewee does not see it being used within the company, but rather to communicate with other companies. The installation would also work well as an eye catcher on a business fair, for example to show what different departments do or to recruit people. However, the information in the fault tree should not be sensitive: people should not get the feeling a system is unsafe. The marble track is a simplification of the risks in a system; safety critical aspects have

very low probability of occurring and that is not visible in the installation. It should therefore mainly be used for introducing the concept of fault trees. To make it more realistic, the marbles could roll into the system with a certain frequency, to show the probabilities of the basic events. However, the AND-gates should be automatically resettable in this case.

The interaction seems fun and not too childlike: in the interviewee's company they used toys before to show the technical aspects of a system.

### **Semi-structured interview 3 (30 minutes)**

Question	Time (minutes)
Welcoming the interviewee	3
Could you tell me something about your work in risk management? (How) Do you work with FTA?	5
In what way do you experience difficulty when explaining fault trees to others?	5
Watch the video. <ul style="list-style-type: none"><li>- In what way do you think this installation can help in explaining fault trees?</li><li>- In what contexts would you see it in use?</li><li>- Future additions?</li></ul>	15
Thanking the interviewee	2

### **Work with risk management and FTA**

The interviewee works as a safety engineer in a broad context: from dangerous substances to system reliability. They analyse the effect of failure modi on safety in a qualitative manner and use fault trees to analyse the functionality of a system with a specific safety objective. While RAMs engineers make block diagrams about the reliability of complex systems, the interviewee focuses more on safety: e.g. what are the safety consequences when a certain sensor fails?

### **Difficulty explaining**

In general, people have difficulty understanding risk models. Many people are confused about the role of reliability and safety: not everyone sees how they are related. The methods of risk engineering, like using fault trees, and the taken measures based on these are difficult to understand as well. However, managers do not really look at fault trees if the number that is



calculated based on it is beneficial for the project. When the number is not beneficial, they might ask for more explanation. The fault tree can also be used to show to engineering teams why redundancy or adding extra components can be beneficial for the system.

### **Feedback on the installation**

The interviewee thinks the marble track helps well with showing how a risk model is built and to explain redundancy in a system. It could also help within a project to communicate about the risks of a system or during training sessions, but the installation should be used as an introduction in these contexts. If the concept of the marble track becomes more popular, it could be made to be adaptable for different fault trees and contexts (instead of trains). A qualitative fault tree works well (rather than a quantitative one), since it is important to get an overview of the whole system: a number is not always needed to analyse the risks in a system. AND and OR gates are also often enough, rather than adding more complex logic gates. An addition to the installation could be the possibility to deactivate certain branches of the tree, since they are only used in specific contexts.

## A5: Survey for user tests

This research is meant to design an installation that explains the propagation within fault trees. Participants in this research are asked to give feedback on the design and can help make the design of this installation more effective.

This research has been approved by the EWI ethics committee. Please note you can withdraw from this study at any time before June 22 2020, by simply closing this survey. Your personal information will not be included in the study; only the answers to the survey will be saved and published. You have to be 18 years or older to participate in this study. If you have any questions, contact Karlijn Wiggers (k.m.wiggers@student.utwente.nl) or Prof. Dr. M.I.A. Stoelinga.

Finally, I want to thank you for your participation in this questionnaire.

If you have any complaints about this research, please direct them to the secretary of the Ethics Committee of the Faculty of Electrical Engineering, Mathematics and Computer Science at the University of Twente, P.O. Box 217, 7500 AE Enschede (NL), email: ethics-comm-ewi@utwente.nl)

I have read and understood the study information. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason. I understand that information I provide will be used for the design of a physical installation explaining fault trees and the accompanying bachelor thesis.

☐ Yes

☐ No

### Section 2 of 6

## General information

Description (optional)

What is your gender \*

- ☐ Male
- ☐ Female
- ☐ Prefer not to say
- ☐ Other...

What is your age group? \*

- ☐ 18-30
- ☐ 30-40
- ☐ 40-50
- ☐ 50-60
- ☐ 60+

What is your highest educational level (graduated or currently a student)? \*

- ☐ High school
- ☐ MBO
- ☐ HBO
- ☐ University Bachelor
- ☐ University Master
- ☐ PhD
- ☐ Other...

Do you have any prior knowledge about fault trees? \*

- ☐ Yes
- ☐ No
- ☐ Other...

Section 3 of 6

## Randomizing the survey

Description (optional)

Click on the upper answer. This will lead you randomly to one of two surveys. \*

☐ %%

☐ &&

## Textual group

Section 4 of 6

## Textual Understanding

Below you are going to read a text that explains how fault trees work, accompanied by an image of a fault tree about a train system. Please read the text thoroughly and then answer the questions below.

### Fault trees

We all ride the train from time to time. However, a train is a machine and all machines are prone to fail. The process that causes machine systems to stop working can be displayed by means of a fault tree.

The failure of a system can have various origins, which are called basic events. Certain combinations of basic events can cause the whole system to fail. The failure of the whole system is called the top event. The basic events are at the root of the fault tree (the circles in the image), while a top event is at the top.

The basic events and top event are connected through logic gates, such as AND and OR gates. An AND gate has multiple input paths. If and only if there is an information stream about occurring failures on ALL of these input paths, there will also be a stream with failure information on the output path. An OR gate also has multiple input paths. However, here only one input stream is needed to create an output failure stream.

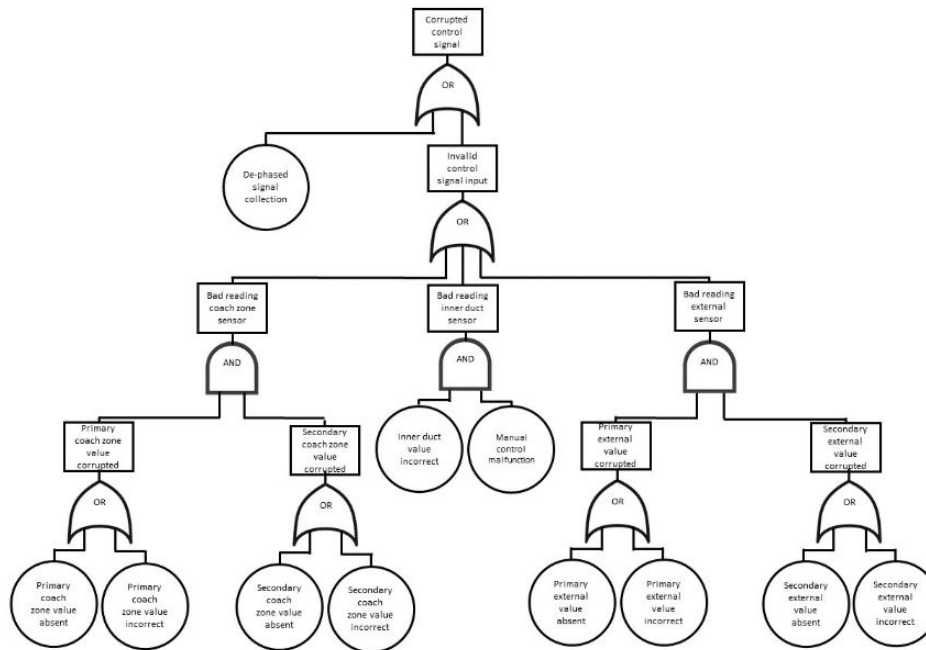
In a fault tree, each basic event is connected to the top event with a specific path. On this path lie multiple logic gates, which decide what kind of combinations of basic events lead to the top event.

In this case the basic event "Primary external value incorrect" in itself does not lead to the top event. The same holds for the basic event "Secondary external value absent". However, the paths of these two basic events are connected with an AND gate. This means that the combination of the two basic events does lead to the top event.

In the case of the occurrence of the basic event "De-phased signal collection", the top event is always reached, without the need of other basic events. This means this basic event forms a high risk for the failure of the system.

Pinpointing these types of risks is one of the uses of a fault tree. Other uses are finding ways to make a system more reliable or tracing back why a system fails. Therefore, fault trees can help us find the safety and reliability of technological systems, like trains.

Train fault tree



The fault tree in the image is visually pleasing. \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

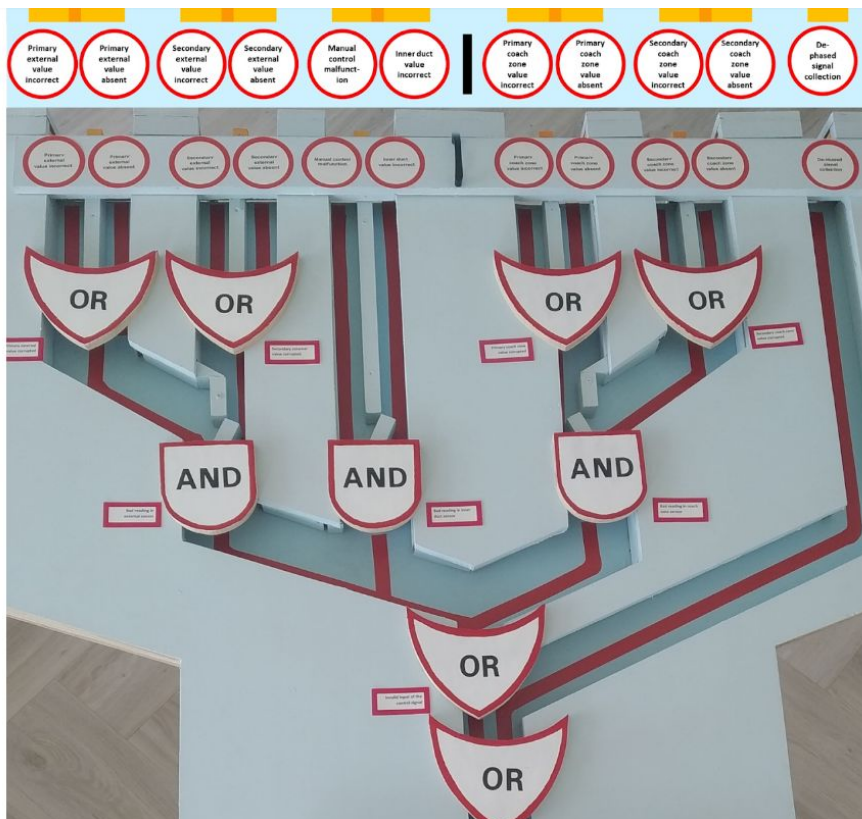
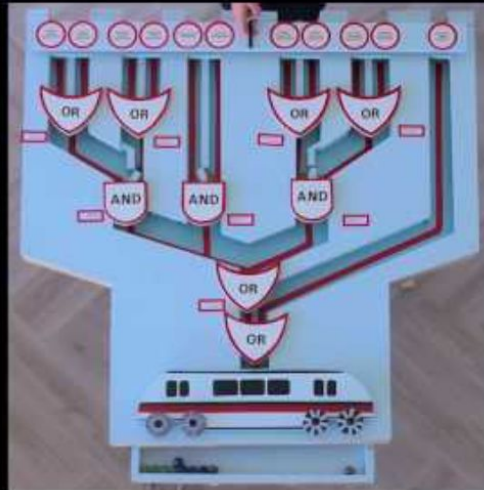
## Video group

### Examples

In the video below, you are going to see three combinations of basic events and the result on the top event (the wheels stop spinning when the top event is reached). Please watch the video and answer the following questions. These questions ask you to figure out what combinations of basic events cause the top event to happen. A photo of the installation, accompanied with a detail of the basic events, is supplied as memory support before all questions. If it is difficult to see, please zoom in on the fault tree / basic events (circles on top). To avoid having to scroll up and down, it is practical (but not necessary) to use an extra screen or tab to open the photo on (right click to open the image in a new tab) and have the photo of the fault tree and basic events next to the questions.

3 Cases (To watch on full screen, click the YouTube logo in the bottom bar of the video.

## Case A





## Questions for both groups

I feel like I understand how fault trees work. \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

### Combinations of basic events

Now you are asked to determine what kind of basic events lead to the top event. For this, use the image of the Train fault tree, which is repeated (so it is THE SAME everytime) above all questions. If it is difficult to see, please zoom in on the fault tree. To avoid having to scroll up and down, it is practical (but not necessary) to use an extra screen or tab to open the fault tree image on (right click to open the image in a new tab) and have the image of the fault tree next to the questions.

If the following basic events occur: Primary coach zone value absent, Primary coach zone value incorrect, De-phased signal collection; will the top event occur? \*

- ☐ Yes
- ☐ No

Did you reason about your previous answer or did you guess? \*

- ☐ I reasoned about my answer
- ☐ I guessed

If the following basic events occur: Secondary coach zone value absent, Secondary coach zone value incorrect, Inner duct value incorrect, Primary external value absent, Primary external value incorrect; will the top event occur? \*

☐ Yes

☐ No

Did you reason about your previous answer or did you guess? \*

☐ I reasoned about my answer

☐ I guessed

If the following basic events occur: Secondary coach zone value absent, Primary coach zone value absent, Manual control malfunction, Secondary external value incorrect; will the top event occur? \*

☐ Yes

☐ No

Did you reason about your previous answer or did you guess? \*

☐ I reasoned about my answer

☐ I guessed

If the following basic events occur: Manual control malfunction, Inner duct value incorrect, Primary external value incorrect; will the top event occur? \*

☐ Yes

☐ No

Did you reason about your previous answer or did you guess? \*

☐ I reasoned about my answer

☐ I guessed



If the following basic events occur: Manual control malfunction, Primary coach zone value absent, Primary external value incorrect; will the top event occur? \*

☐ Yes

☐ No

Did you reason about your previous answer or did you guess? \*

☐ I reasoned about my answer

☐ I guessed

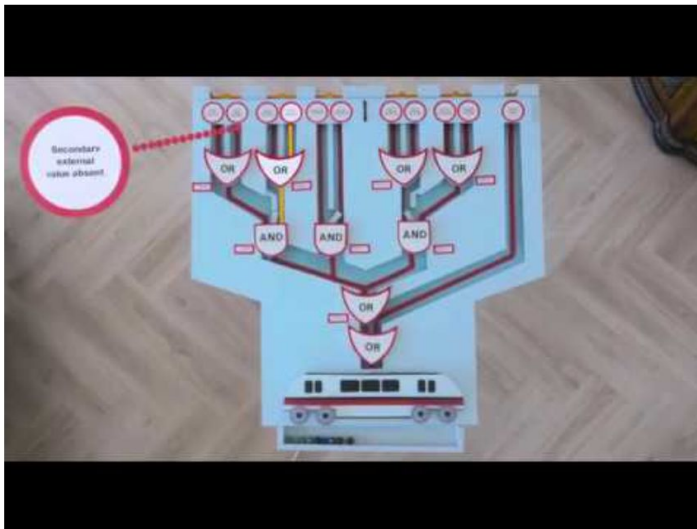
## Attractiveness questions

### Section 6 of 6

## The installation

Watch the video below. To watch on full screen, click the YouTube logo in the bottom bar of the video. Then please answer the following questions.

Fault tree explanation through a marble track



I feel like I understand how fault trees work \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

The installation in the video is visually pleasing. \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

The installation in the video is informal rather than formal \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

The installation is too childlike \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly agree

Interacting with the installation seems like a fun thing to do \*

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly Agree

Do you have any other comments on the installation?

Long answer text

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## The Physicalization of Risk Models - Karlijn Wiggers

Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even	Did you reason about you if the following basic even
					Agree	Strongly agree	Neutral	Strongly disagree	Strongly Agree
					Strongly agree	Agree	Neutral	Neutral	Strongly Agree
					Strongly agree	Strongly agree	Agree	Disagree	Strongly Agree
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
					Strongly agree	Agree	Neutral	Agree	Strongly Agree
					Agree	Strongly agree	Disagree	Disagree	Agree
					Agree	Agree	Neutral	Neutral	Agree
I reasoned about my ansv Yes	I guessed No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv Yes	I reasoned about my ansv Yes	I reasoned about my ansv Yes	I reasoned about my ansv Yes	I reasoned about my answer				
					Agree	Agree	Neutral	Disagree	Neutral
					Strongly agree	Strongly agree	Disagree	Disagree	Agree
					Strongly agree	Strongly agree	Agree	Disagree	Neutral
I guessed Yes	I guessed No	I guessed No	I guessed No	I guessed No	I guessed				
					Strongly agree	Strongly agree	Agree	Strongly disagree	Strongly Agree
					Strongly agree	Strongly agree	Disagree	Disagree	Agree
					Strongly agree	Agree	Agree	Neutral	Neutral
I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
					Strongly agree	Strongly agree	Agree	Neutral	Agree
					Strongly agree	Strongly agree	Neutral	Disagree	Strongly Agree
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
					Strongly agree	Neutral	Strongly agree	Disagree	Neutral
					Strongly agree	Strongly agree	Agree	Neutral	Agree
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				
					Strongly agree	Strongly agree	Agree	Disagree	Agree
					Agree	Strongly agree	Disagree	Disagree	Neutral
					Strongly agree	Strongly agree	Neutral	Strongly disagree	Strongly Agree
I reasoned about my ansv Yes	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my ansv No	I reasoned about my answer				

Do you have any other comments on the installation?

7 responses

Good work, clear explanation

The footage of the train wheels coming to a halt was a very effective visual support to the spoken words. It helped visualise that the system would stop working

Pretty straightforward and easy to understand.

Is it easy to adjust the installation to display an updated scenario?

-

Given the fact that the AND-/OR- gates are well displayed, you can get the overview pretty fast.

the video is very informative



Do you have any other comments on the installation?

8 responses

I think it works pretty well for people that don't understand the working of and/or gates and that it is a nice way to represent the fault tree, however it does look way to much work for people that can reason how this tree works. I do like the explanation.

love it

I personally prefer the IEC symbols.

Simplicity is often best

It doesn't look too stable. Also, it doesn't look very durable, or premium to me.

It feels redundant, I would understand how it works even without the marbels.

ik zie dit wel gebruikt worden als installatie om het aan studenten uit te leggen, maar ik weet niet of dit op deze manier gebruikt zou worden in het werkveld om dit proces uit te leggen.

Looks really nice! I think that the train wheels stopping when the system fails is a nice visualisation. Also the simplisity of the system (marbles) helps understand the effects the logic gates have on the outcome. The only thing I could think of to make it easier for all people to understand is make the basic events simpler (like loss of power or something). Also you could add some lights to the train that turn off when the marble crosses to add on the cool effect it already has. Because the train also stops at stations when the system hasn't failed.