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Faculty of Electrical Engineering,
Mathematics & Computer Science

A new approach to visualizing FMEA data

Zanur Krol

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Supervisors
prof. dr. M.I.A. Stoelinga
dr. C.E. Budde

Formal Methods Group
Faculty of Electrical Engineering,
Mathematics & Computer Science

dr. A.J.J. Braaksma

Faculty of Engineering Technology, Design Engineering

UNIVERSITY OF TWENTE.

Risk visualization

A NEW APPROACH TO VISUALIZING FMEA DATA

Zanur Krol
University of Twente
Faculty of Electrical Engineering, Mathematics & Computer Science
z.m.t.krol@student.nl

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ABSTRACT

Failure Mode and Effects Analysis is a widely used tool to reduce risk in a system and making it more reliable. One flaw however is that it is very resource intensive and the amount of information being displayed can be enormous, especially in more complex systems. This makes understandability and usability one of the issues with the current FMEA. This study proposes a new visualization method that uses an interactive Node-link tree diagram to increase the users' understanding of the system. It is designed to have less information displayed, provide focus and show relatedness among different failure modes. The proposed visualization was tested for a chair system and a slight increase in effectiveness was perceived, yet there was no significant improvement measured. Based on the feedback from the participants, the prototype seems promising and further development is required.

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1 INTRODUCTION

With constant technological developments, more and more systems are created that become available to large groups of people. This has brought many people fortune and joy, but they also can cause harm: environmental, societal, economical or individual harm.

With new and old technologies alike, there is always risk. Technologies like nuclear power plants, autonomous cars, the Internet of Things and rapid accessible travel all have an enormous impact on a large part of society and all can cause harm. The rapid and accessible travel allowed for instance the Covid-19 virus to spread more rapidly and widely, which has and is causing harm in the form of death, sociological issues and economical issues amongst others.

In order to reduce risks and make sure unwanted scenarios do not happen, reliability and safety engineering was introduced with the aim to increase the quality and reliability of products and decrease the risk in systems.

There are many approaches to risk analysis, Failure Mode and Effects Analysis (FMEA) is such a tool and the topic of this study. It is a proactive approach that analyzes failure scenarios and mitigate them before they happen [1].

The creation, understandability and usability of the FMEA however, is tedious, involves a lot of experts and scales relative to the complexity of the system being analyzed [2]. This makes it hard for both novice as well as expert users of the tool to make sense of the information being displayed. Many articles address issues with the FMEA such as the debatable risk calculation method. Yet the way FMEAs are displayed have remained mostly unchanged over the past 60 years [3].

Therefore the main aim of this study is to improve the method in which the data is visualized to the user and more concretely improve the usability and efficiency of usage.

This study tackles this goal by: identifying the problems with the current methodology, investigating potential visualization methods and selecting one, developing a prototype for the new visualization method and lastly, evaluating the prototype based on effectiveness principles and comparing results with the current method.

2 BACKGROUND ON FMEA

This chapter presents main background information about the importance of risk management and more concretely the FMEA risk analysis tool, how it is used and visualized.

2.1 Reliability Engineering

Risk assessment or reliability and safety engineering is a fairly recent development in engineering. After the war, around 1950, a lot of the defense equipment was in a terrible state, which was a catalyst to increase development into the reliability and maintenance branch in engineering. Since 1960 many industrial developments, mostly defence related lead to the creation of now well-known and still used concepts to evaluate risk, such as: Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA). These were extensively used in the aerospace and nuclear industries. As time progressed, more research into reliability and risk was conducted and other aspects were included into reliability engineering like the human aspect and software reliability [3].

Reliability is defined by IEEE, the Institute of Electrical and Electronics Engineers [4] as the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

Reliability in engineering is divided into many aspects: maintainability, quality, availability, risk, safety and reliability. Which all have different measures and approaches to take into account when designing a system. One thing they have in common is their aim, which is to minimize the risk of failure [3].

The importance of minimizing failure in systems becomes clear when we look at the outcomes. When not managed properly, incidents with varying impact happen: personal injury, economic loss, environmental impact or even death. Major incidents like the Chernobyl Nuclear disaster and Deepwater Horizon Oil spills in the gulf of Mexico had an enormous impact on everyone, economically, environmentally and also live-wise.

The failing of a single component, like the failing of an escalator at a subway station in London can result in a terrible fire and cost many lives[1].

[1] King's Cross fire 25th anniversary marked https://www.bbc.com/news/uk-20383221

It is needless to say that without proper risk assessment through approaches like FMEA, FTA or many others described by [5], many more disasters would have taken place.

Especially now, with more increasing complexity in the products and systems we use, the impact of a failing component should not be underestimated. Risk management tools give insight into the 'how' and 'why' failure occurs and are necessary for a reliable future.

2.2 Failure Mode and Effects Analysis

FMEA is a tool first introduced by the aeronautics industry in 1960, NASA. It is a proactive approach that aims to determine all risk of a system beforehand and is based on translating functional requirements of a system into failure modes and the corresponding effects, causes and detection levels [3].

It tries to accurately identify all these risks by zooming in on the system, targeting system level, sub-system level and component level failure. Furthermore, it also tries to look at the system from different perspectives (e.g. engineering, maintenance, ecological and economical perspectives).

Normally an FMEA is given form by a cross-functional or multidisciplinary team of experts with different perspectives and knowledge. These experts collect data about the system on which the failure-modes are identified. For each failure mode additional information such as: the effect, the cause and preventive actions are also identified.

The failure modes that are identified are evaluated on three aspects, derived from the cause, effect and preventive action: the Severity (S), Occurrence (O), and Detection (D). The severity evaluation describes the effect of failing. The occurrence describes how often failure would take place and detection indicates how difficult it is to detect the failure before it happens. All these are ranked from 1 to 10, where a higher value means a more severe, more often occurring and more difficult to detect failure mode [6].

Based on these three rankings, the Risk Priority Number (RPN) is calculated by multiplication. This ranking can then be used to prioritize and mitigate risk. The steps involved to create an FMEA are shown in figure 2.1.

As mentioned before, FMEA is a proactive approach that provides useful basis to improve product quality, eliminate failure and predictive maintenance planning. The FMEA is suited to tackle all sorts of systems like processes, plants, products or projects [1]. Many extensions to the standard FMEA have been developed to make it fit better with a particular industry like the healthcare industry where changes to the FMEA are used as a tool to improve the drug discovery process [7].

Lastly, criticality of failure modes is often added to the standard FMEA. This is a changed version of the FMEA namely the: Failure Mode Effects and Criticality Analysis (FMECA). It has an additional numerical prioritization by multiplying the severity with the occurrence. Risk prioritization and more in-depth analysis is based on the criticality [8]. Figure 2.2 shows such a criticality analysis.

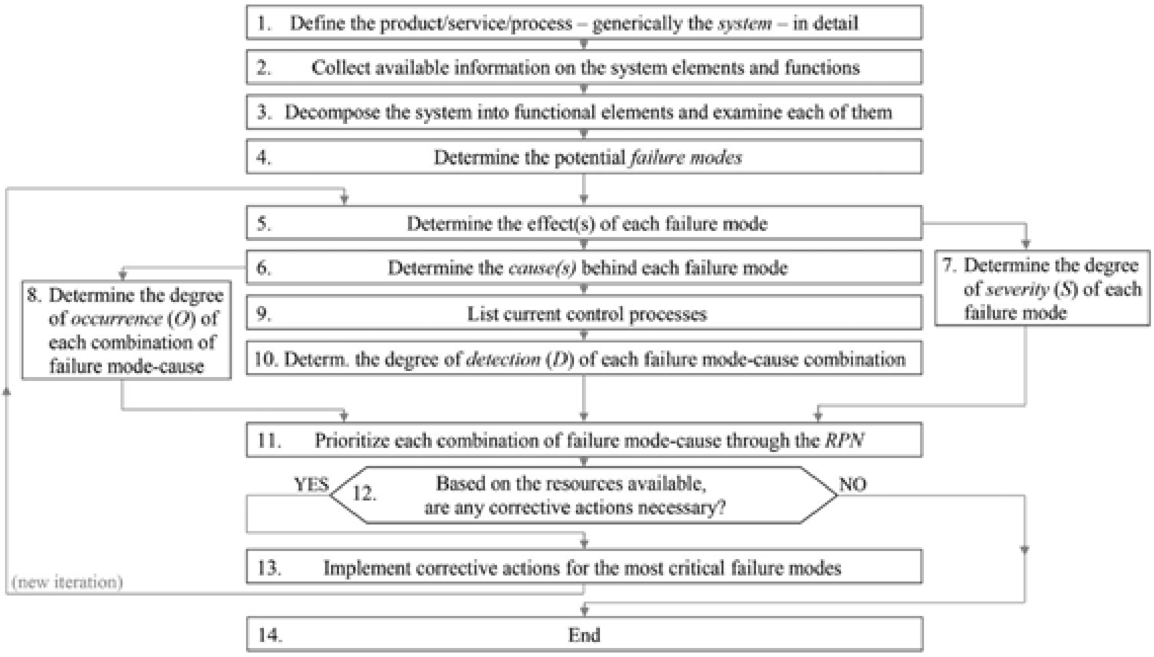


Figure 2.1: Flowchart showing stages of an FMEA [1]

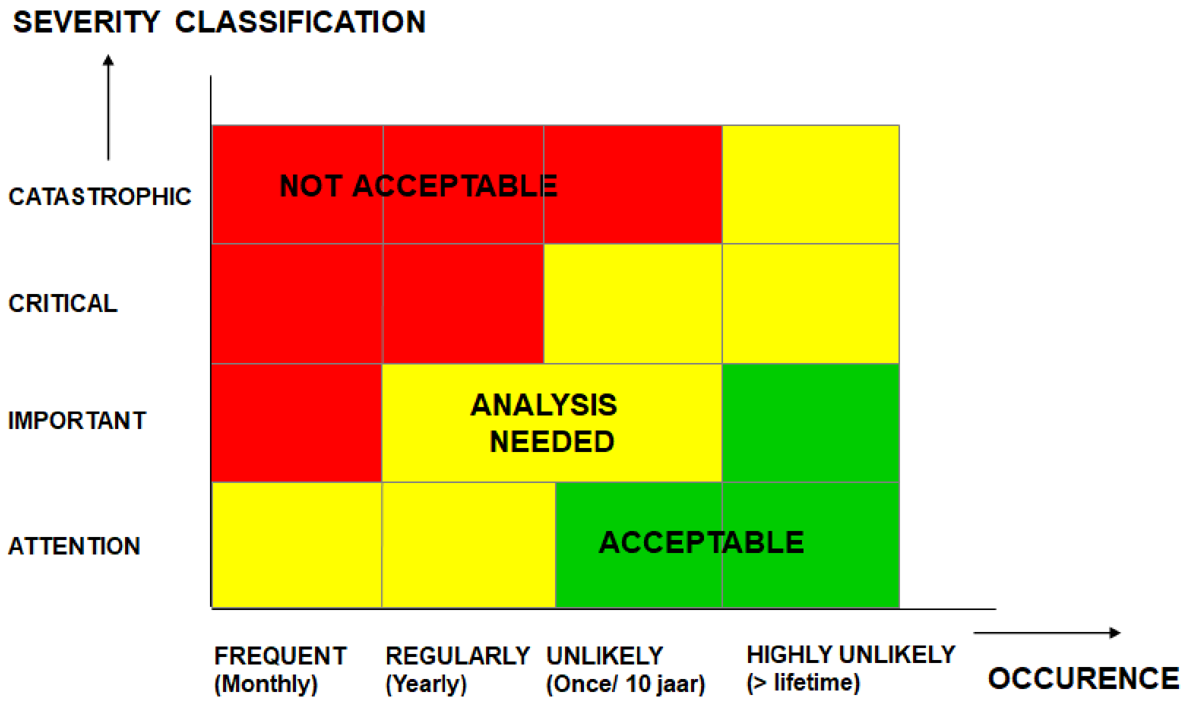


Figure 2.2: Criticality analysis for risk prioritization based on severity and occurance

2.3 Visualization

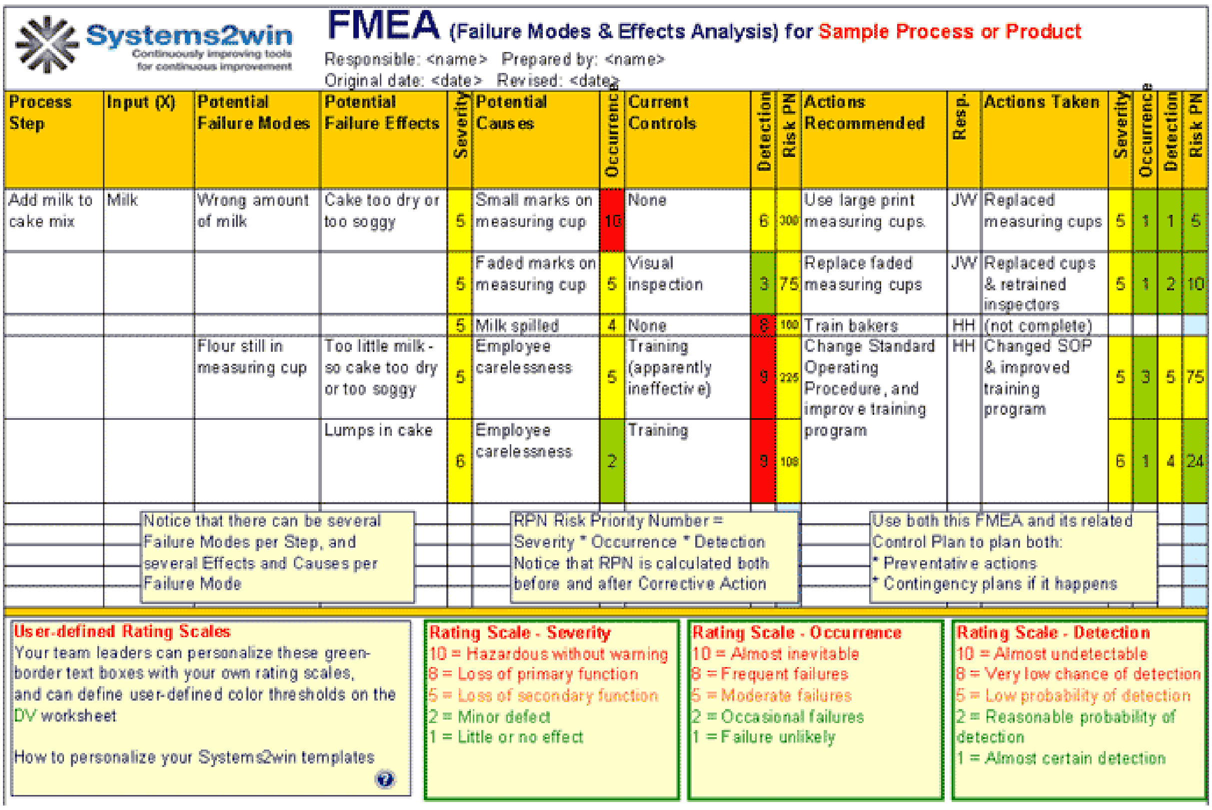
The standard FMEA table is usually displayed and created in an excel spreadsheet and is mostly filled with textual data: system name, sub-systems, components and maybe even further divisions (depending on the complexity and scope of the FMEA).

If it were a Process FMEA then it would be separated by general processes and by more concrete process steps.

For each of the components, the function and failure modes is identified. For each of the failure modes, the effect, root cause and detection methods. As mentioned before, the FMEA also includes RPN values and S, O, and D rankings on a scale from 1 – 10. These numerical values often are visual encoded with a higher RPN being red and the lower RPN values being green.

Lastly, meta information is also displayed, often at the top and include information like whom created the FMEA, the date, project title etc.

Figure 2.3 below shows a part of an FMEA including colors[2].



Systems2win Continuously improving tools for continuous improvement

FMEA (Failure Modes & Effects Analysis) for Sample Process or Product

Responsible: <name> Prepared by: <name>
Original date: <date> Revised: <date>

Process Step	Input (X)	Potential Failure Modes	Potential Failure Effects	Severity	Potential Causes	Occurrence	Current Controls	Detection	Risk PN	Actions Recommended	Resp.	Actions Taken	Severity	Occurrence	Detection	Risk PN
Add milk to cake mix	Milk	Wrong amount of milk	Cake too dry or too soggy	5	Small marks on measuring cup	10	None	6	300	Use large print measuring cups	JW	Replaced measuring cups	5	1	1	5
				5	Faded marks on measuring cup	5	Visual inspection	3	75	Replace faded measuring cups	JW	Replaced cups & retrained inspectors	5	1	2	10
				5	Milk spilled	4	None	8	160	Train bakers	HH	(not complete)				
		Flour still in measuring cup	Too little milk - so cake too dry or too soggy	5	Employee carelessness	5	Training (apparently ineffective)	9	225	Change Standard Operating Procedure, and improve training program	HH	Changed SOP & improved training program	5	3	5	75
			Lumps in cake	6	Employee carelessness	2	Training	9	108				6	1	4	24

Notice that there can be several Failure Modes per Step, and several Effects and Causes per Failure Mode

RPN Risk Priority Number = Severity * Occurrence * Detection
Notice that RPN is calculated both before and after Corrective Action

Use both this FMEA and its related Control Plan to plan both:
* Preventative actions
* Contingency plans if it happens

User-defined Rating Scales
Your team leaders can personalize these green-border text boxes with your own rating scales, and can define user-defined color thresholds on the DV worksheet

How to personalize your Systems2win templates

Rating Scale - Severity
10 = Hazardous without warning
8 = Loss of primary function
5 = Loss of secondary function
2 = Minor defect
1 = Little or no effect

Rating Scale - Occurrence
10 = Almost inevitable
8 = Frequent failures
5 = Moderate failures
2 = Occasional failures
1 = Failure unlikely

Rating Scale - Detection
10 = Almost undetectable
8 = Very low chance of detection
5 = Low probability of detection
2 = Reasonable probability of detection
1 = Almost certain detection

Figure 2.3: FMEA example

[2]FMEA displayed from http://powerpointbuy.web.fc2.com/free-essays/21/paper/thesis-design-mode/

3 PROBLEM STATEMENT AND APPROACH

The goal of the project is to create a novel visualization of the current textual FMEA tables such that the user will have a better understanding of the system and use this in decision making for risk management. Therefore, the question that shall be answered through the course of this report is:

How can FMEA tables be translated into a visualization which helps users and managers to improve their understanding of, and the usability of the method?

In order to answer the main question, sub-questions have been formulated and methodologies for answering these questions are stated below.

1. What are the main flaws/implications of the current method of the FMEA that makes it hard to understand or use the tool?
   - Method: Literature research and expert interview.
2. In what ways can textual data tables be translated into a visualization that copes with the complexity of FMEA data?
   - Method: Literature research on visualization techniques.
3. How can the flaws/implications described in research question 1 be improved with the use of new visualization methods described in research question 2?
   - Method: Brainstorming and prototyping.
4. What is the effectiveness of the improved visualization method compared to the previously used method?
   - Method: Hypothesis testing on effectiveness that compare the current method with the proposed visualization method.

4 STATE OF THE ART

This chapter is divided into three sections: the first section will go into detail about the flaws and implications of the standard method for FMEAs. The second section will show existing solutions to tackle the flaws described in the first section. The last section will introduce visualization techniques and guidelines that help with the creation of a more understandable and clear visualization.

Some of the implications that were found for the current FMEA standard are the complexity, resource constraints, reliance on expert knowledge and limited re-usage of the tool. Nesting and clustering are methods to reduce information and can be applied in many visualization of which Node-link diagrams, sunburst diagrams and Sankey diagrams are just a few. Lastly, guidelines for a good visualization are presented that focus on highlighting, color coding and the use of other visual encodings. Also the importance of interactive elements is emphasized here.

4.1 Problems with the current methodology

This section represent the findings for the problems of the current methodology based on literature research, an expert interview and additional findings from a case study.

4.1.1 Problems identified by literature

There are four categories in which the problems with FMEA can be categorized, these are: 1) Applicability; 2) Cause and Effect; 3) Risk analysis; and 4) Problem solving [9].

Below each of these categories flaws identified from literature are stated.

Applicability

Especially in complex systems, FMEAs can become very large, complex and difficult to comprehend. Due to it becoming so large and complex, it is hard for the engineer or designer to see all the different ways a system can fail [2, 10–12]. Due to resources constraints such as time, knowledge and money not all aspects of a system can be analyzed and often a specific scope or level of detail is maintained in the FMEA analysis [13, 14].

Because a multi-disciplinary team is formed for the creation of an FMEA, many perspectives on the systems are given, which makes it difficult for the experts to reach a consensus the 'how', 'why' and evaluation of the failure modes. The collaboration of multiple experts makes an FMEA analysis often very resource intensive as it requires manual effort.

FMEAs are often created for complex and new systems. For such systems, the knowledge of failing is often limited and even though experts are involved during the analysis, the knowledge is inadequate [15, 16].

Since the meaning of stated failure modes depend on the formulation and interpretation of the team members, the re-usability of an FMEA is often limited. The interpretation can fluctuate greatly when a new FMEA team looks at the data. Even when the same team is used, their interpretation over time can change. This flaw is because of the fuzzy natural language system that is used to describe the failure modes [17, 18].

Cause and effects

Failure modes are regarded as isolated items, connections between components and possible combinations of failures are often not analyzed. To take the combinations of failures into account, it becomes too impractical to analyze and comprehend [2, 10, 19].

FMEA is a textual representation of failure, [20] describes the necessity for more precise descriptions of the technical risk, less experience driven and more formalised failure analysis.

Risk evaluation

There are many issues with the risk evaluation including: 1) the relative importance of S, O and D are all the same, whereas in reality this could differ per situation; 2) different combinations of S, O and D can result in the same RPN, making prioritization difficult; 3) due to vagueness, lack of knowledge and team/human judgement risk evaluation is difficult; and 4) the calculation method by multiplication remains debatable [10, 16, 19, 21].

Problem solving

This category focuses on decision making based on the FMEA [9]. Decisions derived from the FMEA are not consistently indicated and referred to. The standard [1] does propose a method for which to implement decision making, by the addition of recommended actions, responsible person and setting deadlines. Nonetheless, as mentioned before, a FMEA often is not re-used, which means this is often neglected and a feedback loop is not present. In [22] it is also mentioned that FMEA could greatly be improved by implementing some sort of feedback loop like the addition of real live tracking of incidents.

The researchers in [9] determine a need for infographics, ontologies and other representations to communicate the results and form the basis for problem solving. Furthermore, the use of historical data, functional analysis and simulation can be used to for problem solving as well, yet often industries do not use these tools in addition to the FMEA.

4.1.2 Expert interview

An interview was performed with expert Jan Braaksma, from this interview many problems were identified and some coincide with the findings of the literature research, including flaws like: 1) FMEAs are complex, requiring a lot of time and effort, are tedious and rely on expert knowledge; 2) Risk evaluation issues due to incorrect calculation methods, reaching consensus among a team and relative importance of S, O and D; 3) Reusability of the FMEA is often not the case; and 4) not many other tools for cause and effect are implemented in the system.

Problems that were apparent during the interview and not mentioned prior are stated below.

First, FMEAs are often created for one-time usage only (e.g. in order to do maintenance the system gets analyzed through FMEA and based on this, a maintenance planning is created. However when change occurs, this does not get updated in the FMEA and also not in the related maintenance planning. For instance: oil pipes are maintained for a specific pressure, however when less oil gets produced over time, the pressure reduces and less maintenance should be required. This example is given by an engineer from a case study in [23].

In some cases, quantitative data can be used rather than expert knowledge and this could be very helpful in determining the risk and mitigating it. However in most case, quantitative data is missing.

FMEAs are very context specific, the operation of a system (e.g. F-16) in the Netherlands versus Afghanistan leads to many different failure modes. In the Netherlands, dust is not an issue, whereas in Afghanistan this could pose a significant threat to the operation of the system. Experts are the ones that need to identify these context specific failure modes and to do this right can be difficult[1].

The integration of other risk mitigation systems in the FMEA is limited. For example, Reliability Centered Maintenance (RCM) can be added to the standard spreadsheet, when this is done however, the result does not show any decision making process or justification for the decision making.

Suppliers make a FMEA for a specific product they sell but often do not transfer this FMEA to the manufacturer, requiring them to redo the FMEA.

[1] Jan Braaksma give the specific example of an F-16 in the Netherlands compared to Afghanistan

4.1.3 Case study

The case study gives a little more insight into the application of FMEA in reality or tries to put the problems in a different perspective. The identified problems are listed below

As mentioned before, an FMEA is large and complex and due to time constraints often there is a limited scope. The importance of the problem can be debatable because the business is aware of the problem and tries to focus on the most critical parts with the most impact [23].

Identification of failure modes, causes and effects is not accurate due to lack of knowledge. However as an engineer revealed, FMEA itself is limiting knowledge in a loop-wise manner: *"since maintenance is performed, we lack information on actual failure, but since we do not want failure, we perform maintenance and information on actual failure cannot be obtained"* [23]. Still, the accuracy of the FMEA is largely related to the knowledge and experience of the involved team.

FMEAs are often a one-time exercise, to create or update the maintenance plan. References to the FMEA are often not available and decision making could not be traced back to the FMEA. Even if the FMEA were to be referenced and the team FMEA session members were asked on their rationale for decision making, they often cannot recall most of the details [23].

Due to unclarity in corporate guidelines, different software and different approaches for FMEA can be used within the same company [23].

4.1.4 Summary

Based on all the problems stated above, it is clear that the complexity and difficulty to create and comprehend the FMEA is the main issue. All the flaws like relations among components and failure modes, lack of knowledge and re-usability of the FMEA, find its roots in the complexity of display of the information.

Simply put, the tabular setup does not allow for clarity and therefore a better way to communicate and represent results should be created. In the next section, proposed solutions from the literature are investigated to indicate what has already been done in order to create a better FMEA.

4.2 Related work

There are both existing tools and papers that aim to solve the aforementioned issues with the FMEA. Similar to the previous section, also the solutions shall be categorized along the four main categories: 1) Applicability; 2) Cause and effects; 3) Risk evaluation; and 4) Problem solving [9].

Applicability

Both [2] and [11] provide an automation method, which in particular for electrical circuit systems can be a huge improvement as it allows simulation of all the components and automates the creation of an FMEA based on the simulation. Furthermore, it looks at more than just individual failure modes, combination of failure modes are explored, which for an engineer is impossible to achieve especially considering electrical circuits are becoming more complex each day. Although this is a system focused on electrical circuits, similar methods can be applied for different fields.

Since experts are not always located at the same site, [6] shows a distributed FMEA process as a solution to manage team decision making when not everyone is available on site. [17] offers a solution in the form of a collaborative web based GUI supporting multiple users and an experience database to prevent knowledge to go lost. There are other tools such as [24] that also allow decision making among many users.

To prevent incorrect decision making due to the lack of knowledge, [15] offers a knowledge base system in which FMEA is incorporated. [25] also states that failure of a component depends on quantitative information such as age, usage, operating conditions etc. Based on information which can be captured in a knowledge base, the failure of a component can be predicted and prevented. Adding a knowledge base can be interpreted in other ways as well, like the adding of product visualizations through Computer Aided Design (CAD) models and potentially even Virtual Reality (VR) [26].

As [12] stated, the FMEA is unwieldy, hard to produce and hard to understand, FAM offers a more kind and comprehensible alternative to the FMEA. This alternative is similar, yet not intended to be a complete replacement. It leaves out mitigation plans and focuses only on a handful of failures.

Cause and effects

By integrating or combining other tools with the FMEA such as a Failure Tree Analysis (FTA), the determining of failure modes and their effects can be done in a recursive manner [14]. Where FMEA investigates on specific components, the FTA then can determine relations among the other components and by doing so can maintain scope on only the most critical components in the system.

Other tools or approaches that can be used, to describe cause and effect are Root Cause Analysis (RCA) or ontology based software that aims to show the cause and effect of components [19].

Risk evaluation

Natural language is an issue with both the transfer of knowledge and decision making. Cloud modelling and linguistic computation offers an interpreter which can compute and rank the linguistic set of information and deals with human fuzziness of language [16]. TOPSIS is another way to manage team decision making based on individual linguistic assessment of failure modes which trough cloud TOPSIS model deals with weighing, randomness and fuzziness. [21] offers a RPN calculation method which also depends on linguistic information. It considers the rankings and linguistic information and develops a digraph that represent interrelations which then together with the rankings of individual failure modes should lead to better risk prioritization.

There exist many other methods, similar to the ones described above, they focus on evaluating linguistic terms based on fuzzy set theory and a different approach such as MULTIMOORA [27] or VIKOR [28].

Problem solving

Clustering of failure modes based on neural networks or evolving trees to represent less information in a more effective way [29] and Self Organizing Maps (SOM) [30] to represent relations among corrective actions and failure modes.

In [31] a method is proposed which does not regard the separate failure modes but rather looks at failure scenarios, the probabilities of them occurring and the cost of failure. It facilitates for economic decision making about the system design.

Also some solutions in the applicability category, can be seen as in the problems solving class. Especially the knowledge base proposals, since they aim for better decision making in general.

4.2.1 Summary

Many of the existing tools and papers describe improvements for the FMEA that are only incremental solutions for specific problems such as RPN calculations [9]. There are some solutions that aim to expand the knowledge base in order to make more informed decisions, increase team-based decision making or tools that aim to make fuzzy human judgement more qualitative through neural networks.

A general solution with the aim to make the FMEA more user-friendly however does not really exist. The only proposed method is a simplified FMEA in [12] that does not cover all the aspects the FMEA contains like mitigation.

None of the solutions focus on creating a more clear visual representation of the information without altering what is contained in the FMEA. Therefore, in the next section, visualization techniques that could be applied to the FMEA are discussed.

4.3 Visualization techniques

As mentioned before, the main problem that is addressed and shall help with making the information more understandable and clear is the complexity and the high quantity of displayed information in the current method.

The first part of this section shall mention methods used to limit the amount of data being displayed. Afterwards, potential visualizations types are presented and lastly the use of visual aids is made more clear through guidelines for a good visualization.

4.3.1 Data limitation

For data reduction, the most important aspect is to not show all the information at the same time, which can be achieved by the elimination of data, dimension reduction, clustering and nesting of information.

Elimination of data is a destructive method in which non-important data is destroyed in order to have less information. In the case of FMEA this is not optimal, since all information should be kept in order to make informed and correct decisions.

Similarly, the **reduction of dimensions** or transformation of multi-dimensional data into lower dimensional data also can be considered non-optimal, since dimensions will be reduced that normally are regarded as ‘less important’ for the understanding of the dataset [32]. The ’how’ and ’why’ of a failure mode and all the other attributes are carefully determined by the experts and give input to evaluation and the mitigation of risk. All aspects are important, thus none of the dimensions of a failure mode can be discarded.

Clustering is the classification of items or observations with similar properties based on some criteria [33] (i.e. a sheep and a mouse are both animals whereas a notebook and a pencil are inanimate objects used for writing). Classification can also be used to group observations in the FMEA that have similar properties. In [29], such techniques are applied. The FMEA data is clustered based on the proximity of the severity, occurrence and detection rankings and the clusters are put in a 3 dimensional space. It aims to display clusters of failure modes based on these values and displaying each cluster as an entry, limiting the shown data entries. Clustering can also be applied in a different way, namely the clustering of Failure modes with similar attributes (e.g. similar materials being used).

Nesting is the aggregation of information by another higher level node or parent. It is used to increase information density, yet providing a compact way of representation [34]. Depending on the node selected, the information of lower level nodes can be made visible.

Since the FMEA data is hierarchical, nesting can be done to limit the amount of information. The different levels in the hierarchy of data can contain the lower levels of the hierarchy. Clustering can also be performed on FMEA data. The criteria on which to base the categorization however needs to be determined to do so.

4.3.2 Data visualization types

FMEA data can be categorized as hierarchical, network and multidimensional data. The hierarchical category as mentioned by [35] is a dataset that consists of groups within groups of data. In the FMEA dataset, this is basically the idea of a sub-system containing one or multiple failure modes, each with its own groups of data. [35] also mentions that for this category, tree diagrams, sunburst diagrams and ring charts are potential representations. Especially the tree diagram is most simple to follow because of its linear path.

The network category is characterized by a dataset that has connections to other datasets. If you consider each failure mode a dataset, you establish a network of datasets. For this category, matrix charts, Node-link diagrams, word clouds and Sankey diagrams are potential options.

Lastly there are also multidimensional datasets, typically characterized by many dimensions or layers for each observation. In the case of the FMEA, each failure mode can be considered an observation, with the severity, occurrence, detection, preventive actions, effects, causes etc. as layers or dimensions. For this type of data, scatter plots, pie charts Venn-diagrams and some others are useful representations depending on the dataset.

4.3.3 Visual aids

As the FMEA standard contains mostly textual data, it is difficult to encode data into visual attributes. Nonetheless, there are some attributes that can be turned into a visual variant. These are the RPN, severity, occurrence, detection attributes, the relationships among entities and any selection of entities.

There are many visual aids and it requires a whole book to discuss all the different visual aids that can be used [36]. Guidelines that are used in the final prototype shall be mentioned in this chapter and include a reference to the guideline. All the references can be found in appendix A.3.

For showing a selection or highlight specific information, visual attributes should be made visually distinct **G.1** like shown in figure 4.1. The best suited option to use for highlighting and selections is a visual dimension least used in other parts of the visualization **G.11**.

For the numerical attributes (RPN, severity, occurrence and detection) of the entities in the data there are many ways to visually encode this. Trough colors, size, symbols, thickness, shading etc.

Color is one of the most used visual aspects to indicate specific properties that the entity contains. It is also used for drawing attention to the specific entity. The properties can be: being of the same classification, representing a value or intensity. When using color however [36] also mentions that if you want to reliably identify the colors, no more than 10 colors must be used **G.6** and more saturated colors should be used for smaller objects, whereas less saturated colors are best suited for larger areas **G.3**.

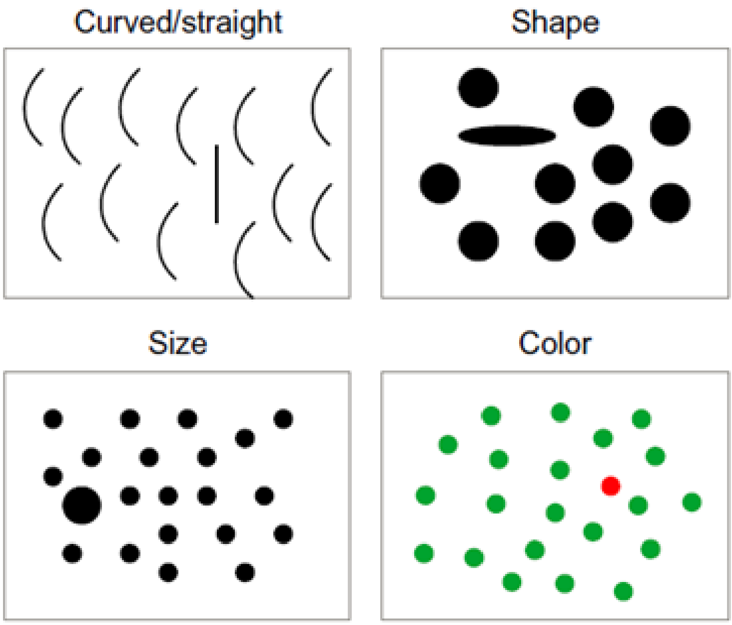


Figure 4.1: Visual attention guidance techniques [36]

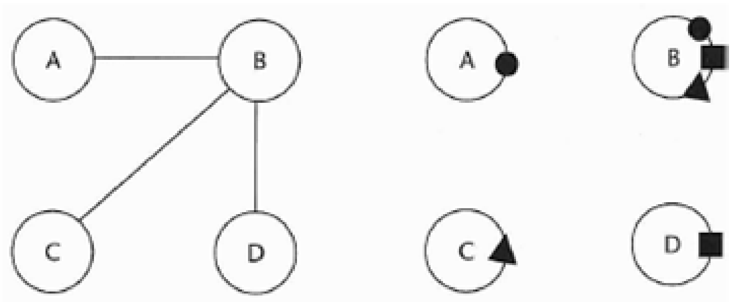


Figure 4.2: Two different methods for showing relationships [36]

Like all other visual aids, symbols are also used in order to simplify and describe specific properties the entity has. As figure 4.2 shows, relationships or classification can be shown in multiple ways, the figure shows this by linking it with an edge and to use symbols. Other options are also possible, like color coding, the use of shapes and many more.

One advantage of a symbol is that they themselves contain information, which is shown in figure 4.3. In the example, the symbols used show that the entity contain information about papers, authors or venues. A disadvantage is that not always everyone interprets the symbols the same way.

In addition to symbols, figure 4.3 also uses other visual encodings like size, links and colors to display the same information or relationships **G.15**, **G.20** [37]. When using symbols, they must be really distinctive and one method to make them distinctive is by redundant visual encoding (e.g. using both symbols and colors) **G.12**.

A key characteristic of visualizations that help with problem solving is interactivity. Interaction that is epistemic (an action with the intention to uncover new information) helps the user make

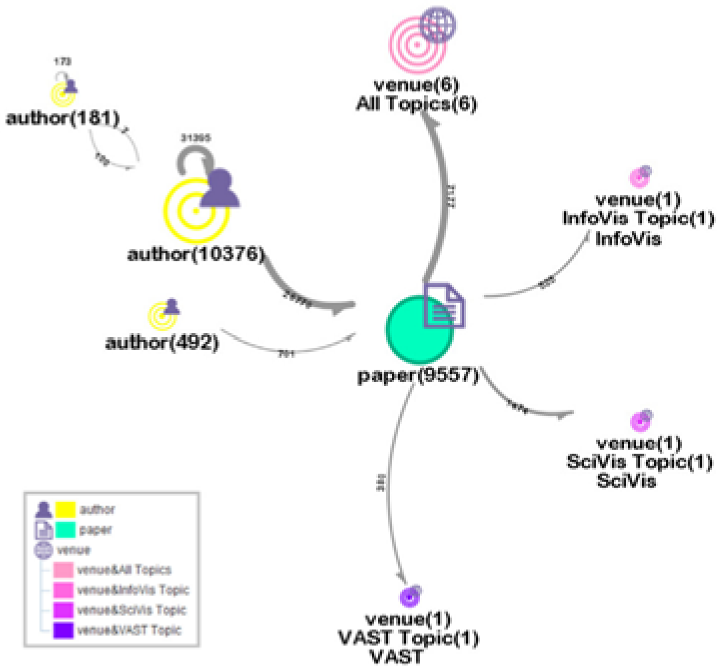


Figure 4.3: Using visual aids in a Node-link diagram [37]

more informed decision [37]. Interactive elements that allow for the exploration of new information are hovering, selecting, expansion / collapsing of data, zooming, panning, highlighting, searching and more. As [36] mentions, every data object must be active, capable of displaying more information as needed and disappearing when not required. One of the key interactive elements that can be used are hovers **G.21** which is a interactive element with the intent of exploration of information.

Since FMEA data is mostly textual, other guidelines indicate that if possible, the usage of symbols should be used rather than words **G.18** and words only should be used when space is available **G.19**. Lastly, **G.16** suggests that when the hierarchical structure of a dataset is of importance, a Node-link representation might be a good fit.

4.3.4 Summary

Data limitation techniques such as There are many guidelines that offer directions regarding color coding, the use of symbols, highlighting, limiting information and more. Color coding guidelines indicate that not to many colors should be used, symbols should be distinct and widely familiar and for highlighting, the least used dimension should be used. For data limitation, nesting and clustering of information are useful techniques. Finally, interactivity is in particular a key aspect of a visualization that helps the user to freely explore the data and make informed decision.

5 IDEATION

In this chapter, results from brainstorming about potential ways to show textual FMEA data in unison with the structure of the system are shown. The four ideas presented here are based on techniques to limit information (nesting and clustering) and are: a 3D model, a sunburst diagram, a Node-link diagram and a onion layered diagram.

3D Model

The first idea was designing a CAD (Computer Aided Design) Model for the target system and make this model interactive trough clickable and selectable components. Each component contains the FMEA information for that specific component. The idea was inspired from 3D software which allows for flexibility and interactivity. Figure 5.1 shows a 3D design of a chair which could form the basis for this idea. The interface of 3D software however requires more expert knowledge to operate. In order to make such a system still reasonably understandable and not requiring 3D model knowledge, the FMEA related information can be displayed on the side (highlighted by the red outline in the figure).

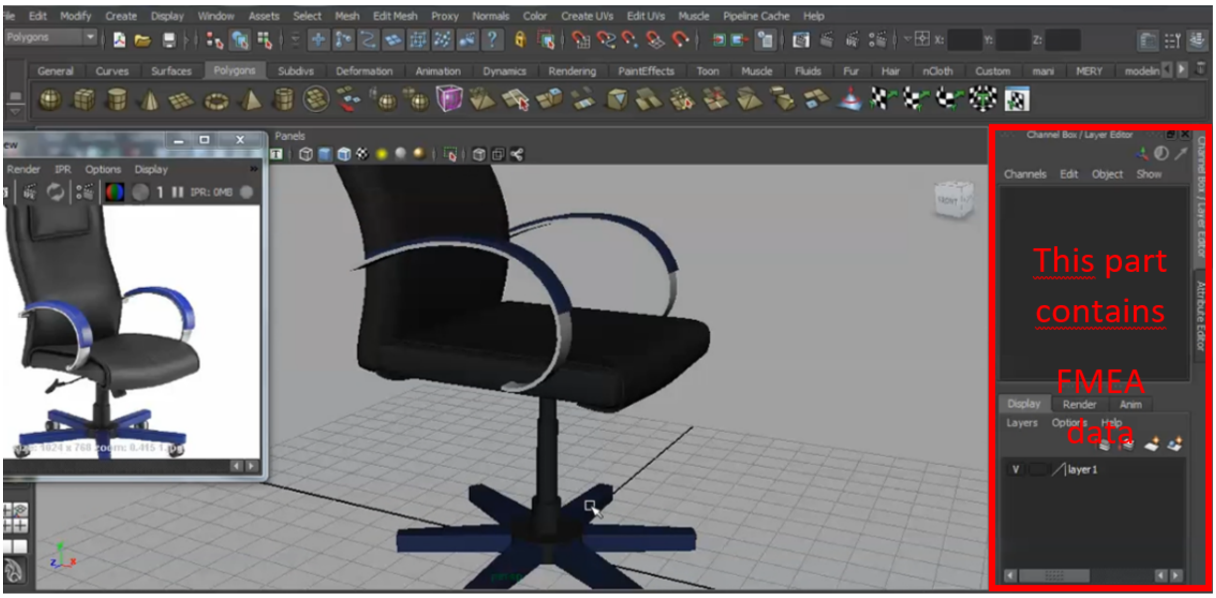


Figure 5.1: Cad model combination for a more effective display of FMEA related information[1]

[1]Source: https://www.youtube.com/watch?v=RAF2GEQ1Lyg

Literature mentions that a knowledge base as a basis for the creation of FMEA information is required to properly analyze the system. CAD models display a lot of information of a system and are a basis for a knowledge base. In [26] virtual reality is proposed to see the 3D model of the system when determining the failure modes of the system. This article does not suggest the integration of FMEA data inside the 3D model, which is the proposed idea in this chapter.

The 3D model should help give an overview of the system and colors could be implemented to indicate risk levels of components. However, the use of colors can also make the system unrecognizable and should be thoughtfully considered.

Sunburst diagram

Another possible idea for visualizing the data was by creating a sunburst diagram and making the different levels contain the textual FMEA data. The first level are the sub-systems, second layer is the components, function etc. This could make the structure of the system clear and also show risk levels through color coding or change in the sizes of the rings. The textual FMEA data can be displayed in the layer and even interactive components like changing focus to the selected layer could mean that you continuously zoom in and the amount of data shown can be limited.

There is one big issue with this design, when the data becomes very complex, the structure does not allow the data to be readable, since it would be very small and also curved. It also is difficult to indicate relatedness among failure modes especially when the focus changed and previous layers are not visible anymore. See figure 5.2 for the imagined sunburst diagram indicating the layers and how they could represent the system.

Node-link / Tree structure display

As the literature suggested, FMEA data can be categorized as multidimensional, structured and network data. A good representation for this type of data is a Node-link diagram, especially the traditional tree format is suggested by [38] as it outperforms radial trees and orthogonal trees in terms of task performance time and accuracy.

Node-link diagrams are build with nodes representing data points and uses links between nodes to display relations. This structure allows for interactivity made clear by figure 5.3.

Visual encodings of data that can be done and also visible in the figure are: the encoding of risk by size, sub-systems by color and levels by depth of the node. It should give an overview of the system, related nodes and at the same time give the user the ability to dive into the information till the required info is found. Figure 5.3 shows three steps (indicated by a number in the top-left corner) that expand selected node and collapse non-selected nodes to reduce clutter.

A problem however is that the nodes themselves cannot contain all the textual information.

[2] Source: http://visualizingrights.org/kit/charts/sunburst-diagram.html

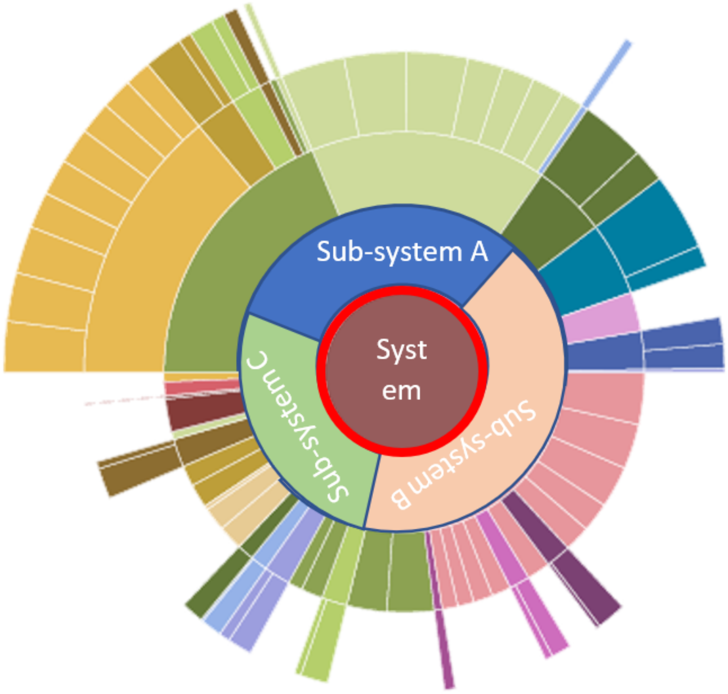


Figure 5.2: Sunburst diagram for FMEA ideation[2]

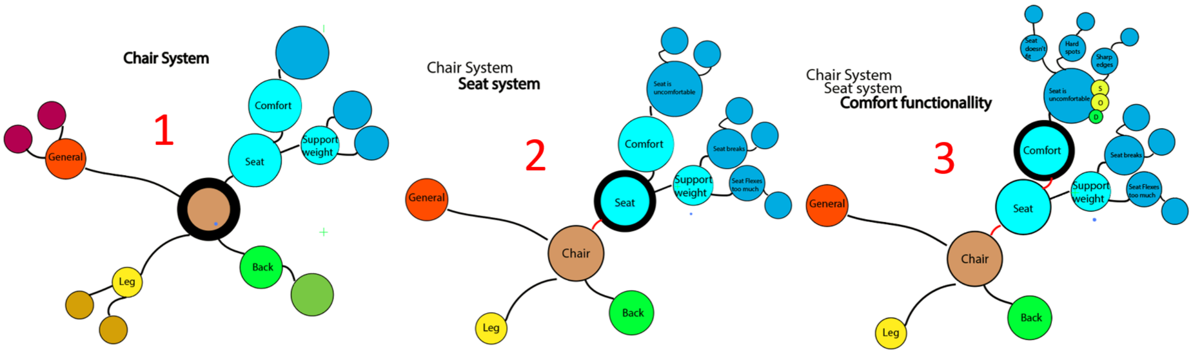


Figure 5.3: Node-link diagram idea for FMEA information

Onion layered structure

Figure 5.4 is an expansion of the previous ideas, where a colored background should indicate the layers of the system. By adding these layers, the type of nodes should be clear without depending solely on the links between nodes.

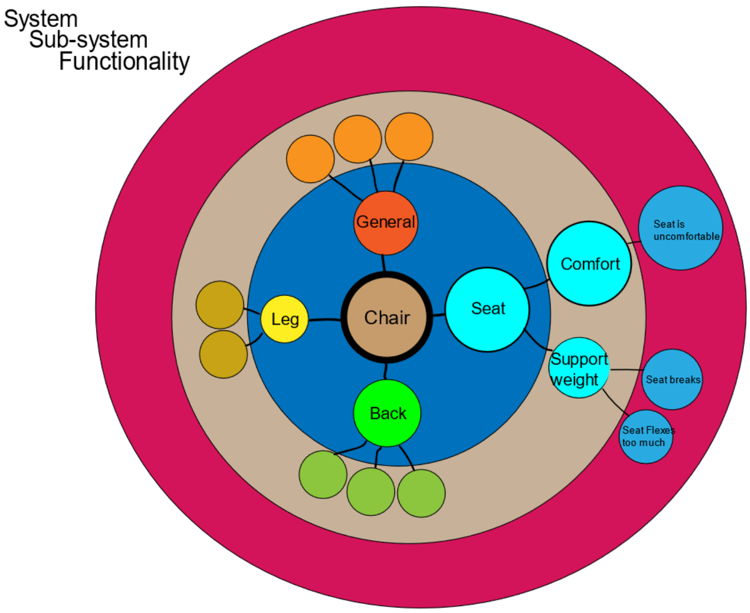


Figure 5.4: Onion structure for the Node-link diagram

6 SPECIFICATION

Based on the problem with the current method, the complexity of displaying large quantities of information and making this comprehensive, a new visualization approach shall be chosen in this chapter.

The new visualization should be more effective in communicating the information than the current method therefore in this chapter, it is stated what the requirements for this more effective design are. These requirements are based on the guidelines for a good visualization in chapter 4 and are based on effectiveness principles that are described here. These requirements are given form in the MoSCoW table and include requirements such as that the visualization must be interactive, that the RPN must be immediately clear and that the structure of the system must be accurately displayed.

In this chapter they are also used to determine the initial prototype design best suited among the ideas previously described. This resulted in the selection of a Node-link diagram as a starting point.

6.1 Effectiveness requirement

The main objective of this research is to make an existing risk analysis approach more effective in the hands of non-experts and experts alike. Therefore it is necessary to state what makes an visualization effective. As [39] states, there are alternating perspectives on how to describe an effective visualization. Where some researchers claim it all has to do with the structure that matches the data and maximizing the data to ink representation [40], others claim that the main focus should be on task performance [41, 42].

In this study, task performance is used as a measure for effectiveness. This perspective is based on three principles: the principle of accuracy, the principle of utility and the principle of efficiency [39]. Each of these principles' meaning are described below.

"Principle of accuracy: For a visualization to be effective, the attributes of visual elements shall match the attributes of data items, and the structure of the visualization shall match the structure of the data set".

This principle determines how accurate data attributes are translated into visual attributes. For example the translation from RPN values to color. The principle describes how well the attribute is still represented by this visual representation. Another translation into the visual domain is the row and column structure translated into the new chosen structure.

The perception of the user is key to determining the success of this principle [38]. How the user perceives the data shall be measured by looking at visual encoded data and find out whether or not the user perceives this encoding correctly or not. This principle shall be measured in a semi-structured interview after the participants are finished with the task and will aim to let the participants mention and rate the structure and visual encodings of the prototype.

"Principle of utility: An effective visualization should help users achieve the goal of specific tasks".

The principle states that an effective visualization should help find the correct answer to these specific tasks. The degree to which the user is able to perform the task correctly. This shall be measured by having a control group and a test group perform the same tasks and their responses are compared based on the number of correctly performed tasks. This gives a score for each group that indicates the utility principle. With the scoring for each group a hypothesis test shall be conducted to see if the differences are statistically significant.

"Principle of efficiency: An effective visualization should reduce the cognitive load for a specific task over non-visual representations".

This shall be tested by measuring the time it requires the participant to complete the tasks. Similarly to the above mentioned principle, this also shall be measured by having a control group and a test group that perform the same tasks. However now, not their correctness but their required time to completion shall be compared. Also for efficiency a hypothesis test shall be conducted to reach a conclusion whether the effect is statistically significant.

Lastly, [39] also mentions that there is a difference between novice users and experienced users in terms of visualization readership skills. Therefore it is important to question the participants for their experience and take this into account when making conclusions about the aforementioned principles.

6.2 Design requirements

Requirements to reach an effective visualization that are not part of the principles are described here. These requirements are listed in this chapter based on the MoSCoW (must, should, could, won't) model for requirements.

Necessities in the final design are (Must haves):

- Interactive elements are used to help with problem solving and finding new useful information.
- The visualization is able to show the full structure of the system and all FMEA information

can be displayed. Relations between information must be clear and explorable.

- The visualization should limit the amount of information being displayed through nested information. This makes sure that the user is not overwhelmed by the complexity and quantity of the data.
- The visualization must be scalable to more and more complex data.
- The risk level is visually encoded, directly recognizable and distinctly represented.
- An easy to interpret system of a simple chair is used for prototyping.
- The prototype must be clear to novice users.

The use of interactive elements and nesting from chapter 4 are requirements that allow to deal with large quantities of information and are therefore necessary to tackle the complexity flaw of the standard FMEA. Other requirements are a must based on the principle of accuracy: the complete structure should be present and risk levels should immediately be recognizable. Lastly, the easy to interpret system, the chair, is chosen as a prototype since most users would be able to understand this system and a dataset for this system was available.

Should-be included features (Should-haves):

- The visualization should be available online. Almost everyone has the ability to access the internet, allowing this solution to be available to a wide range of users.
- The visualization should comply with the guidelines mentioned at the end of chapter 4: the guidelines for a good visualization. (these are basically requirements to take into account when designing).
- Visually encoded data is distinguishable from other objects in the visualization. These include but are not limited to: selections, encoding of the RPN level, relations and layers of the structure.

Additional features (Could-haves):

- The information should be search-able and filterable on key aspects of the FMEA information (e.g. filtering on linguistic values or RPN values).
- Adding a knowledge base to failure modes as an ‘attribute’ (e.g. the possibility of adding video or audio fragments, notes or other information to a failure mode).

Not included features (Won't haves):

- The prototype shall not include a full-stack deployed system, meaning it shall not include a database and other framework integration. This is due to programming skill restraints of the researcher.
- The prototype shall not allow the FMEA data to be manipulated. The prototype is static and only displays the chair.

Must	Should	Could	Won't
Interactive elements are used to allow for explorative actions	Web-based visualization	Filtration of information based on user input	Database integration
The complete structure & relations are displayed	Compliance with the guidelines for a good visualization	Knowledge base for adding extra information to the system	Other framework integration
Limited amount of information being displayed at once	Clear distinguishable visual aids		No allowance for data manipulation
The visualization must allow for scaling of information			
The risk level is immediately clear			
Chair data is used			
Clear to novice users'			

Figure 6.1: MoSCoW model for requirements

Based on the requirements, the prototypes in chapter 5 shall be briefly discussed and the best suited option is chosen as the prototype to realize. The must-haves are used primarily to base the choice on.

6.2.1 Evaluation

The 3D model allows for an interactive visualization and an accurate structure of the data. If the side pane is used to display information, the information is limited. There is one issue, one of the most important feature of the FMEA, the RPN should be immediately clear, when making these clear in the 3D model through colors, the 3D model will be difficult to comprehend, making the components not distinguishable and therefore difficult to identify the RPN correctly. Furthermore, the 3D model requires more knowledge and skills about 3D model interaction.

The Sunburst diagram can be interactive and show limited information. Colors or sizes can be used to display RPN values and should be clearly distinguishable. The issue with this display however is to accurately display the structure of the system when it becomes more complex, the information becomes very tiny and thus unreadable. Furthermore, it requires the user to tilt his head in order to read the information since it is curved, which is not optimal.

The Node-link diagram can be interactive and limit the amount of nodes being displayed. Colors or sizes can be used to display RPN values and should be clearly distinguishable just like the sunburst diagram. The difference is that with the Node-link diagram, the structure is more easier to interpret due to the links, as [35] mentions it has a linear path of exploration. The links also make it possible to show relatedness between one type of node. The data is also scalable to more complex data (when zooming and panning are included).

The Onion layered diagram is similar to the Node-link diagram. The advantage it has is that the layers are explicitly emphasised by color.

Based on the analysis of the ideation prototypes, the Node-link diagram is selected as the prototype to realize. The emphasis of the layers by color as the Onion layered diagram suggests might be incorporated in the prototype as well.

6.2.2 Summary

Based on the set requirements and the three principles for an effective visualization: accuracy, utility and efficiency, the final prototype shall be evaluated.

The requirements were defined to create a complete and freely explorable visualization with interactivity aspect and clear visual encodings.

From the 4 ideas that were presented: the 3D model with FMEA data on the side, an interactive sunburst model, a interactive Node-link diagram that contains FMEA information in the nodes and is expandable and lastly a similar Node-link diagram with the addition of extra visual cues on the background in the form of a onion layered display.

Each of these visualizations has its strengths and weaknesses but based on the principles and requirements, the Node-link diagram was selected as the best suited.

7 REALIZATION

In this chapter the progress for creating the node-link diagram is presented. It shows the different prototypes created along the way and elaborates on some of the design decisions during the progress. As mentioned, a chair FMEA is used as a basis for creating the prototype. For each of the prototypes, a link is provided to the web visualization which allows you to interact with the different stadium of development.

This chapter is meant to give the reader a grasp of how the realization of the final prototype came into being.

7.1 Prototype I

Based on the requirements, a Node-link diagram to represent the FMEA data was chosen as the initial prototype since it would allow for an interactive design, is scalable for more data, allows for the nesting of information and can display the structure and relations between information.

To create the prototype, the initial preference for a programming language, was Python since one of the supervisors had knowledge with this programming language and could provide help when technical difficulties were encountered. However, after research into potential libraries suited for creating an interactive visualization it became apparent that JavaScript and in particular the D3.js library was best suited.

D3.js is a JavaScript library for producing dynamic, interactive data visualizations in web browsers. It makes use of Scalable Vector Graphics, HTML5, and Cascading Style Sheets standards.

Scalable Vector Graphics (SVG's) allows for zooming without loss of quality for detail in a picture, which is very useful when a large system of nodes is being represented. With the chair prototype, zooming might not be necessary but when this is applied for a more complex systems it becomes necessary.

To create the Node-link diagram for the chair, first some references were sought, which were provided in the D3.js documentation. Some examples of references and codes that I used from other developers are: radial-tidy-tree, force-directed-graph and tidy-tree[1].

[1] https://observablehq.com/@d3/radial-tidy-tree, https://observablehq.com/@d3/force-directed-graph , https://observablehq.com/@d3/tidy-tree

The first working solution of a Node-link diagram was actually a collapsible tree diagram, a snapshot from the example from the D3 documentation can be seen in figure 7.1.

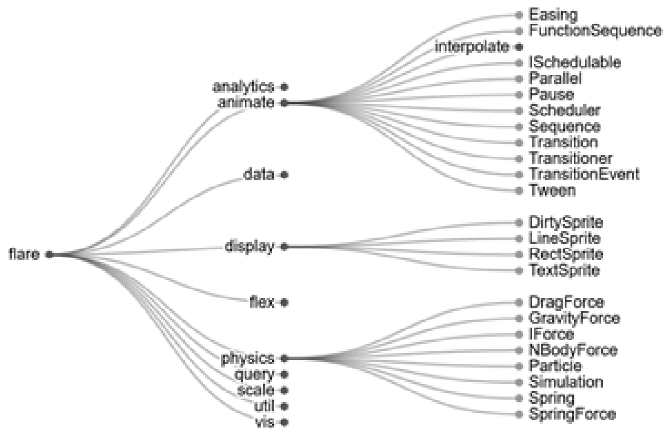


Figure 7.1: D3 example of a collapsible tree from[2]

This example had the functionality of expanding and collapsing nodes with information. More interactive elements such as zooming and panning and data encodings by color, size and text size were implemented to create the first basic prototype containing chair FMEA data. This was a force-directed-graph that uses a simulation of forces between nodes to determine their positions. The result is Prototype I, of which a snapshot can be seen in figure 7.2 and is fully explorable via: https://portfolio.cr.utwente.nl/student/krolzmt/prototypeI.html

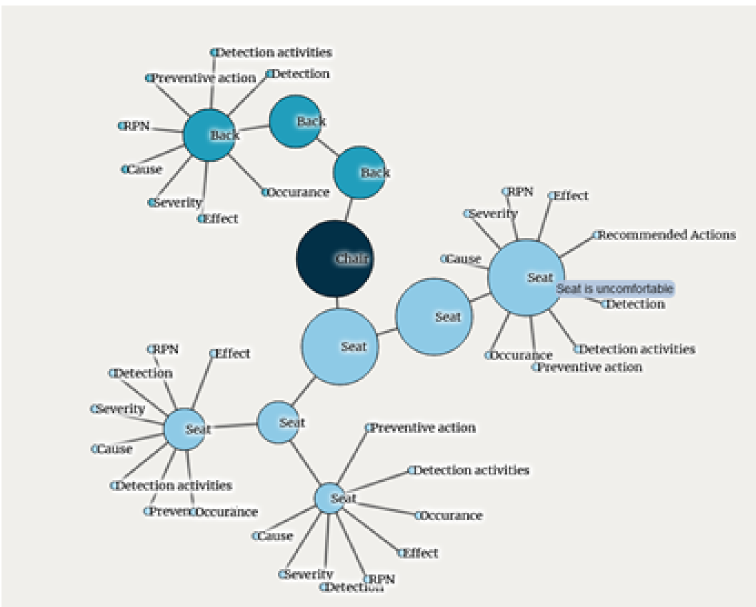


Figure 7.2: Prototype I, all nodes opened with all attributes of the Failure Modes accessible in node-form

This incorporated different sizes of nodes to represent the RPN, different colors to indicate which sub-system they belonged to, text to indicate what type of node it was, text size and

[2]Source: https://observablehq.com/@d3/collapsible-tree

border thickness to show the top level nodes flowing down into lower level nodes and a hover to show additional information about the nodes.

7.2 Prototype II

For Prototype II, the details of the failure mode like effect and cause (which first were represented by individual nodes) were unclear, small and took away focus from the nodes that represent the hierarchical structure. These small, lowest level nodes made the visualization cluttered.

Since creating a clutter free display is a priority in the design, it required the details to be displayed in a different manner. Which resulted in a side pane that displays information of the selected node. This would ensure that at all times, only one node would be shown completely.

Because colors were used to indicate sub-systems, the sizes of the nodes still represented the risk. The hover feature still showed node information such as the type and description. The border thickness was used to show the different hierarchical layers of the system (system /sub-systems / function / failure mode).

The guidelines that were earlier mentioned suggested the use of motion or blinking to show selections of nodes, which lead to the use of blinking for highlighting selections.

In personal communications with the project supervisors, it was mentioned that the layers were not really clear and should be more accentuated.

At first the idea to make this clear was to use icons, which when used correctly can tell immediately what the node is about. After searching for useful icons however, only one icon could really be used to tell the content of the node (the failure mode) exemplified trough a warning sign, see figure 7.3. The other layers were more difficult to select distinct and clear icons for (e.g. a sub-system versus a system). This resulted in no implementation of symbols to show the hierarchical structure.

Figure 7.3: Potential failure mode icon[3]

Even though icons could not be used, the levels of data still had to be distinct, which resulted in the use of symbols to do so. In the D3. library, a couple of symbols could be used (star, square, circle, cross, triangle and diamond) to indicate the different levels in the system. Unfortunately

[3] Source: Font Awesome at https://fontawesome.com/icons?d=gallery&q=danger

the symbols were not very intuitive and another solution was required to show the levels.

The prototype where symbols were used to indicate layers can be seen in the snapshot of figure 7.4 and is fully explorable via: https://portfolio.cr.utwente.nl/student/krolzmt/prototypeII.html

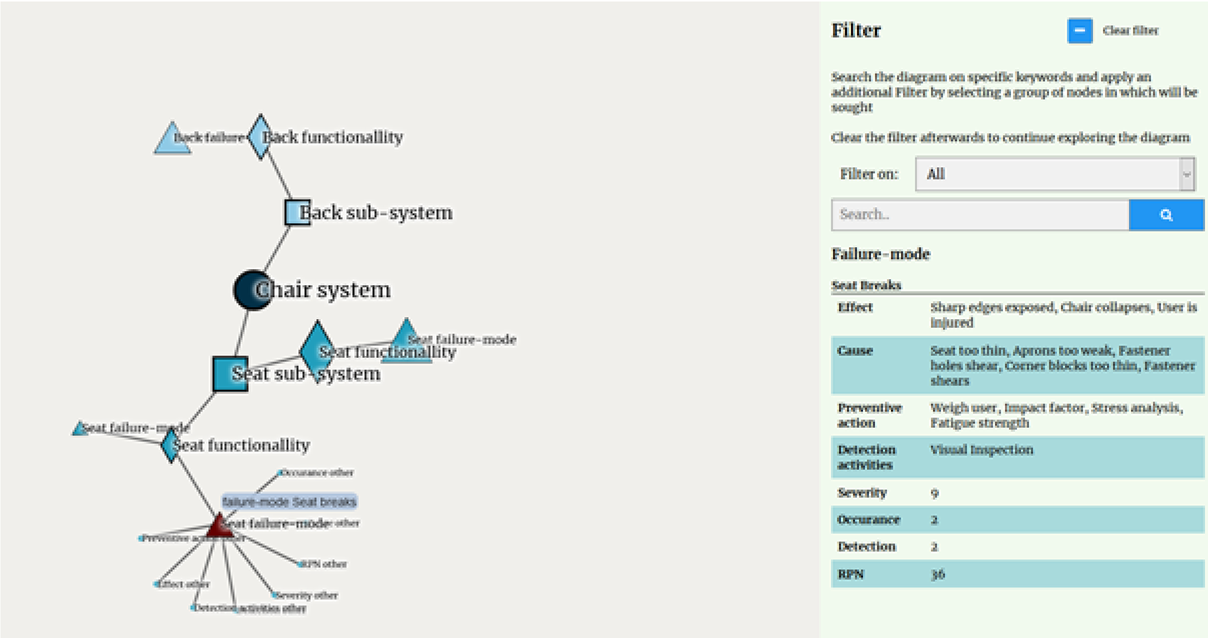


Figure 7.4: Prototype II with highlighting of the selected node and extra details displayed on the right part of the visualization

7.3 Final prototype

The force-directed graph used simulations to determine positions, which could vary and overlap and made the structure difficult to comprehend. To tackle with these drawbacks new designs for a more clear visualization were suggested that would give the user more clarity on the structure. These new designs are displayed in figure 7.5 - 7.7.

Figure 7.5 shows the structure in a tree diagram with the failure modes colored representing risk and propagating this risk through the links. It shows the sub-systems with a background color to indicate these belong together and shows the different layers based on their position on the x-axis. The size of the node represent the depth of the system (in which layer you are).

Figure 7.6 shows the division of the sub-systems in a radial manner, each sub-system has also a background color to indicate they belong to this sub-system. Only the failure modes are colored to indicate risk level.

Figure 7.7 shows the propagation of risk level trough the links and also through the node-border color. The inner color of the nodes represent the layer of the node.

In [38], a study about Node-link trees show that a traditional tree diagrams outperform both the orthogonal tree layouts and radial tree layouts when it comes to the users' understanding.

A Node-link tree diagram was created to show the layers more clearly. The same distances between levels makes sure that the different levels of data are more clearly represented.

The original color-coding to represent risk levels in FMEA were used because they are easily associated as 'bad' and 'good' risk levels. The three colors are red, yellow and green for bad, average and low levels of risk respectively.

The sizes of the nodes were not a good representation of a numerical value, since the radius of the circle increases with the square root of its area (having a 25 times larger circle shows a circle with only a 5 times larger radius). Differences in the size therefore are not perceived well and often can be misleading. Nonetheless one of the guidelines recommend redundancy in visual encodings, therefore the risk level is both indicated by the size of the node as well as the color of the edge.

The inner part of the node was chosen to be white. This allows the inner part of the node to change depending on the selection made. When a node is selected, the inner part gets colored. The selected node is the only one that is colored, which makes it distinct.

Furthermore, when searching for a term, also the resulting nodes must be made clear via highlighting. This is done by having the opacity for all the non-highlighted nodes be reduced which end up with one or more nodes popping out of the visualization. Since opacity is not used for any other visual encoding, this also enables the highlighting to be more distinct.

Lastly, the hover information was formatted to show more details on hovering, to allow for easier exploration. The extra details that were added are the risk level and description.

This resulted in Prototype III , which can be seen in figure 7.8 - 7.10 and the interactive visualization is available at: https://portfolio.cr.utwente.nl/student/krolzmt/vis.html

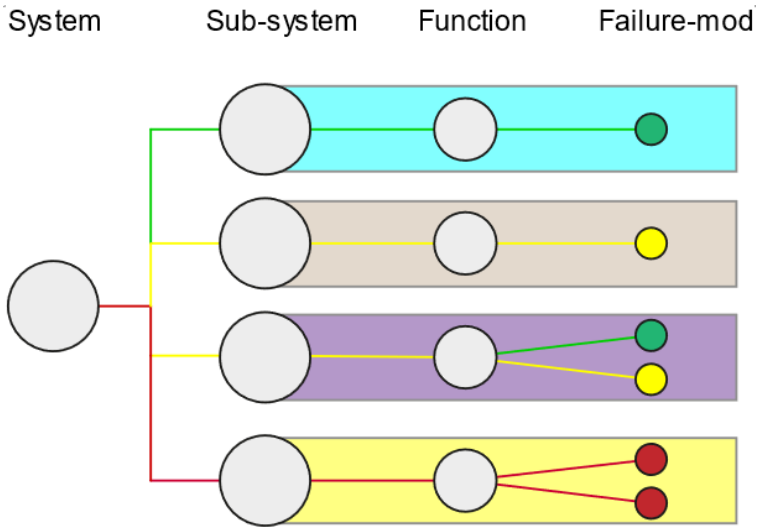


Figure 7.5: Prototype sketch of a tree structure

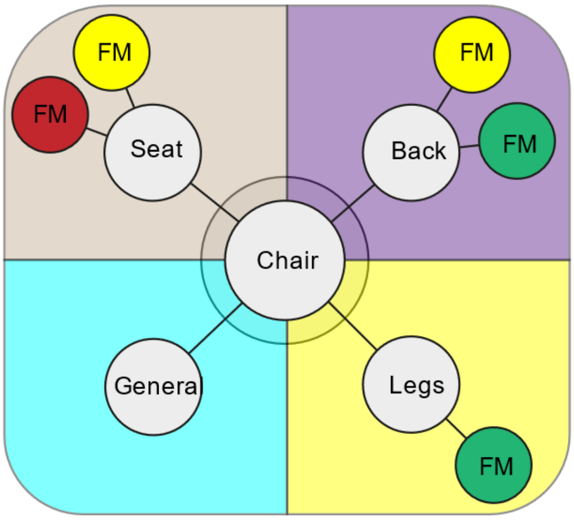


Figure 7.6: Prototype sketch of a radial tree structure

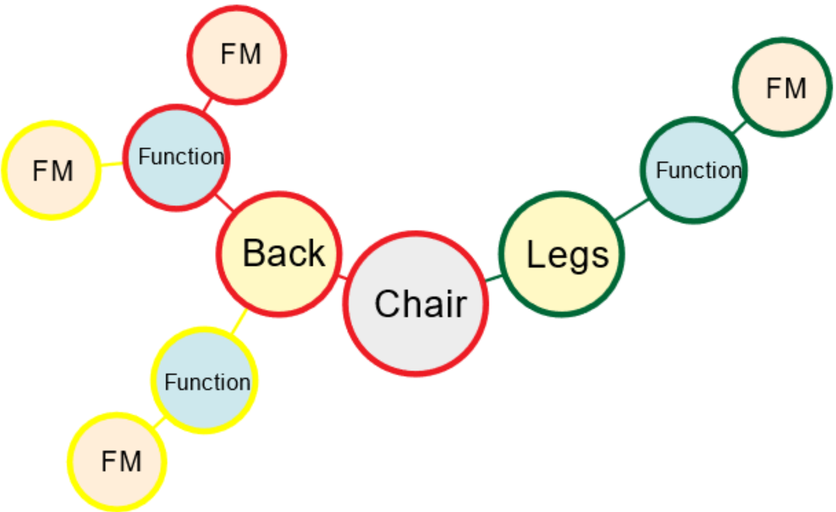


Figure 7.7: Prototype sketch of a Node-link system

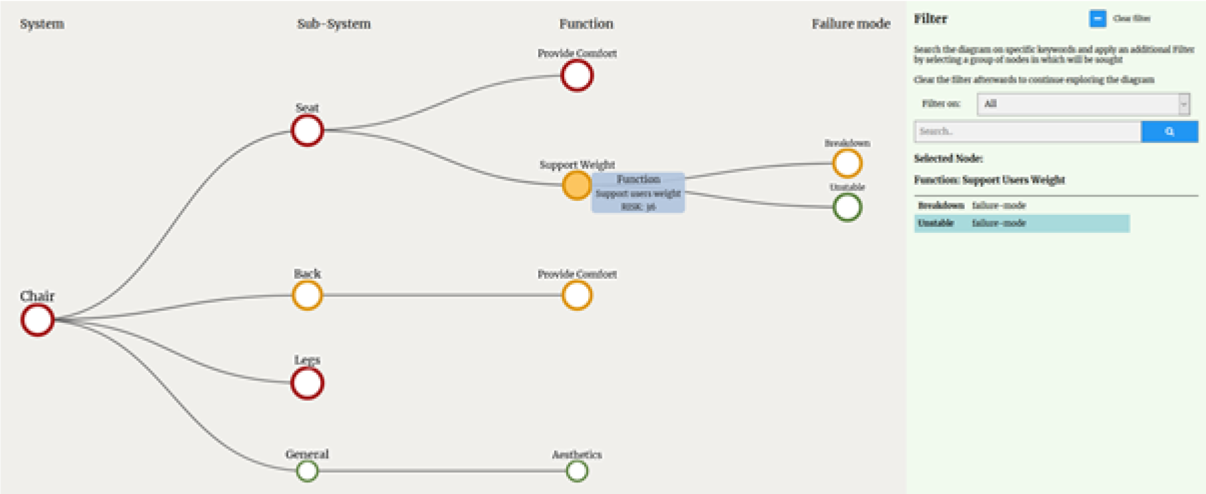


Figure 7.8: Final prototype not fully expanded with hover and child-node details

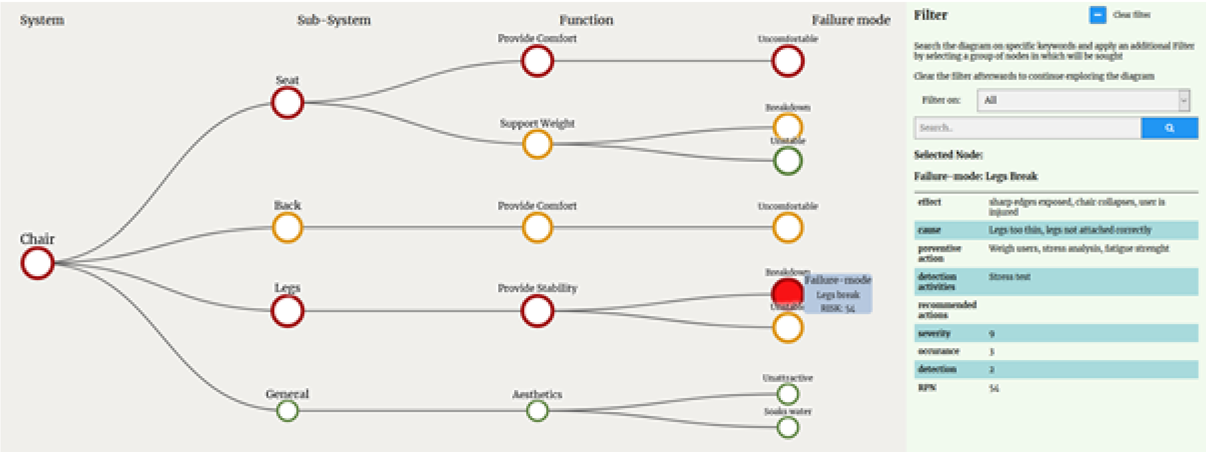


Figure 7.9: Final prototype fully expanded, with a selection of one node, hover and display of details of the selected node

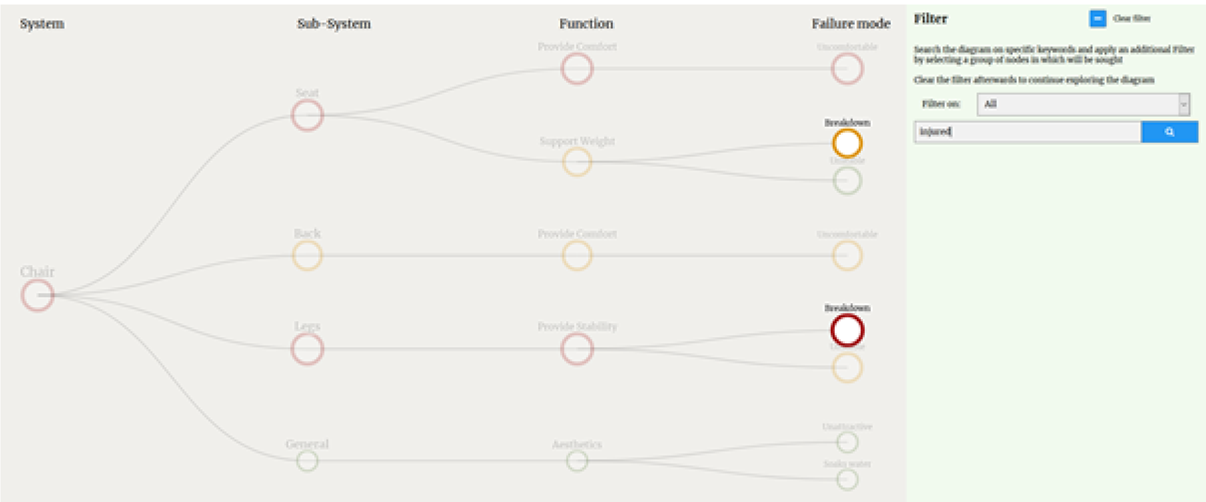


Figure 7.10: Final prototype fully expanded and highlighting trough the search feature with two related results

8 EVALUATION

In this chapter, the evaluation of the prototype is performed. First the setup and key information about the involved participants are introduced. The tasks are described including relations between the tasks. Lastly the prototype is evaluated based on the design requirements and a Mann-Whitney U hypothesis test. The hypothesis test evaluates the prototype based on the principles for an effective visualization. Unfortunately insufficient tests were conducted to determine a significant difference between the test and the control group in terms of efficiency and utility. Feedback from the test group however indicates that the participants liked the prototype and believed that in a more complex system the Node-link diagram would outperform the standard.

8.1 Test setup

The test was set up so that there were two groups, a control group and a test group. Both groups consisted of 8 people whom were shown only one visualization, being a in between-subject study design [43]. This means that different people only test one interface. This test setup was chosen because of the reason that the same dataset and questions were used for both visualizations. By having two independent groups of participants, the test results would be unbiased.

A user study requires you to set independent variables (manipulated by the researcher) and dependent variables (that which you measure based on the independent variable) [43]. In this study, the independent variable include all aspects related to the visualization and the dependent variables are the time the participant requires to perform the task and the amount of correctly chosen answers.

The participants were required to do some tasks, namely the identification of the information displayed in the visualization.

The tasks were displayed in another browser on a different display as is shown in figure 8.1. This was so that the participant could see both the tasks as well as the visualization at the same time.

Before the test started, the participants got a small briefing about what the test entailed and a small briefing about the type of information that is being conveyed by an FMEA. This briefing

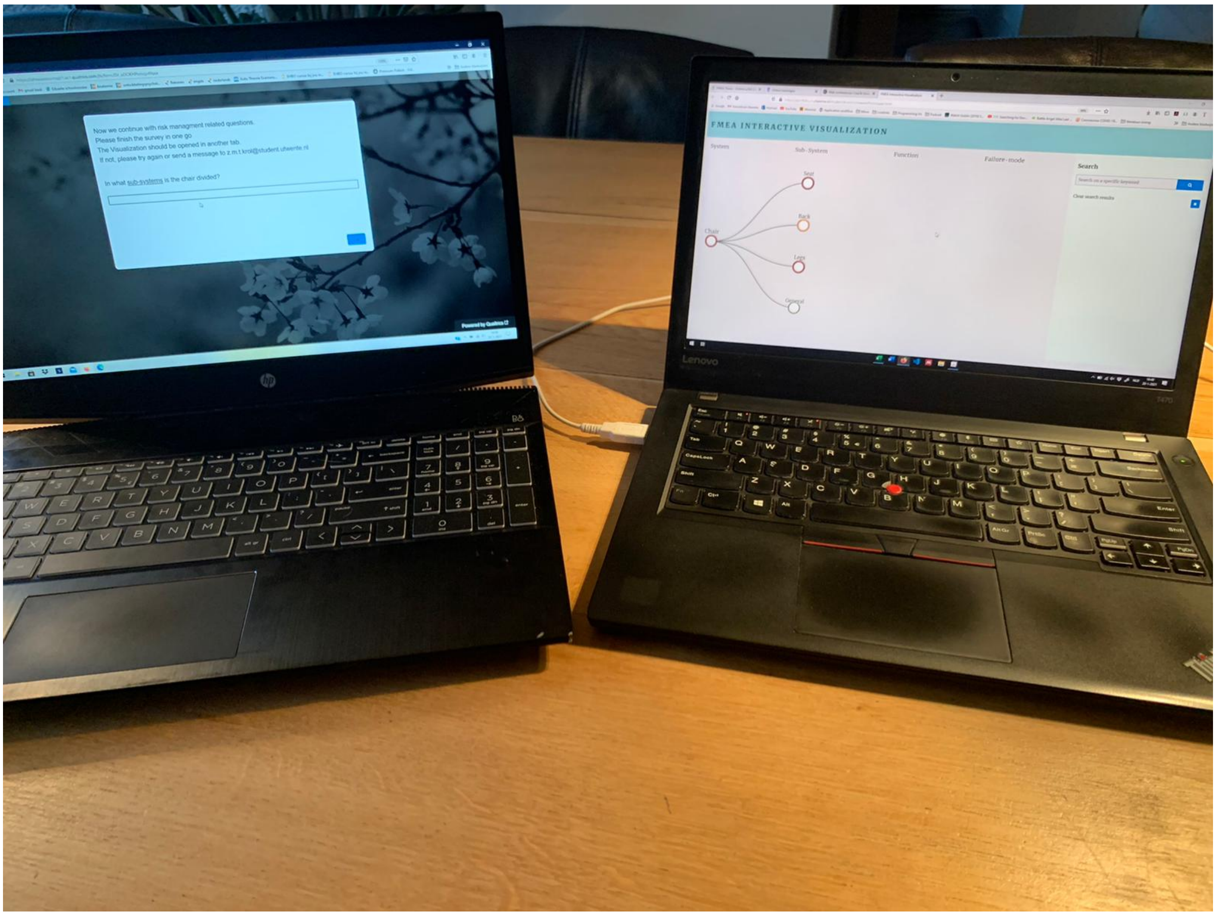


Figure 8.1: Test setup used while testing

for all participants was the same and was the following:

"The test is about Failure Mode and Effects Analysis (FMEA), a structured approach to identify risk in a system/plant/product or process. It does so by looking at the system and divides it into smaller components and determines for each of them, the potential ways it can fail. For each of these so called failure modes, more information is collected to classify the risk, such as the effect, cause and preventive actions. Altogether these failure modes are classified with a ranking based on all this collected information, which can be used to manage risk more effectively."

During the test itself, the researcher did not intervene or answer questions regarding the test. Only in the following case, did the researcher intervene: there was a small bug with the search feature of the visualization (if no capitals were used in the search, no results were given), thus the researcher had to intervene and tell the participant he/she should use a capital letter in the beginning and type the term on which to search correctly. Other than this, no intervention was necessary.

The participants were not able to return to previously answered questions. While performing the tasks, for each individual task, the required time was measured without the user being aware of it. Qualtrics[1] survey tools allowed for the time to be measured. After the test, a semi-structured interview was conducted with the participant about their experience with the visualization and

[1] Qualtrics at: https://www.qualtrics.com/

feedback.

The results from each participant were afterwards checked by the researcher.

The full test setup and planning can be found in appendix A.2.2 and include the consent form, evaluation plan and user study sheet.

Figure 7.8 - 7.10 from chapter 7, is the visualization that was shown to the test group.

Figure 8.2 is the FMEA standard, which was shown to the control group.

System / Function	Potential Failure Mode	Potential Effects of the Failure mode	Severity	Potential Causes of the Failure Mode	Current Prevantative Activities	Occurance	Current Detection Activities	Detection	RPN	Recommended Action(s)	Actions taken	Severity	Occurance	Detection	RPN
Seat / provide seat comfort	Seat is uncomfortable	User is uncomfortable	5	1) seat doesn't fit user 2) seat has sharp edges 3) seat has hard spots	1) measure users 2) round al edges 3) smooth surfaces	5	Customer clinic	2	50	Add customer clinic for structural prototype		5	2	2	20
Seat / support user's weight	Seat breaks	a) sharp edges exposed b) chair collapses c) user is injured	9	1) seat too thin 2) aprons too weak 3) fastener holes shear 4) corner blocks too thin 5) fasteners shear 6) wood threads shear	1) weigh users 2) impact factor 3) stress analysis 4) fatigue strength	2	Visual inspection	2	36						
	Seat flexes too much	Seat feels unstable	4	1) seat too thin 2) aprons too weak 3) fastener holes shear 4) corner blocks too thin 5) fasteners shear 6) wood threads shear 7) fasteners loosen	1) deflection analysis 2) fastener shear analysis	4	Visual inspection	2	32						
Back / provide back comfort	Back is uncomfortable	User is uncomfortable	5	1) back doesn't fit user	1) measure users 2) round al edges 3) smooth surfaces	4	Visual inspection	2	40						
Legs / provide stability and support	Chair is unstable	User is uncomfortable	7	1) legs not attached correctly 2) legs are different sizes	1) measure legs 2) stress analysis	3	Visual inspection	2	42						
	Legs breaks	a) sharp edges exposed b) chair collapses c) user is injured	9	1) legs too thin 2) legs not attached correctly	1) weigh users 2) stress analysis 3) fatigue strength	3	Stress test	2	54						
General / make the chair longer lasting and aestheticly pleasing	Chair is unsightful	Chair is not used	2	1) chair has no consistant color 2) paint corrodes	1) check paint before use 2) apply paint and coating evenly by spraypainting	2	Scratch test	2	8						
	Seat soaks water	Chair is not used	2	1) water gets soaked by seating	1) check coating before usage	2	Water test	2	8						

Figure 8.2: Spreadsheet visualization shown to the control group for testing

8.2 Test results

In this chapter, the results of the test are discussed and summarized. First the test participants are introduced. The question setup is elaborated on and lastly the results are shown.

8.2.1 Test participants

The initial plan to get a random group of participants, was to go to a public place on the campus of UTwente and ask for participants there. This would have resulted in a test and control group were the participants were mainly UTwente students which generally would have had a similar educational level and age.

Unfortunately, due to Covid-19, this was not possible, since no students were present at the University. This required the researcher to use different participants like flatmates, close friends and family.

Both the test group and the control group had the same amount of higher educated participants and lower educated participants, see figure 8.3.

Similarly, the average age of the participants in the two groups also matched with 26 being the average.

Important to note that there are two participants with the age above 50. These two participants were divided between the control and test group.

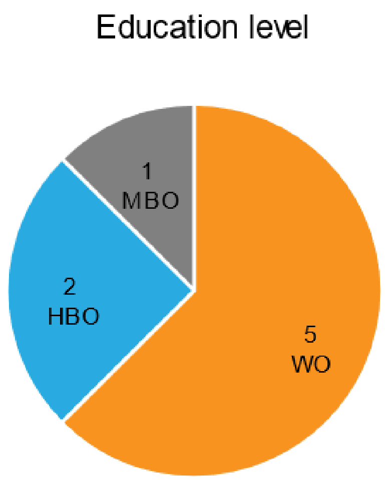


Figure 8.3: The educational level for both participant groups

There were in total 6 female participants and 10 male participants. Figure 8.4 shows the distributions for each participant group.

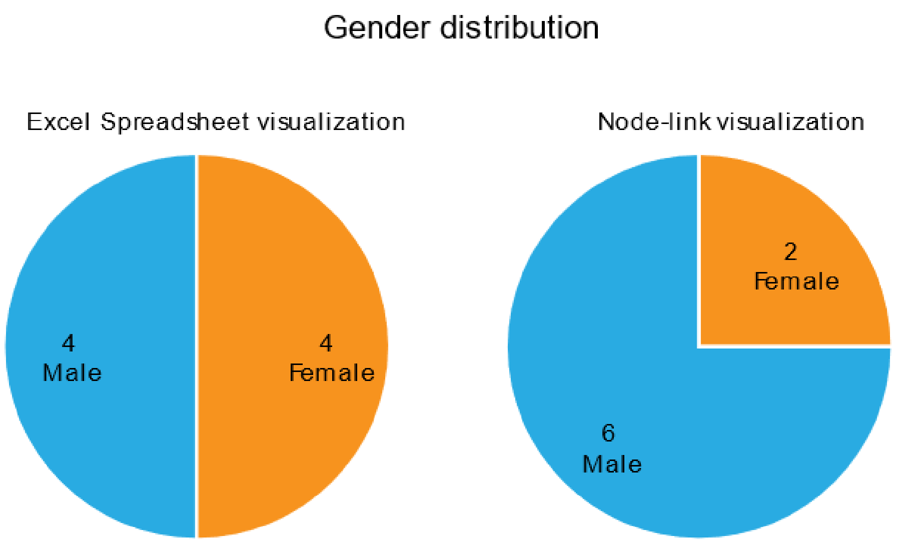


Figure 8.4: Gender distribution for both groups

Lastly, as mentioned in the specification, the familiarity with FMEA or risk analysis was asked of the participants. Most of them were not familiar with this approach. Only 4 participants were familiar and they were evenly distributed among the two groups. The results of these individuals also is given later in section 8.2.3.

8.2.2 Questions

The tasks that a participant was required to do were the following (the formulation of the questions included the formatting as can be seen below):

- Q1: In what <u>sub-systems</u> is the chair divided?
- Q2: Identify the <u>failure mode</u>, that has been classified with the <u>highest</u> risk?
- Q3: What is the <u>cause</u> for failing identified for this specific failure mode?
- Q4: This failure mode is part of which <u>sub-system</u>?
- Q5: Identify the failure mode or modes with the <u>consequences</u> that the <u>user is injured</u>?
- Q6: What are the <u>main functionalities</u> of the Chair system?
- Q7: What are <u>all</u> the failure modes that are somehow related to the <u>seat</u>?
- Q8: Select the <u>failure mode</u>, that has been classified with the <u>lowest risk</u>?
- Q9: What are the <u>causes</u> of failing identified by this specific failure mode?
- Q10: This failure mode is part of which <u>sub-system</u>?
- Q11: Identify the failure mode or modes with the <u>effect</u> that the <u>chair is unused</u>?
- Q12: What are <u>all</u> the failure modes that are somehow related to the chair being <u>unstable</u>?
- Q13: What can be done to <u>prevent</u> the chair being <u>unstable</u>?
- Q14: If you were the product manager of this chair, which <u>failure mode</u> would you tackle first?
- Q15: Which one <u>second</u>?

These questions were formulated in such a way to make it very clear what the required answer was (e.g. sub-systems is underlined, so the correct answer must be a sub-system or more than one sub-systems).

Nonetheless, some participants were confused with some of the questions. For example Q8, where the task is to identify a failure mode. Many participants were confused since the question was interpreted to identify one failure mode whereas the correct answer is actually two failure modes.

Q1 and Q6 were included in the test to see whether the participant was able to see the structure of the data. Q4 and Q10 also had a similar purpose, to see whether they could trace back a failure mode to a sub-system level.

Q14 and Q15 were questions that were added in order to see, based on what part of the visualization, the participant would manage risk. It tries to get a picture of the problem solving and decision making capabilities of the participant.

The other questions focused mainly on the visual search capabilities of the user, the capabilities to connect entities with their attributes.

Some questions were added with the aim to measure the learning curve of this visualization. These questions are represented by two groups: Q1 till Q5 and Q6 till Q11 (Q7 is not part of this). The questions are only slightly different, so that efficiency can be measured for both groups and see if there is any progression in task completion time.

8.2.3 Results

Figure 8.5 and 8.6 show the general results of the two groups. 8.5 shows the required time for the group and 8.6 shows the number or correctly answered questions.

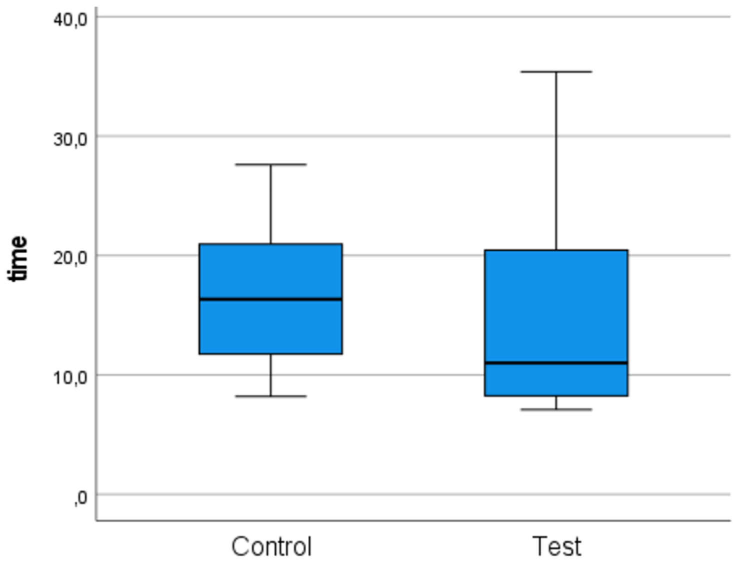


Figure 8.5: Results in a boxplot for the test group

Interesting to note here is that the median required time of the test group was smaller than the control group. 50% of the participants were generally faster than the control group. It also shows that the 25% (2 participants) worst performing participants did require more time than the other participants in this group. This also is shown in figure 8.7 which shows the individual required time per participant per group. Furthermore both figures shows that there is a large variance in required time.

Also figure 8.6 shows that there is a higher median for the number of correct answers. It shows that the median is higher for the test group and also that 50% of the answers for the test group are generally higher compared to the control group

Individually, the results are shown in figure 8.7 and it shows that only except the last two entries, the test group was performing better than the control group. The difference however was only a slightly higher performance. In section 8.3.2 a non-parametric test shall be done based on this data to test whether this difference between the control group and test group is significant.

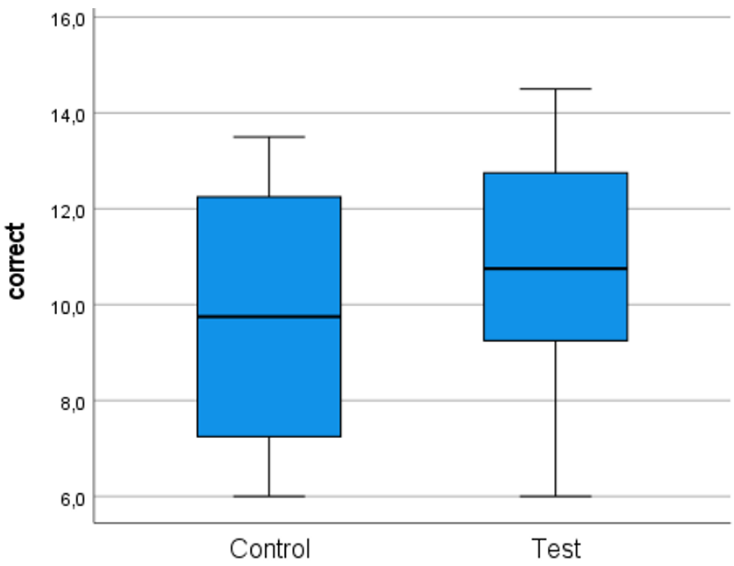


Figure 8.6: Results in a boxplot for the control group

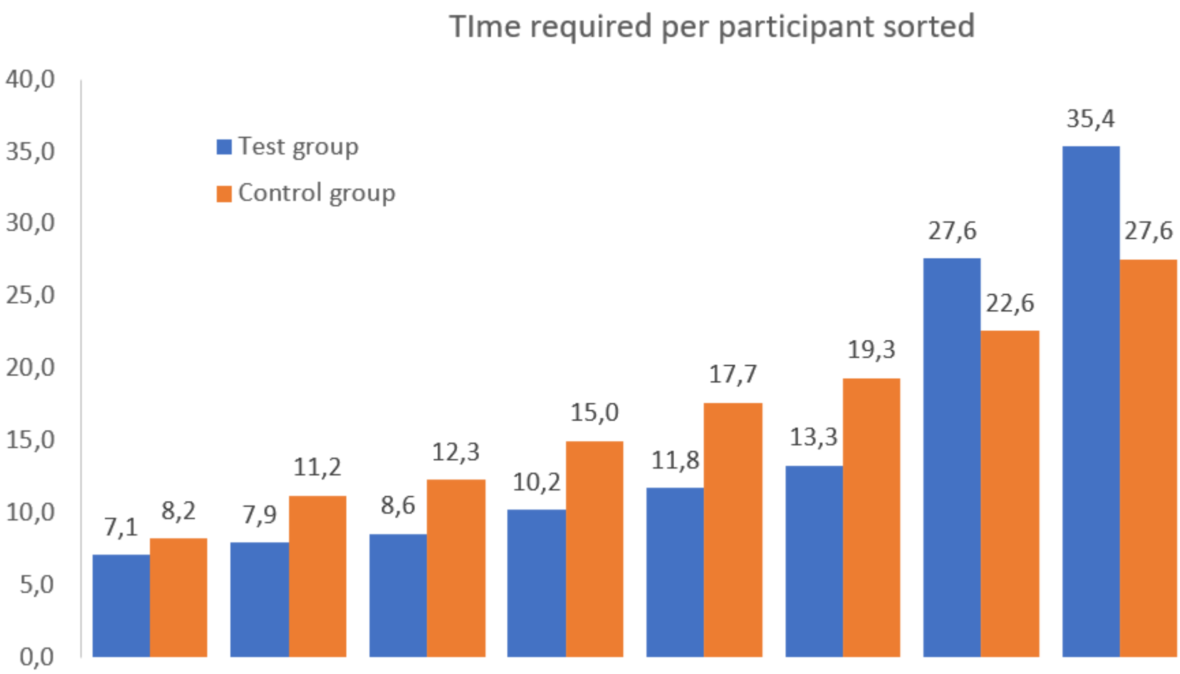


Figure 8.7: Individual results per group sorted from smallest time to largest time

For both the control group as well as the test group the worst scoring participant had 40% of the tasks correct. From the data no correlation between required time and degree of correctness could be determined.

Regarding the structure of the system, Q1, Q4, Q6 and Q10 would show insight in their ability to see the structure of the system. Q1, Q4 and Q10 were except one participant all correctly performed. The functionalities (Q6) on the other hand were wrongly identified by most of the participants. When this is compared to the FMEA standard, the participants scored especially better on task 1 and 4 for the Node-link diagram.

As mentioned in the previous section, the questions were formed with the aim to determine the learning curve. This looks at the tasks completion time for Q1, Q2, Q3, Q4 and Q5 and compare this to the task completion time for Q6, Q8, Q9, Q10 and Q11. Also the number of correct answers is important and Figure 8.8 and 8.9 shows these results.

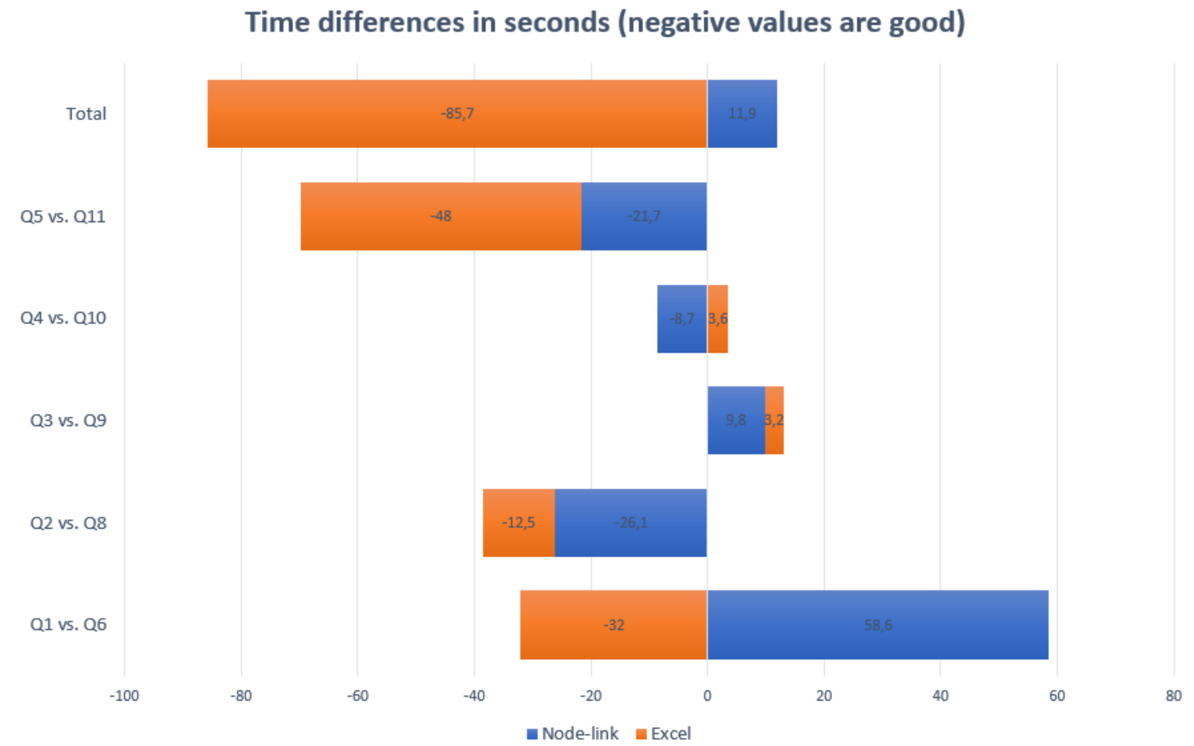


Figure 8.8: Differences between questions for the required time

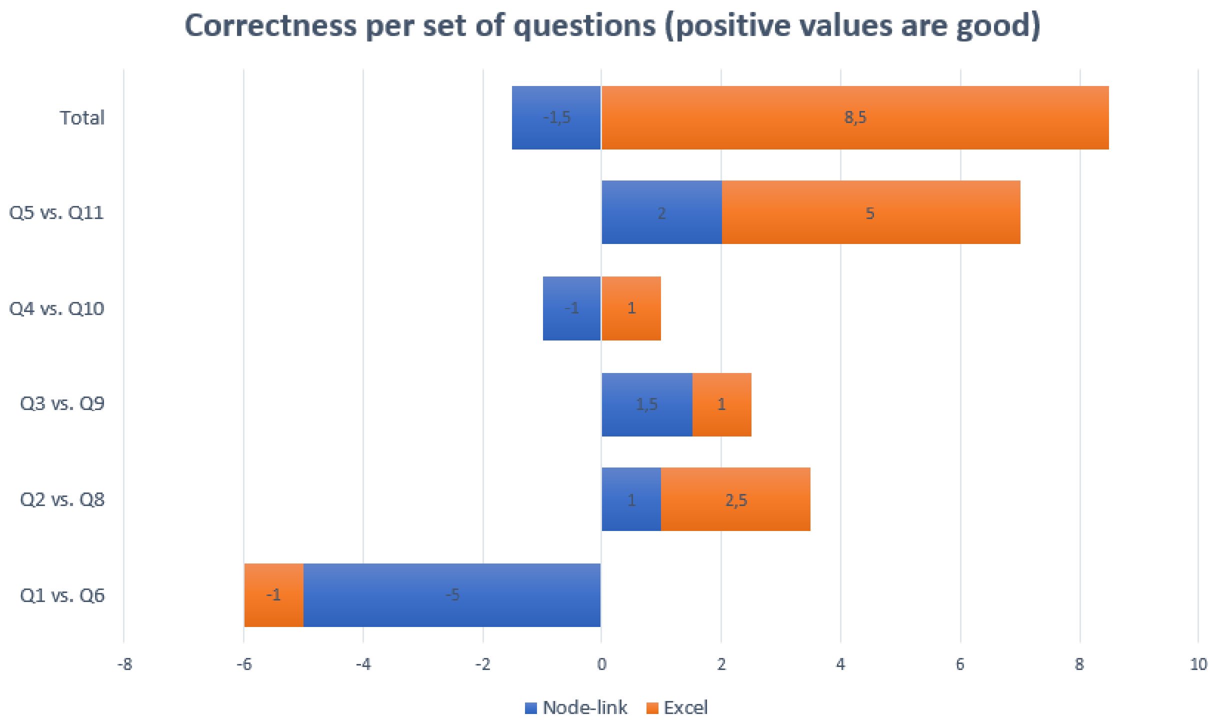


Figure 8.9: Differences between questions for the correctness

Figure 8.8 shows the total time over all the participants that it took less to complete the task compared to the same task that was performed earlier. For example: Question 5 & 11 were formulated so that in essence the same task is done, only about a different part in the system. The time required to complete task 11 minus the required time for task 5 for all the participants is the result that is displayed. In this case the Excel visualization has a -48 seconds increase, meaning that over all the participants they performed 48 seconds less on the same task. For the Node-link visualization, the participants on the contrary required more time to complete the same task.

Also the amount of correctly performed tasks was greater for the excel visualization. A large portion of why the Node-link visualization was performing worse than the excel visualization was due to Q1 being available and very clear from the start whereas the functions require the user to search and explore more.

As mentioned before, the relation between skill level and performance should also be investigated. This is shown in figure 8.10. It shows that the participants with more knowledge performed better with the Node-link diagram than all their peers with quite a big margin. Only 2 participants in both groups were familiar with Risk management or FMEA, thus this is only indicative.

	Required time [Min.]	# Correct
Node-link [familiar]	8,7	13,25
Excel [familiar]	19,4	9,5
Node-link [not familiar]	17,4	9,9
Excel [not familiar]	15,8	9,8

Figure 8.10: Average performance of the two groups for two familiarity levels

8.3 Prototype evaluation

In this section, the requirements are used to evaluate the prototype. The first part looks at the design requirements formerly displayed via the MoSCoW methodology. The last part takes a look at the requirements for an effective visualization.

8.3.1 Design requirements

After the tasks, the participants were asked in an interview setting about their experience with the visualization. Some of the questions that were asked in the interview were aimed at identifying and evaluating the design requirements.

The questions aimed at evaluating the design requirements are:

- Did you think the structure of the system was displayed correctly and did this help for you to get a complete picture of the system?

- Was the information being displayed at once limited and clear?
- Was the use of visual cues understandable and helping you make choices?

The responses to these questions give answer to the following design requirements respectively:

- Complete structure of the chair displayed
- Limited amount of information being displayed at once
- Clear distinguishable visual aids

Almost all of the participants mentioned that the system was completely displayed, only one participant mentioned that to his belief, there were some missing nodes and links to represent the chair correctly. Moreover, they believed that the information was limited and clear. Information not necessary for the given tasks like severity, occurrence and detection was seen as unnecessary and not limited.

Based on the interview, all of the visual attributes were clear to the user. The user was able to identify the following visual attributes: color to represent the risk of each node, size to also represent this same risk level and selections by the fill of the node.

Furthermore, the results show that for Q1, Q4 and Q10, the participants scored high which indicate a grasp of the structure. Unfortunately Q6 was performed not so good, which shows that the functions of the system are not clear in the prototype.

The other requirements' evaluations are based on the researcher's assessment and can be found below the requirements in table 8.11.

An interactive visualization has been created that allows for hovering, expanding, collapsing and selecting nodes.

All the information is available and freely explorable by the user. By clicking on nodes, the user is able to hide or collapse the child nodes. This also makes sure that only a limited amount of information is being displayed at once. At all times, only one node is completely visible, whereas the total structure of the system can be open or closed based on the users' desire. The participants mentioned, that all the information was there, freely explorable and limited to what is being shown at once.

It is a web-based visualization created with D3.js and uses SVG objects that allow for scaling without loss of detail. It is deployed online and available for usage on: https://portfolio.cr.utwente.nl/student/krolzmt/vis.html

Links are used to connect related data together and the position of the nodes is used to represent the hierarchy of the system, where it is divided up in: system, sub system, function and failure mode.

Must	Should	Could	Won't
Interactive elements are used to allow for explorative actions	Web-based visualization	Filtration of information based on user input	Database integration
The complete structure & relations are displayed	Compliance with the guidelines for a good visualization	Knowledge base for adding extra information to the system	Other framework integration
Limited amount of information being displayed at once	Clear distinguishable visual aids		No allowance for data manipulation
The visualization must allow for scaling of information			
The risk level is immediately clear			
Chair data is used			
Clear to novice users'			

Figure 8.11: MoSCoW model for requirements evaluated

Lastly, when searching on a term, the related nodes are highlighted by setting the other nodes with a opacity. This makes sure that the related nodes are clearly distinguishable.

The guidelines were taken into account when designing the prototype.

Filtration is possible through the filter, search terms can be filled in and related nodes are displayed. You can adjust this search based on types of nodes you want to search for.

8.3.2 Effectiveness

Based on the three principles mentioned before: accuracy, utility and efficiency, the visualization shall be evaluated here.

Accuracy

As mentioned in the results before, the participants were asked whether the structure of the visualization matches the data of the chair. In all cases they thought the structure was displayed very well and showed the complete chair.

Only one participant stated that they would expect connections between other nodes too (e.g.

the sub-system Back with the function to provide comfort should also be related to the function to provide stability).

Also the questions to determine their interpretation of the structure (Q1, Q4, Q6 and Q10) indicate a understandable structure. Only the functions of the systems are considered not clear.

The meaning of the visual attributes such as color, selections and size were also correctly identified by the participants. The only thing that was not clear from the beginning for most users' were the interactive elements. After some experimentation with the visualization, this became clear though.

All of the above show that the data structure fits the hierarchical FMEA data and that the user is able to understand the structure of the data well.

Efficiency

For each task, the required time was measured to do statistical analysis.

When doing a Shapiro Wilk test for normality, to measure whether both groups have the same normal distribution, the result was negative. The control group has a normal distribution, but there is not enough evidence to prove that the test group also has a normal distribution. This makes it so that no T-test can be done and instead the Wilcoxon Rank Sum test / Whitney-Mann U test must be performed.

The Whitney-Mann U test takes two independent samples and will compare the medians of both samples based on a ranking of the values.

The hypotheses are:

$$H_0 : Median_{Testgroup} = Median_{Controlgroup}$$

$$H_1 : Median_{Testgroup} < Median_{Controlgroup}$$

The result of this is a p-value of 0,382 which is not below the α: 0.05. Thus, the null hypothesis cannot be rejected.

This means that there is not enough evidence at α: 0.05 to support the statement that based on the required time, the test group performed better than the control group.

Utility

Similar to the efficiency measure for the prototype, to determine whether the Utility requirement was met, statistical analysis is performed in the same way.

Just as before, the Whitney-Mann U test takes two independent samples and will compare the medians of both samples based on a ranking of the values in order to determine a statistical significance.

This resulted in a p-value of 0.442 which is not enough evidence to reject the null hypothesis that the medians are equal.

Although the results seem promising, not enough tests are conducted to reject the null hypothesis. This means that there is no prove for a improvement in the prototype on the degree of correctness.

8.3.3 Feedback

In this section, feedback from the participants is stated. First, the feedback on the prototype is elaborated on. Later, a short summary of the feedback on the current standard is also given.

Prototype

Many participant stated that in the beginning it is not clear you can click on the nodes. Through observations this was also noticed by the researcher. The first question (what are the sub-systems?) is easily solvable since the sub-systems are displayed from the start. When the 2nd question comes (which Failure mode has the highest risk?) some participants are searching and discover the colors and use this as input for further exploration. Often the next thing they discover is the hover feature.

For some participants this resulted in selecting a sub system (based on the original displayed information) as a failure mode. This means they did not click on the node till they discovered the failure modes. 2/8 had this problem, whereas 6/8 of the participants did discover the expanding of the nodes upon clicking them.

Yet, another problem arises here. 2/8 of the participants that do discover the failure modes end up not clicking on them (not discovering the details of the failure mode). This also resulted in the users not answering the complete failure node, only the assigned title above the node.

After the third question however, the interactivity of the visualization was clear since it asks for the cause and therefore requires the user to search and explore the information more. Nevertheless, many participants stated they would like some sort of instruction to make clear that you can click and expand nodes.

Similar for the search function, many participants did not bother to search or filter the displayed information. This was mainly because of two reasons: 1) the information was already limited, which did not require searching or filtering, and 2) the focus of the visualization lies on the Node-link diagram, which resulted in them not noticing the search feature.

If they were instructed that they could use this function and be shown how it works, they potentially would use it (still depending on the complexity of the data though). For the participants that did use the search feature, they said that it worked well when exploring the information and they believe that especially in a more complex system this would speed up their search drastically. As of now, there is a bug with the search feature namely, you must fill in the exact term you are looking for.

Since in Q5 and Q11 some parts are underlined, the participant would search on this exact term, which ended up with no results since in the data it is not written like this exactly. This flaws requires to be improved for later prototypes. Also the 'filter on' input above the search bar was not clear to the participants. They thought it would only display the failure-mode for example, but when no results were given the participants assumed it did not work and did not use it again.

To almost all the participants, the color and their encoding of risk was very clear. They gave feedback on this color to make it scale according to the actual value, not only the red, yellow and green to indicate risk.

The sizes were noticed by most of the participants. Only some, did not understand what the sizes represented. The feedback was to make the differences in sizes more visible. Since it did not really help with decision making however it might even be better to leave out the differences in size.

Many participants suggested that the total visualization should be shown completely at first and allowed for the user to collapse nodes as they wished. This would show the structure of the data more clearly from the start. Also many suggested the use of '+', '$\Rightarrow$' signs or movement to make clear you can expand the node.

One participant thought that the detailed information on the right side was a little bit cluttered, especially when you compare them to the nodes and links. The feedback is to make this more intuitive, with more short descriptions and limited to only the required data for the tasks.

Some people really liked the aesthetics of the visualization. Whereas others believed it not the be nice looking but very workable (clear and not cluttered). Most of the participants were indifferent about the aesthetics of the tool. One suggestion to increase the aesthetics is adding transitions for moving objects.

Standard

The most interesting feedback from the spreadsheet visualization was that finding the correct answers required them to search the entire visualization. Each cell had to be explored which they were not fond of. 2 out of the 8 participants wanted to use the Ctrl+F search function in Excel to find the answer to the question in order to not have to search each cell.

Although they imply that there was much information being displayed and that it was cluttered, they also stated that the information was clear and not cluttered.

8.3.4 Summary

The test was conducted with 16 participants whom were divided in a control group and a test group. The test group was shown the prototype and the control group was shown the original current FMEA method. The participants were required to perform the same tasks and their required time and correctness was measured to determine improvement.

The collected data shows a decrease in required time for the prototype and an increase in correctly performed tasks. Yet, no statistical significance with the Mann Whitney U test was determined.

The received feedback mainly pointed out the necessity of informing the participant on interactive elements, the functioning of the search feature and the possibility of improvement in with more complex data.

9 DISCUSSION

Textual data is difficult to encode visually. In this research a Node-link diagram was chosen due to it being effective with large datasets and complying with the requirements. Although many visualization types were considered, some might have been overlooked or deemed impossible to show FMEA data in, like a word-cloud for example. However, this actually might be an interesting visualization form since FMEA data is mostly textual information.

There was no significant improvement of the proposed method. As mentioned by [39], studies show that visualizations have little impact on task performance when the task complexity is low. In the case of this study, the chair excel spreadsheet was not considered difficult or complex by the participants which confirms this statement. Therefore, it is debatable if the user tests fit the goal of this study. At least further research through more tests should be conducted before any conclusions can be made.

In [38], the researchers used eye tracking to determine the effectiveness of a visualization type. Eye tracking determines to precision where the focus of a participant is and how often he/she would check his or her answer. The use of eye tracking was also mentioned by [39] as a possible method to measure the accuracy of a visualization. This method was not chosen to determine accuracy in this study. Nonetheless, this is an interesting method and something which could provide more insight in the decision making during the exploration of FMEA data.

Furthermore, [38] also mentions that Node-link tree diagrams suffer from scalability problems for large hierarchical datasets. In this study however, one of the reasons to opt for a Node-link diagram was, that it actually fits large and hierarchical datasets very well [35]. This was not further investigated in this research but should definitely be explored.

As mentioned by the supervisor of this project, the combination of Fault Trees together with FMEA might be beneficial to both models, due to the FTA also using a tree structure. In [14] the researchers suggest a recursive manner in which FTA and FMEA can be combined and where the FMEA as nodes are displayed alongside the FTA. It uses FTA as an indication for components on which to perform FMEA analysis. This FMEA analysis is then used to perform FTA analysis etc. This article still keeps the FMEA data in the table format however. In this study, no research to this was performed.

10 CONCLUSION

Finally an answer can be given to the main research question: *How can FMEA tables be translated into a visualization which helps users and managers to improve their understanding of, and the usability of the method?*

The flaws of the FMEA include the complexity, resource constraints, reliance on expert knowledge, limited re-usage of the tool and more. The problem that was addressed in this research is the complexity in terms of the amount and manner in which the information is displayed. The current method shows the information in a spreadsheet format, which is not suited to identify relatedness among failure modes, it is tedious and incomprehensible to work with.

Through nesting, the amount of visual datapoints being displayed can be limited. This leads to a more clear and focused visualization. The use of interactive elements such as hovers, expansion and collapsing of data allows the user to explore all the information while maintaining focus.

An interactive Node-link diagram was created to adhere to the findings. It uses nesting to reduce clutter and the following interactive features: hovering, selecting, searching, expansion and collapsing of data.

This prototype has been compared with the standard FMEA spreadsheet where for both visualizations, 8 participants were asked to perform the same tasks. The goal of these tests were to measure an improvement in the required time to task completion and the degree of correctness for the prototype.

The result of this comparison is that not enough tests were conducted to determine an improvement in effectiveness of the prototype.

Although testing was not sufficient, participant feedback suggests that the proposed method would increase effectiveness for more complex systems. With more testing, the improvement on the effectiveness will likely be proven as well.

11 FUTURE WORK

Here I propose three directions for future work: 1) iterative improvement to the prototype based on the given feedback, 2) more user testing with a more diverse population for a more complex system, and 3) creating other visualization options for the display of FMEA information.

Iterative improvement

The tests resulted in a lot of valuable feedback on the prototype. The most important aspects of the given feedback (see section 8.3.3) should be incorporated in the prototype before testing for effectiveness again.

The most important feedback aspects include:

- increase the users' understanding of the visualization being interactive (e.g. tutorialization of the tool)
- improve functionality of the search and filter tool
- find a better trade-off between information being displayed initially and the amount of closed nodes

Testing with a complex system

Current testing was performed with an easy to understand system, namely a simple chair. This was chosen as to not make it complex, however the main issue this research tackles is the complexity of data. Thus, the same or improved version of the proposed approach should be tested with a more complex dataset to determine if it truly affects the comprehension and usability for complex data.

Furthermore, the population that was tested on were mainly students with no to little FMEA or risk management knowledge. To determine whether such a visualization would also work for users of the FMEA, they should be included.

Explore other visualization options

This research focused on the Node-link diagram to display FMEA information. Other earlier proposed ideas for displaying the information were the sunburst diagram and the use of 3D models. Those ideas did not make it into a final prototype based on the design requirements. Nonetheless, these visualization options and possibly others, can prove to display the information more effectively than the FMEA standard and should be explored.

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A APPENDIX

A.1 Interviews

Interview met Jan Braaksma 18-09-2020 Online

Er zijn 2 stromingen om een FMEA analyse te doen; rigorous, streamlined

Rigorous → Diepgaand, per systeem, per component etc. → heel erg tijdrovend en duur

Streamlined → Ingezoomd op 1 specifiek 'critical' onderdeel van het systeem.

Er zijn veel beperkingen aan een FMEA.

1. Vaak eenmalig gemaakt, 1malige gestructureerde analyse van een proces, systeem → maatregelen bedacht (vaak maintenance), deze ingepland en daarna vergeten. Vb. oliebuizen worden periodiek onderhouden, druk in de leidingen neemt af, door afname van hoeveelheid olie in de leidingen. Ondanks dit worden de leidingen nog steeds op dezelfde wijze (hoge druk) onderhouden.

2. Kost veel tijd en expert kennis om te maken. Vaak in groepen van experts met verschillende betrokken engineers (reliability, maintenance en design engineers bv.)
   - Bepalen tot op welke diepte het zin heeft de analyse toe te passen → literatuur zegt hierover op de diepte die aansluit bij de onderhoudspolicy binnen het bedrijf.
   - Expertkennis nodig altijd!
   - Schalen (ranking van S,O,D) zijn niet gestandaardiseerd in veel industrieën (sommige wel). Blijkt lastig te bepalen en vaak niet gebaseerd op kwantitatieve gegevens.

3. Complex → veel regels

4. Nieuw product → nieuwe FMEA: eerdere kennis wordt niet meegenomen. Als het product bijna hetzelfde zou zijn, wordt dit alsnog opnieuw gedaan. Veel kennis tekstueel (geen audiofragment of video bijvoorbeeld (waarin veel meer informatie gestopt kan worden))

5. Onzekerheid → is dit een faalmodus of niet? Veel dingen weet je niet, en op een gegeven moment zie je de faalmodi ook niet meer.

6. RCM toegevoegd in FMEA → bevat geen uitleg tot besluitvorming (overigens ook bij andere gemaakte keuzes (waarom deze schaal gekozen → geen duidelijkheid))

7. Aangezien de FMEA veel regels/info bevat, is het makkelijk om de weg kwijt te raken.
8. Omstandigheden afhankelijk $\rightarrow$ f16 in Afghanistan vs. in Nederland hebben hele andere faalmodi.
9. Kennisoverdracht van bedrijf tot bedrijf ontbreekt vaak, waardoor een bedrijf soms opnieuw een FMEA moet doen, terwijl de kennis al bestaat.
10. Zelfde faalmodi $\rightarrow$ verschillend effect

Mogelijke andere interessante raakvlakken (om visueel te maken) zijn:

Rankings, Combinatie FTA, Systeem hiërarchie, 3D CAD Model, database

Huidige systemen/methodes:

FlowCad, Optimizer+ Maxgrid, Vera, Avix FMEA, AVEVA

Genoeg onderzoek en Jan Braaksma is zeer enthousiast

A.2 Evaluation documents

A.2.1 Evaluation plan

Purpose

The user evaluation consists of two parts, the two goals that the research hopes to achieve, being: to measure effectiveness and to find improvements to the prototype.

Set-up

The user test shall be done on a PC where half of the group shall do tasks with the new visualization method and the other half shall do the same but with the standard excel spreadsheet.

Both systems represented are the same, the structure is the same, so only the way they are visualized is different.

Participants

In total the number of participants shall be 22, according to Sauro, J.(2015)[1], this is required to do a between subjects test to state a difference in effectiveness for a confidence interval of 90%. The difference in effectiveness would then be 50%. In order to measure a smaller difference in effectiveness, a larger sample size would be required.

Mostly, non-experts shall be asked to do the tests.

If possible already knowledgeable people (FMEA or Risk Management Professionals or Engineering students) shall be included in the tests as well and they shall be also evenly dispersed among the control group and the test group.

For the non experts, a small explanation prior to the execution of the task shall be given.

Other

Due to Covid-19 extra measures shall be taken into account (study information sheet). Prior to testing, the tasks shall be executed by some test users with the aim to improve them so that they in most cases should be clear to the user. These tests shall not be part of the results.

Main goal: find whether or not, there is an increase in effectiveness when using the proposed visualization compared to the standard excel spreadsheet format that is normally used.

Effectiveness is a broad term and it is often not clear what effectiveness means as part of a visualization. Effectiveness is characterized by three principles, the principle of accuracy, the principle of utility and the principle of efficiency [1].

Zhu, Y. [1] also offers both quantitative and qualitative measurement techniques for each of the

[1] Sauro, Jeff. May 6, 2015, MeasuringU, How to Find the Sample Size for 8 Common Research Designs via https://measuringu.com/sample-size-designs/

principles. Some of those, shall be applied to the user tests and include:

1. The measuring of the number of interpretation errors (accuracy)
2. The measuring of achieved goals (utility)
3. The measuring of task completion time (efficiency)

This leaves out three quantitative measurements for effectiveness due to time constraints

- The measuring of number of times the visualization is picked for the task (utility)
- The recording of eye movement (efficiency)
- The measuring of a learning curve (efficiency)

The exact tasks still need specification (which probably only can be done after the visualization is finalized) but shall be similar to the ones listed below.

1. Interpretation errors
    - Describe what the function is of component X and system Y
    - How risky would you classify this system?
2. Achieved goals & Task completion time
    - Find the item in the system with the highest priority
    - Find the RPN value of the following failure modes
    - Of what sub-system is component X a component?
    - Navigate from component X to Y and describe their relationship

Qualitative measures: Furthermore, through observations, interesting interactions, or phrases shall be noted and clarification for specific actions shall be asked about during the interview that follows afterwards.

In the interview also the participant shall be asked to rate the effectiveness of the visualization based on the three principles, accuracy, utility and efficiency and include elaboration with their statements.

Secondary goal: find ways the prototype can be improved to increase effectiveness, aesthetics, navigation or other aspects.

This is achieved two fold. First by observing the user, where they get frustrated, their remarks about the method; and second by performing a semi-structured interview with the user and ask questions regarding potential improvement (see interview questions below (it gives a main outline)). These questions are asked to be rated on a Likert scale from 1 – 10 and give elaboration.

1. How easy could you navigate within the tool and execute the tasks?
2. Was it difficult to understand the tool and what it was trying to inform you about?
3. Was the information displayed concise and interesting (for all the moments)?
4. Did the tool succeed in you making the correct decisions as where to navigate to?
5. What did you like about the tool and what did you not like about the tool?
6. How do you rate the aesthetics of the tool?
7. What would you improve to make your experience with the tool better?
8. (for the risk managers) would you make use of the tool in order to get a clear image of the risk?

Informed consent form

You shall be given a copy of this informed consent form

The goal of the study is to find out whether the new visualization method of the FMEA shall result in an increase in effectiveness of understanding and decision making capabilities for the user. This study shall take approximately 20-30 minutes and includes both a testing situation as well as an interview with the researcher.

Read before filling in this consent form, the study information sheet about what the study entails.

Please tick the appropriate boxes	**Yes**	**No**
I have read and understood the study information sheet, 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 the information I provide shall be used to determine the effectiveness of the visualization as well as for the improvement of the prototype.	○	○
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], shall not be shared beyond the study team.	○	○

Signatures

______________________	______________________	________
Name Participant	Signature	Date

I have accurately read out the information sheet to the 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 more information: Zanur Krol, z.m.t.krol@student.utwente.nl

Contact information for questions about your rights as a participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions or discuss any concerns with this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee of the EEMCS at the University of Twente by ethics-comm-eemcs@utwente.nl

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A.2.2 Study sheet

Purpose of the Study The goal of the study is to find out whether the new visualization method of the FMEA shall result in an increase in effectiveness of understanding and decision making capabilities for the user.

Procedure

This study shall take approximately 20-30 minutes and includes both a testing situation as well as an interview with the researcher.

First, the participant shall be presented a consent form and the study information sheet that presents the purpose and setting of the study and is aimed at informing the participant.

The testing situation involves the participant to do some tasks on the computer that revolves around the FMEA in either the standard format or the newly devised format and is aimed at determining the effectiveness of the tool.

During the time, the participant is performing the tasks, the researcher shall be present but shall not interfere, guide or help the participant in any way. Interference with the task shall only be the case if problems outside of the scope of study arises [such as issues with the computer].

The interview shall take place at a public place and during the interview, the interviewee shall take notes. Personal identifiable information shall be kept out of the interview.

Both the interview as well as the testing shall take place at a convenient environment. A location at the University of Twente shall be made available for testing and interviewing purposes.

After the test and interview, if the participant believes that his safety or personal information was not safeguarded. The information from the interview and testing can be destroyed as the participant wishes.

FMEA FMEA is a risk management tool that is used by a company to identify for a system (this can be anything from a chair to a nuclear power plant) all the different ways something can go wrong. The failing of every part of the system is thoroughly investigated and evaluated based on some criteria such as how often it would occur in a timespan, if it is easy to detect and how severe the effect would be if it fails.

This offers the managers of the company to have insight into this information, create maintenance plans or perform countermeasures when a part of the system fails. This is all done in order to mitigate the effects of failing or make a system better.

An FMEA is mostly textual information based on the expertise of the team that creates it. The scope of the FMEA is determined by the team and limits to a system, process, product, plant or project which can be complex or not so complex.

Often it is displayed in a spreadsheet format in excel and depending on the complexity of the system, it can be very large and difficult to understand.

Another format in which it can be shown is through a node-link diagram that shows the parts of the system and accordingly show the information necessary.

Tasks You shall be shown a visualization and are asked to perform some tasks for each of the visualizations.

The tasks are simple ones and some examples of potential tasks are: you need to find a specific way the system can fail, describe the severity of failing of a system, find the most harmful way the system fails or determine the structure of the system.

While you are performing the task, the observer shall measure your performance, trough the time it takes to complete the task and measure the amount of deviations from the fastest /best approach.

The researcher measures this in order to determine the intuitiveness and effectiveness of the current visualization.

Interview The researcher shall have a small semi-structured interview with you after the tasks have been completed and ask you to elaborate on you decision making during the tasks. Furthermore, you shall be asked to rate the visualization on effectiveness, intuitiveness and ease of use.

Lastly, you shall be asked for feedback on the visualization, ways the visualization could be improved.

Covid-19 Due to Covid-19, extra measures shall be taken.

The participation in the test requires the use of a computer which shall be operated by multiple participants, therefore before and after doing the tasks, disinfection hand gel shall be prepared and the user is highly encouraged to use the disinfection gel at both times.

With the interview, both the participant as the interviewee shall wear a mouth mask (if the participant does not have any with them, multiple mouth masks are present).

Personal information of the user [name, email and telephone number] shall be gathered, only for contacting the participant in case there was exposure to the covid-19 virus.

This personal information shall be destroyed a month after the study takes place and no exposure was found.

Potential Risks and Discomforts There are no obvious physical, legal or economic risks associated participating in this study. You do not have to answer any questions you do not wish to answer. Your participation is voluntary and you are free to discontinue your participation at any time.

Potential Benefits Participation in this study does not guarantee beneficial results to you. If the information of the study is interesting to the user, the results of the study can be made available to you after the study. In this case the email address shall be kept till after the study is completed and available for your disposal.

Confidentiality Your privacy will be protected to the maximum extent and no personally identifiable information will be reported in any research product.

Right to Withdraw and Questions Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.

Statement of Consent Your signature on the consent form indicates that you are at least 16 years of age; you have read both the consent form and this information sheet or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree that you will participate in this research study. You will receive a copy of this signed consent form.

Data collection and handling To summarize, the data that will be collected are the following:

During the task: performance measured by time to completion of a given task, intuitiveness measured by deviations from the best approach to complete a task, remarks or comments being said during the task to clarify your reasoning on performing a task and other interesting remarks that arise during the interview.

During the interview: elaboration of your performance, rating of the effectiveness and intuitiveness, feedback and potential improvements and other interesting remarks that arise during the interview.

Lastly also age, gender and prior knowledge of FMEA shall be collected. They solely cannot identify you.

Only the researcher and his supervisor shall have access to the information.

The data can be used to elaborate or clarify any conclusions or recommendations that the researcher makes in the report. As no personally identifiable information shall be stored, this shall be represented in the report with *"participant A"* and *"participant B"* etc.

A.3 Guidelines

These Guidelines can also be found in [36] Information Visualization by W. Colin. (2004) at Appendix D.

G.1 Important data should be represented by graphical elements that are more visually distinct than those representing less important information. [G1.2]

G.2 Greater numerical quantities should be represented by more distinct graphical elements. [G1.3]

G.3 Use more saturated colors when color coding small symbols, thin lines, or other small areas. Use less saturated colors for coding large areas. [G4.1]

G.4 When small symbols, text, or other detailed graphical representations of information are displayed using color on a differently colored background, always ensure luminance contrast with the background. This guideline is a variation of G3.4. [G4.2]

G.5 To create a set of symbol colors that can be distinguished by most color-blind individuals, ensure variation in the yellow-blue direction. [G4.14]

G.6 Do not use more than ten colors for coding symbols if reliable identification is required, especially if the symbols are to be used against a variety of backgrounds. [G4.15]

G.7 To minimize the cost of visual searches, make visualization displays as compact as possible, compatible with visual clarity. For efficiency, information nodes should be arranged so that the average saccade is 5 degrees or less. [G5.1]

G.8 Use different visual channels to display aspects of data so that they are visually distinct. [G5.2]

G.9 To make symbols easy to find, make them distinct from their background and from other symbols; for example, the primary spatial frequency of a symbol should be different from the spatial frequency of the background texture and from other symbols. [G5.3]

G.10 Make symbols as distinct from each other as possible, in terms of both their spatial frequency components and their orientations components. [G5.4]

G.11 For highlighting, use whatever feature dimension is used least in other parts of the design. [G5.9]

G.12 To make symbols in a set maximally distinctive, use redundant coding wherever possible; for example, make symbols differ in both shape and color. [G5.11]

G.13 Place symbols and glyphs representing related information close together. [G6.1]

G.14 To show relationships between entities, consider linking graphical representations of data objects using lines or ribbons of color. [G6.3]

G.15 Use connecting lines, enclosure, grouping, and attachment to represent relationships between entities. The shape, color, and thickness of lines and enclosures can represent the types of relationships. [G6.23]

G.16 Consider using a node-link representation of a tree where the hierarchical structure is important, where internal (non-leaf) nodes are important, and where quantitative attributes of nodes are less important. [G6.29]

G.17 When creating diagrams showing entities and relationships, use properties such as size and thickness to represent the strength of the relationship between entities. [G8.14]

G.18 When a large number of data points must be represented in a visualization, use symbols instead of words or pictorial icons. [G8.18]

G.19 Use words directly on the chart where the number of symbolic objects in each category is relatively few and where space is available. [G8.19]

G.20 Graphical elements, rather than words, should be used to show structural relationships, such as links between entities and groups of entities. [G9.2]

G.21 For the fastest epistemic actions, use hover queries, activated whenever the mouse cursor passes over an object. These are only suitable where the query targets are dense and inadvertent queries will not be overly distracting. [G10.1]

A.4 Test results

Participant	Q1 In what sub-systems is the chair divided?		Time	Q2 Identify the failure mode, that has been classified with the highest risk?		Time	Q3 What is the cause for failing identified for this specific failure mode?		Time
Node-link	Seat, Back, Legs, General	1	18,483	Breakdown	0,5	55,715	Legs too thin, legs not attached correctly	1	19,626
Node-link	seat, back, legs, general	1	26,999	breakdown	0,5	50,577	legs too thin, legs not attached correctly	1	44,578
Node-link	seat, back, legs, general	1	11,575	Leg breakdown	1	44,093	legs too thin, legs not attached correctly	1	25,904
Node-link	seat, back, legs, general	1	10,545	uncomfortable, unstable, breakdown of chair legs, 54	0	128,821	leg(s) break(ing)	0	34,817
Node-link	Seat, back, legs, general	1	44,621	Breakdown of legs	1	78,221	Legs too thin, legs not attached correctly	1	20,307
Node-link	seat, back, legs, general	1	32,019	legs break	1	95,105	legs too thin, legs not attached correctly	1	83,446
Node-link	seat, back, legs, general	1	13,608	legs	0,5	14,102	breakdown	0	27,275
Node-link	seat back legs general	1	148,137	legs	0,5	123,058	legs break	0	76,731
Excel	seat, back, legs, general	1	44,518	legs break	1	19	legs too thin and legs not attached properly	1	21,637
Excel	provide comfort, stability, support, endurance and	0	87,587	seat breaks and legs breaks	0	102,516	legs too thin, legs not attached correctly, seat too thin, aprons to	0	74,321
Excel	Seat, Back, Legs, General	1	84,02	Legs breaks	1	133,808	"1) legs too thin 2) legs not attached correctly"	1	41,028
Excel	Seat provide, seat support, back provide, legs provide, General	1	190,518	Legs breaks	1	42,021	sharp edges exposed	0	19,03
Excel	seat, back, legs	0	92,389	legs	0,5	63,266	legs too thin, legs not attached correctly	1	64,522
Excel	seat, seat/support, back, legs, general	0,5	225,793	sharp edges exposed, chair collapses, injury	0	64,361	to thin, not attachted correctly,	1	56,742
Excel	seat, back, legs	0	117,915	legs break	1	55,008	legs too thin, legs not attached correctly	1	56,731
Excel	system/functions	0	210,797	legs break	1	51,936	legs to thin, legs not attached correctly	1	64,814
	Total Node-link diagram	8	305,987		5	589,692		5	332,684
	Total Excel-spreadsheet	3,5	1053,537		5,5	531,916		6	398,825

Participant	Q4 This failure mode is part of which sub-system?		Time	Q5 Identify the failure mode or modes with the consequences that the user is injured?		Time	Q6 What are the main functionalities of the Chair system?		Time
Node-link	Legs	1	6,761	Breakdown, Breakdown	0,5	64,845	Provide comfort, support weight, provide stability	0	62,032
Node-link	legs	1	12,861	breakdown	0,5	45,194	om te kijken waar risico's liggen binnen de verschillende	0	176,03
Node-link	legs	1	7,316	seat breakdown, legs breakdown	1	60,226	provide comfort, support weight, provide stability, aesthetics	1	36,859
Node-link	Legs	1	6,205	uncomfortable seat, Breakdown seat, Breakdown Legs	0	78,06	provide a stable object to sit on	0	54,071
Node-link	Legs	1	10,942	breakdown of seat, breakdown of legs	1	49,423	Provide comfort, support weight, provide stability, aesthetics	1	53,099
Node-link	legs	1	26,548	Legs break, Seat breaks: sharp edges exposed, chair collapses,	1	406,584	provide comfort, support weight, provide comfort, provide stability	0	66,392
Node-link	LEGS	1	31,202	breakdown	0,5	72,976	provide comfort, support weight, provide stability, aesthetics	1	76,618
Node-link	legs	1	77,607	breakdown	0,5	83,435	provide comfort and support user	0	249,713
Excel	legs	1	10,4	seat breaks, legs break	1	49,448	seating of the customer	0	73,385
Excel	support users weight and provide support	0	35,581	legs breaks	0	32,768	provide comfort, support , stability, aesthetics and durability	0,5	75,401
Excel	Legs (provide stability and support)	1	35,895	Seat breaks, Legs breaks	1	44,092	Provide seat comfort, support user's weight, provide back	1	65,976
Excel	legs/provide stability and support	1	21,119	Seat is uncomfortable, legs breaks	0	158,02	make the chair longer lasting and aestheticly pleasing	0	89,285
Excel	legs/ provide stability and support	1	64,513	seat doesn't fit user, seat has sharp edges	0	144,464	measure users, round al edges, smooth surfaces	0	108,221
Excel	seat support and legs	0	23,954	seat breaks, legs break, back is uncomfortable	0	170,463	systen/function - sub systems	0	178,741
Excel	legs, provide statibilty and support	1	53,694	seat breaks	0	127,102	provide seat comfort, support users weight, provide back	0	83,868
Excel	legs/ provide stability and support	1	39,156	seat/ support user,s weight, legs/ provide stability and support	0	131,658	provide seat comfort, support user,s weight, provide back	1	122,763
		8	179,442		5	860,743		3	774,814
		6	284,312		2	858,015		2,5	797,64

Participant	Q7 What are all the failure modes that are somehow related to the seat?		Time	Q8 Select the failure mode, that has been classified with the lowest risk?		Time	Q9 What are the causes of failing identified by this specific failure mode?		Time
Node-link	uncomfortable/breakdown/unstable	0,5	15,762	Unattractive	0	35,73	Chair has no consistant color, paint corrodes	0,5	12,88
Node-link	uncomfortable, breakdown, unstable	0,5	55,326	unattractive, soaks water	1	48,817	chair has no consistant color, paint corrodes, water gets soaked	1	54,881
Node-link	uncomfortable	0	24,555	unattractive and soaks water	1	27,248	no consistent color, paint corrosion, water gets soaked into	1	33,945
Node-link	seat uncomfortable, seat unable to support weight, seat feeling	0,5	38,971	unattractiveness and 'soaks water'of the seat	1	55,911	no consistent color / faded paint & water soaking into the seating	1	37,921
Node-link	uncomfortable, breakdown, unstable	0,5	29,509	Unattractive/soaks water	1	21,155	paint corrodes, chair has no consistant color, water gets	1	42,5
Node-link	uncomfortable, breakdown, unstable, uncomfortable,	1	94,211	unattractive, soaks water	1	71,58	chair has no consistant color, paint corrodes. water gets soaked	1	49,402
Node-link	uncomfortable, breakdown, unstable, soaks water	1	53,115	unattractive/soaks water	1	42,03	no consistent color, paint corrodes, sucks water	1	29,961
Node-link	seat is uncomfortable and seat flexes to much and seat breaks	0,5	227,146	seat flexes to much	0	78,785	seat to thin, Aprons tooweak, Fastener holes shear, Corner	0	149,613
Excel	seat in uncomfortable, seat breaks, seat flexes too much	0,5	29,476	chair is unsightful or seat soaks water	1	33,838	no consistant color, paint corrodes or water gets soaked by	1	36,18
Excel	seat is uncomfortable, seat breaks, seat flexes too much	0,5	62,445	chair is unsightfull and seat soaks water	1	30,967	cair has no consistent color, paint corrodes, water gets soaked by	1	24,918
Excel	Seat is uncomfortable, seat breaks, seat flexes too much	0,5	44,576	Chair is unsightful/Seat soaks water	1	51,633	"1) chair has no consistant color 2) paint corrodes"/1) water gets	1	37,877
Excel	Seat is uncomfortable, seat breaks, seat flexes too much,	0	90,283	Chair is unsightful, seat soaks water	1	36,018	Chair has no consistant color, paint corrodes, water gets soaked	1	52,988
Excel	user is unconfortable, sharp edges exposed, chair collapses,	0	331,263	chair is unsightful, seat soaks water	1	74,278	chair has no consistant color, paint corrodes, water gets soaked	1	66,031
Excel	seat is uncomfortable, seatbreaks, seat flexes to much,	0	96,589	general: unsightfull, seat soaks in water	1	52,587	chair is not used	0	19,818
Excel	seat is uncomfortable, seat breaks, seat flexes too much	0,5	44,156	chair is unsightful, seat soaks water	1	70,226	chair has no consistent color , paint corrodes, water gets soaked	1	51,937
Excel	seat is uncomfortable, seat breaks, seat flexes too much ,	1	183,455	chair is unsightful, seat soaks with water	1	82,294	chair has no consistent color, paint corrodes, water gets soaked	1	134,334
		4,5	538,595		6	381,256		6,5	411,103
		3	882,243		8	431,841		7	424,083

Participant	Q10 This failure mode is part of which sub-system?		Time	Q11 Identify the failure mode or modes with the effect that the chair is unused?		Time	Q12 What are all the failure modes that are somehow related to the chair being unstable?		Time	
Node-link	General	1	9,558	Seat Soaks Water, Chair is Unattractive,	1	59,845	Seat flexes too much, Chair is unstable	1	50,258	12,88
Node-link	general	1	27,491	unattractive, soaks water	1	56,825	unstable	0,5	77,261	4,881
Node-link	general	1	5,157	soaks water, unattractive	1	29,206	seat unstable, legs unstable	1	44,827	3,945
Node-link	General	1	6,045	unattractiveness & soaks water	1	32,396	seat breakdown, seat unstable, legs breakdown, legs unstable,	0	69,959	7,921
Node-link	general	1	8,742	unattractive, soaks water	1	46,582	Seat flexes too much, chair is unstable	1	48,296	42,5
Node-link	general	1	10,977	failure mode: chair is unattractive. effect: chair unused.	1	247,934	chair is unstable. seat flexes too much	1	163,042	9,402
Node-link	general	1	10,32	unattractive, soaks water,	1	39,566	unstable	0,5	17,42	9,961
Node-link	seat	0	31,697	water gets soaked into the seating and chair has no	0	174,582	legs are not attached correctly and legs of different sizes and	0	167,403	9,613
Excel	general	1	6,681	chair is unsightful, seat soaks water	1	27,275	seat flexes too much	0,5	20,568	36,18
Excel	seat	0	22,081	chair is unsightful and seat soaks water	1	15,515	chair is unstable	0,5	38,376	4,918
Excel	General	1	6,444	Chair is unsightful, Seat soaks water	1	30,251	Seat flexes too much,	0,5	61,411	7,877
Excel	General/ make the chair longer lasting and aestheticly pleasing	1	28,611	chair is unsightful, seat soaks water	1	31,728	Seat flexes too much	0,5	22,108	2,988
Excel	general/ make the chair longer lasting and aestheticly pleasing	1	43,59	chair has no consistant color, paint corrodes, water gets soaked	0	60,833	legs not attached correctly, legs are different sizes	0	54,116	6,031
Excel	General, make the chair longer lasting and aestheticly pleasing	1	58,569	unsightful, soaks in water	1	44,025	seat flexes to much	0,5	21,811	9,818
Excel	general, make the chair longer lasting and aesthetically pleasing	1	49,126	chair is unsightful, seat soaks water	1	41,583	legs are not attached correctly, legs are different sizes	0	126,289	1,937
Excel	general/ make the chair longer lasting and aestheticly pleasing	1	98,324	chair is unsightful, seat soaks water	1	222,448	seat flexes too much	0,5	64,294	4,334
		7	109,987		7	686,936		5	638,466	1,103
		7	313,426		7	473,658		3	408,973	4,083

Participant	Q13 What can be done to prevent the chair being unstable?		Time	Q14 If you were the product manager of this chair, which failure mode would you tackle first?		Time	Q15 Which one second?		Time	
Node-link	Measure legs, stress analysis, Deflection analysis, Fastener	1	18,036	Legs break	1	22,454	Seat breaks	0,5	11,426	12,88
Node-link	deflection analysis, fastener shear analysis	0,5	35,917	breakdown	0,5	22,466	uncomfortable	1	7,759	4,881
Node-link	visual inspection, defection analysis, fastener shear analysis	0,5	23,744	breakdown	0,5	10,99	unstable	0	6,895	3,945
Node-link	weigh user, analyse stability/stress analysis seat,	0	73,701	breakdown	0,5	18,171	uncomfortable	1	21,624	7,921
Node-link	Deflection analysis, fastener shear analysis, measure legs,	1	35,771	legs break	1	67,741	seat is uncomfortable	1	12,55	42,5
Node-link	deflection analysis, fastener shear analysis. measure legs,	1	57,457	failure mode - breakdown seat break and legs break	1	113,168	second breakdown - seat break	0,5	90,104	9,402
Node-link	deflection analysis, fastener shear analysis	0,5	24,353	breakdown	0,5	15,512	unstable	0	16,01	9,961
Node-link	Deflection analysis, Fastener shear analysis, visual inspection,	1	145,735	From subsystem Legs failure mode breakdown	1	185,276	subsystem seat failure mode breakdown	0,5	55,2	9,613
Excel	deflection analysis or fastener shear analysis	0,5	23,618	legs break	1	30,216	seat is uncomfortable	1	30,581	36,18
Excel	measure legs and stress analysis	0,5	25,309	legs breaks	1	12,027	seat is uncomfortable	1	7,957	4,918
Excel	"1) deflection analysis 2) fastener shear analysis"	0,5	28,138	Legs breaks	1	23,18	Seat is uncomfortable	1	13,255	7,877
Excel	1) deflection analysis 2)fastener shear analysis	0,5	30,371	Legs breaks	1	22,217	seat is uncomfortable	1	11,954	2,988
Excel	measure legs, stress analysis	0,5	42,612	legs are different sizes	0	55,988	legs not attached correctly	0	22,862	6,031
Excel	deflection analysis, fastener shear analysis	0,5	59,782	leggs break	1	51,598	seat uncomfortable	1	15,317	9,818
Excel	measure legs, stress analysis	0,5	71,902	legs break	1	31,122	seat breaks	0,5	26,66	1,937
Excel	deflection analysis, fastener shear analysis	0,5	53,187	legs break	1	27,913	seat is uncomfortable	1	33,192	4,334
		5,5	**414,714**		**6**	**455,778**		**4,5**	**221,568**	**1,103**
		4	**334,919**		**7**	**254,261**		**6,5**	**161,778**	**4,083**

Participant	Experience with FMEA	Seconds total	Minutes total	Correct	% Correct	Correct / Time	Time / Correct				
Node link diagram	Novice	476,29	7,94	10,5	70,0%	1,3	0,8				
Node link diagram	Novice	797,86	13,30	11	73,3%	0,8	1,2				
Node link diagram	Familiar	426,49	7,11	12	80,0%	1,7	0,6				
Node link diagram	Novice	705,14	11,75	8	53,3%	0,7	1,5				
Node link diagram	Familiar	611,96	10,20	14,5	96,7%	1,4	0,7				
Node link diagram	Novice	1657,37	27,62	13,5	90,0%	0,5	2,0				
Node link diagram	Novice	514,03	8,57	10,5	70,0%	1,2	0,8		Total Correct	% total correct	Total Minutes
Node link diagram	Novice	2123,73	35,40	6	40,0%	0,2	5,9		86	71,7%	121,88
Excel spreadsheet	Novice	493,00	8,22	12,5	83,3%	1,5	0,7				
Excel spreadsheet	Familiar	672,69	11,21	7	46,7%	0,6	1,6				
Excel spreadsheet	Novice	739,46	12,32	13,5	90,0%	1,1	0,9				
Excel spreadsheet	Novice	899,26	14,99	10	66,7%	0,7	1,5				
Excel spreadsheet	Novice	1354,98	22,58	6	40,0%	0,3	3,8				
Excel spreadsheet	Novice	1159,97	19,33	7,5	50,0%	0,4	2,6				
Excel spreadsheet	Novice	1059,26	17,65	9,5	63,3%	0,5	1,9		Total Correct	% total correct	Total Minutes
Excel spreadsheet	Familiar	1654,90	27,58	12	80,0%	0,4	2,3		78	65,0%	133,89
		959,15	**15,99**	**10,25**	**68,3%**	**0,83**	**1,79**	**Avg**	8	6,7%	-12,01