Storytelling as a Means of Integrating Safety by Design Principles in Engineering Design

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ABSTRACT: The realization of an attractive, as well as practical, functioning and safe machine requires the integration between design skills and technical-engineering competence in order to realize the product through a deep knowledge of the relations between the structure and the mechanical, perceptual and theoretical properties. To produce a safe machine, the designer needs to understand and manage the interaction between materials, context and quality of product's use, as well as combine expressive and material values with technical and operational implications. Despite various theories and methods, as well as harmonized international standards in terms of safety by design, greater safety in engineering could be achieved, also by increasing designers' awareness. The aim of this research paper is to test if and how storytelling could be integrated as a means to teach Safety by Design principles at a university level education in order to increase awareness amongst future engineering designers. Therefore 6 accidents that have occured over the past years have been narrated in the form of written stories and presented to current bachelor engineering students at the University of Twente to gauge their reaction to stories as a means of integrating safety by design principles in engineering design.

Key words: Safety by Design, ISO 12100, Safety Cube Theory, Storytelling, Mechanical Engineering

1 INTRODUCTION

Safety by design, in formal words could be described as a process for identifying, evaluating and eliminating potential threats or risks via the engineering design process, its main outcome being that of avoiding situations where the safety of humans, the environment or the system at hand could be in jeopardy [1]. The importance of safety by design perhaps is best introduced through a small example. In the 1990's, a company known as Salton manufactured a hair dryer which looked like and was coloured like a cartoon duck. The manufacturers wanted a product that would fit in a specific market, by making a playful and fun looking hair dryer they clearly established their target market: children. The idea was commercially good, it was an attractive looking product and worked perfectly. What was not taken into consideration was the playful nature of children and the environment in which the dryer was going to be used. The tragic consequences of playing with a hair dryer in the shower are unfortunately well predictable [2]. The takeaway from this experience is that safety is not always as straightforward and obvious as one may expect. It is to be understood that safety does not solely refer to the product or system at hand; a product is not an isolated element but rather part of a larger context with which it interacts. In the case of the hair dryer, the product itself was safe, the environment itself was also safe but rather the interaction between the two with the addition of the playful nature of the children proved dangerous. With this small example alone, it becomes evident that, whilst our knowledge and understanding of safety integration have grown significantly, there are areas which require further attention. Nowadays, the knowledge and understanding of safety integration has considerably improved and the adoption of International Safety Standards, such as ISO 12100 (in relation to safety of machinery), has increased global levels of safety. ISO standards are a series of recommendation agreed upon by international technical experts, aiming at describing the best way of doing something. This should presumably reduce the chances of making errors that lead to accidents [3]. Nevertheless, accidents unfortunately still do happen, as a result of several factors such as: human error, malfunctioning, misuse, etc as well as an insufficient awareness/understanding of the above standards on behalf of engineering designers. This last aspect is the focal point of this research paper.

2 GOAL/RELEVANCE

A typical engineering design process goes as follows: problem definition, idea development, design solution optimization [4]. Designers are normally mainly focused on performance and quality of their designs alone; safety considerations are generally left to safety engineers to be assessed at a later stage of the process [5]. This sort of task division as well as time deferral are clearly not in favour of achieving a higher level of safety by design. To assess and implement any necessary changes to the system at a later stage might indeed not be optimal both in terms of safety as well as in relation to costs. Therefore, an integration of safety principles in engineering design as well as a interaction between safety and design engineers could be a contributing input to achieve a higher level of safety in products. In light of the relevance of designers familiarity with safety principles and international standards, particularly ISO 12100, the goal of this research paper is to test the adoption of storytelling (and in which possible manner) as a means of integrating safety in engineering design aiming to achieve safer products. The research assesses the reactions, through a questionnaire by prospective designers (present UT bachelor students) to the reading of 6 stories about real world accidents in diverse industrial sectors (civil construction, oil industry, motor vehicular, rail, air and naval transport).

2.1 Research Question

Given the above considerations, the following research question is formulated: *"How can we use stories to raise awareness of Safety by Design principles as formalized by ISO 12100?"*

Notions on safety such as ISO 12100, Safety by Design, Safety Cube Theory as well as storytelling provide the background knowledge and information which have been taken into consideration to develop the basis of the research. Therefore, the aforementioned elements are going to be briefly unpacked and are hereinafter presented in the form of guiding sub questions:

- *What is ISO 12100?*
- *What is Safety by Design?*
- *What is Safety Cube Theory?*
- *What constitutes a good story?*
- *How can we test the extent to which we have reached our goal?*

3 RESEARCH METHODOLOGY

To answer the main research question using the elements introduced by the sub-questions, a survey has been conducted amongst present engineering students at the University of Twente who were asked to read 6 stories and answer a questionnaire. The stories narrated real life accidents, each of them covering one of the fundamental aspects of safety as per the Safety Cube Theory developed by Dr. Mohammad Rajabali Nejad: **the technical system, the human, the environment, the system-environment interaction, the human- system interaction and the human-environment interaction** [6]. The 6 stories - just as the 6 sides of the safety cube - have been selected from a range of 20 accidents which were categorized and analyzed. The main criteria used to narrow down the selection of accidents to 6 were the following:

- Information Available: For the aim of this research it was necessary that there was sufficient information available on the unfolding of events as well as on the findings from the investigations carried out. Said points were required in order to narrate a complete story and develop the necessary recommendation as per ISO 12100 on what could have been done to prevent/mitigate the accident.
- Predictability: In order to write engaging stories, the events should not have been too predictable so as to avoid a non-dynamic and non-engaging story. Technical findings and recommendations could have also appeared to be too obvious and non-appealing to the target audience.
- Safety Cube Theory: In light of clearly explaining and highlighting the importance of the theory, accidents which were clearly linked to one of the six fundamental sides of the cube were preferred.
- Impact: In order to engage and to make the audience care, events selected had to have a significant impact in terms of damages and fatalities.

- Industrial sector: Accidents were selected from six different industries (civil construction, oil, automobile, rail, air and naval transport) to diversify the stories with the aim of entertaining the audience as much as possible and to display the widespread application of safety principles across sectors.

- Time-frame: The idea was to select relatively recent accidents in intending to make said stories feel more contemporary and relevant to the readers. More specifically, four of the stories are from events which happened between 2012-2015. Exceptions to this criteria have been for the deadliest offshore oil disaster (1988) and the deadliest accident in aviation industry (1977) where in this case the criteria *Impact* has been preferred.

- Location: Lastly, stories which took place in Europe (The Netherlands, Italy, Spain, Scotland) have been preferred for the purpose of having settings which could be as familiar as possible to readers from the University of Twente.

Based on the above, the following real life accidents were selected as the basis to develop the six written stories:

1. Koningin Julianabrug bridge in Alphen aan den Rijn, The Netherlands in 2015 whereby a section of a bridge (which was to be installed) was being transported by two cranes on barges which eventually tipped over and collapsed due to the fact the two cranes used were not identical and the engineers had not accurately accounted for this difference. This story covers the technical system aspect of the safety cube [7].

2. Costa Concordia in Isola del Giglio, Italy in 2012 where a large cruise ship sailed too close to the shore due to human negligence and eventually crashed into ocean reefs and capsized. This story covers the human aspect of safety cube [8].

3. Brescia-Edolo railway accident in Cedogolo, Italy in 2012 whereby a boulder from an adjacent mountain detached itself and fell onto the train track causing the accident. This story covers the environment aspect of safety cube [9].

4. AutoMotorSportief 2014 in Haaksbergen, Netherlands whereby a monster truck, during its performance seemingly lost control and ran into the nearby crowd. This story covers the system-environment interaction [10].

5. Piper Alpha oil platform off the coast of Scotland in 1988 whereby the platform caught on fire entirely due to a technial malfunction which was further enhanced by human error. This story covers the human-system interaction of the safety cube [11].

6. Tenerife Airport disaster, Spain in 1977 where two commercial airplanes crashed into each other as a consequence of poor human communication enhanced by poor conditions of the environment. This story covers the human-environment aspect of safety cube [12].

The following table gives an overview of the six stories written connecting the title of each story with which face of the safety cube it represents. The table is then followed by the six front page pictures of each story.

The stories are available and can be read via this link: Stories

TITLE	SAFETY CUBE THEORY SIDES
1. CAPSIZING BARGES	SYSTEM
2. CLOSE UP	HUMAN
3. ROLLING STONES	ENVIRONMENT
4. UNCONTROLLABLE MONSTER	SYSTEM - ENVIRONMENT
5. BURNING PIPER	HUMAN - SYSTEM
6. JUMMED RUNAWAY	HUMAN - ENVIRONMENT

Fig. 1: Table of Stories

All stories follow the same structure being: *Title, Picture, Introduction, Description of events, Analysis of event and recommendations to prevent accident based on the 3-step iterative method of ISO 12100*. The exercise was to present them in a storytelling manner, giving them an interesting title, pictures and introducing the scenario in a narrative manner with the aim of attracting readers' curiosity and facilitate the understanding of the implications of safety principles. The stories maintain a certain level of technical language adequate to the target audience in order to describe the event, assess the cause of accidents and identify possible measures which could have been taken to reduce risk as formalized by ISO 12100 and Safety by Design principles. The main challenge in the process of developing the stories was the need to provide full details on what happened, how and why it happened and to identify and develop suitable recommendations on what could have been done. These required in depth research and collection of available information as well as a sound knowledge of safety principles. Other challenges involved not making the stories too long in order to not lose reader attention and also in avoiding to write yet another technical report on an accident but rather maintain a story narrative whilst including technical details and analysis. In terms of the stories written, some were more difficult to write than others, specifically the stories which involved the technical system were easier to write about because they were closely tied to engineering knowledge and practice and therefore were easier to unpack as well as develop suitable recommendations from an engineering stand point. Similarly, stories relating to the environment were also easier to address as they involved fewer contributing factors and often times became more straight forward in terms of developing recommendations to mitigate damage/risk. The stories which were most challenging were those with human factors involved as often times it is difficult to give a clear reasoning to human mistake and error and in a lot of instances, there were already suitable guidelines to be followed but these were simply often omitted.

The questionnaire students were asked to answer, after reading the stories, sought to verify whether the goal of this research paper had been reached or not and to what extent.

Fig. 2: Front page pictures of the 6 stories representing the sides of Safety Cube Theory

3.1 ISO 12100

In the process of narrating stories the possible measures that could have been taken to prevent the accident have been formalized based on the ISO 12100 principles and process which is briefly described hereinafter. ISO standard 12100 deals with safety of machinery. It is intended to provide designers the necessary framework for the development of safe machinery and safe use. It does so by making use of risk assessment and risk reduction principles. This standard's approach to risk assessment and risk reduction are briefly introduced and presented below [13]:

3.1.a Risk Assessment

Risk Assessment as formalized by ISO 12100 can be broken down into 4 main steps [13]:

- **Determining machine limits**
- **Hazard Identification**
- **Risk Estimation**
- **Risk Evaluation**

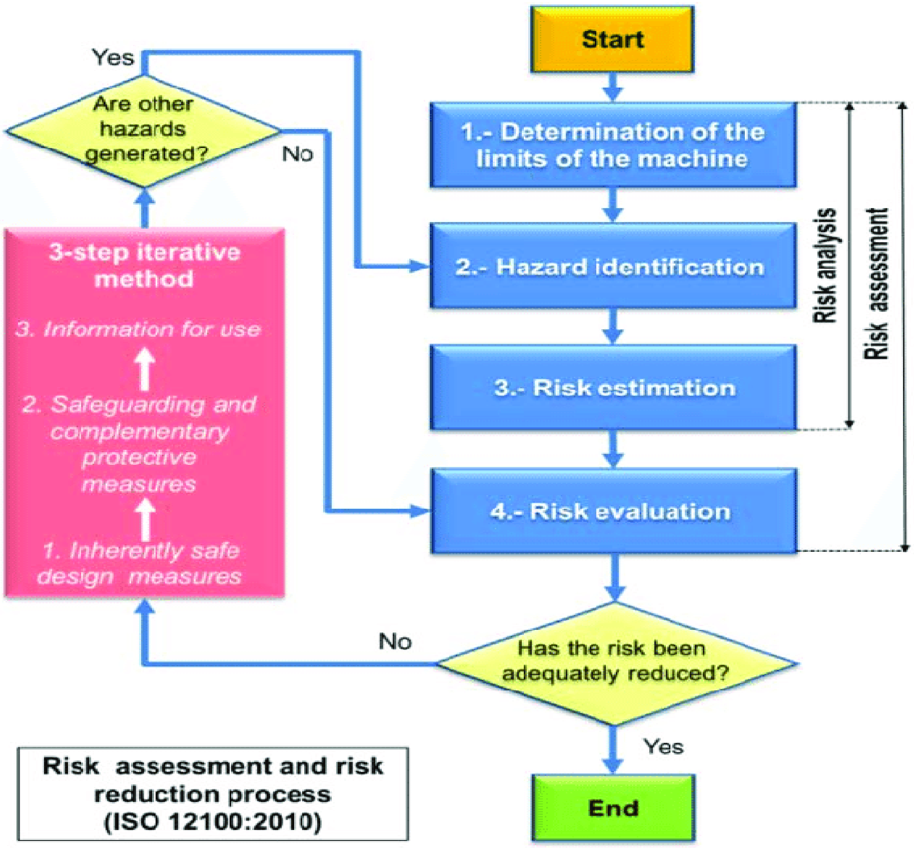

Fig. 3: ISO 12100 Methodology [14]

3.1.b Risk Reduction

In identifying the possible measures that could have been taken to prevent the accidents narrated in the stories, the three levels of risk reduction have been taken into consideration, with the aim of providing the target audience with input based on said levels. The three steps for risk reduction are [13]:

- **Step 1: Inherently safe design measures**: This is rather fundamental, if a design is inherently dangerous, applying risk reduction measures will not yield significant changes in safety. Safety considerations must already be integrated in the design process of the system and risk reduction serves to further reinforce its safety.

- **Step 2: Complementary Protective measures**: As aforementioned, these are measures to further enforce safety.

- **Step: Information for use**: If there are still sources of risk in the design/system, these are made explicit in the information for use attributed with the machine at hand.

3.2 Safety By Design

Additionally, the stories were also written on the basis of Safety by Design principles. Safety by Design is an approach aimed at helping designers create safe products. In order to do so, a solid understanding of the product and its interactions are needed, as well as the ability to predict/for see potential risks and pitfalls [15]. Furthermore, an understanding of the aforementioned is simply the first step, risks must also be evaluated and quantified, if possible, in order for effective design measures to be put in place to minimize said risks [16].

3.2.a Safety by Design Process

The Safety by Design Process includes the: **identification**, **assessment**, **removal and communication of possible risks/hazards** with the aim of avoiding situations where there is a serious threat to the human, technical system and environment. The Safety by Design process follows three essential steps [2]:

- Functional, technical and operational aspects must be observed and associated hazards must be identified.

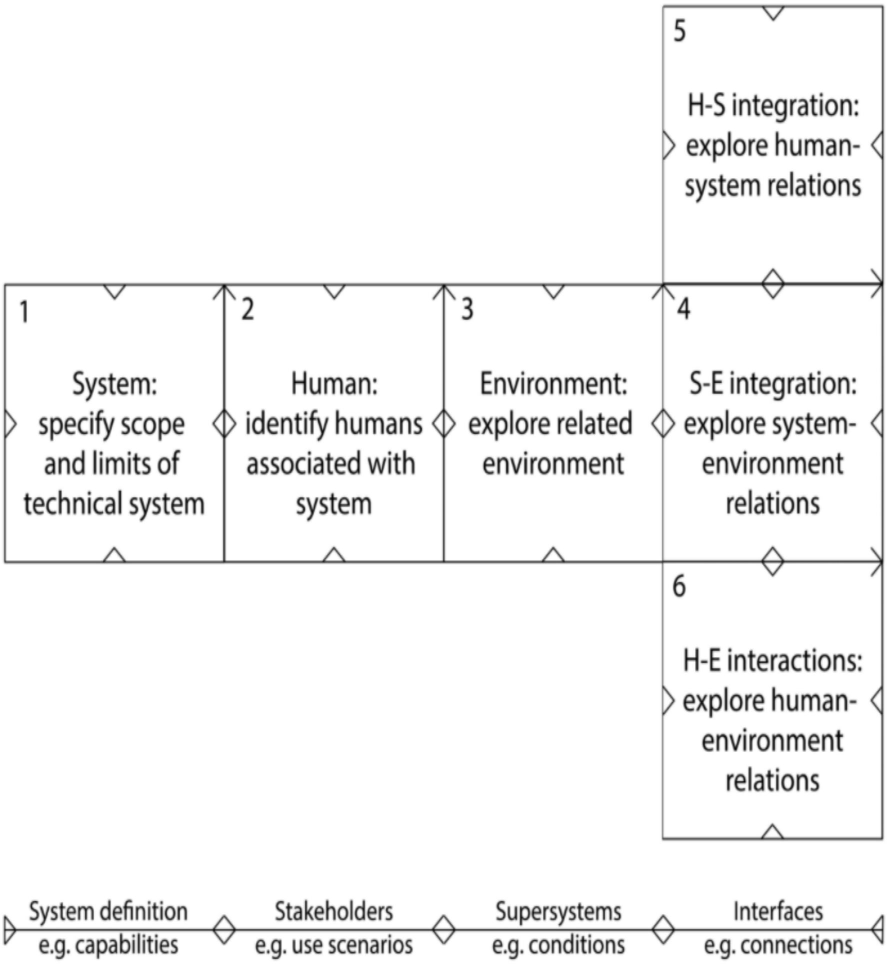

Fig. 4: Sides of Safety Cube[17]

- Conduct risk assessment for all three aforementioned aspects.
- The design must fulfill its objective whilst meeting technical, functional and operational requirements via the "Safety by Design philosophy" which can be read here [18].

3.3 Safety Cube Theory

Safety cube theory formalizes the basis for proper system integration through six crucial aspects. These aspects are the three elements aforementioned (the human, system and environment) but also takes into account the interactions between them as these do not work in isolation but are rather well connected and influenced by one another. These interactions are: Human-System, Human-Environment, System-Environment interaction [19]. Therefore, much like a cube has six sides, there are six critical considerations for safe system integration. Therefore, Safety Cube Theory serves as a visualization of the necessary concepts. These shall now be presented in more detail to get a more solid understanding of these elements and how they are connected the 6 selected stories.

3.3.a The Technical System

The system can be more formally defined as "a set of elements which interact according to a design, where an element of a system can be another system, called a subsystem and may include hardware, software and human interaction" [6]. This definition seems to be rather comprehensive and straight forward. For example, in the story of Alphen ann den Rijn, the technical system refers to the two barges and the bridge that was to be installed. In that case, the defects with the technical system were the sole reason that safety by design was compromised in that situation.

3.3.b The Human

This refers to the stakeholders of the system, that is the people who have some sort of interest in the system at hand. Stakeholders can have very adverse roles/connections to the system as well as influence on the system. Clearly, people's behaviour and actions are far less predictable and controllable compared to the system itself, therefore, it is important to have a good understanding of the interests of said people to promote proper interface and avoid misunderstandings. It must be understood that the interactions between humans affects a system as well, therefore careful attention must be attributed to this [6]. With respect to the Costa Concordia story, we see how all safety measures already put in place in maritime navigation become obsolete due to negligence of the captain of the ship, who, in that situation becomes the only cause of accident. In this regard, it also became rather difficult to identify possible causes and also suitable recommendations when clearly the main reason for the accident is attributed to human negligence.

3.3.c The Environment

This is essentially the larger context the technical system finds itself in. It is all the factors that can influence or be influenced by the system [6]. It includes regulations, infrastructure, standards etc. In Safety by Design, this is a rather crucial aspect as a system which may be deemed safe in one specific context need not necessarily be safe in another context and therefore it is clear that factors related to a systems environment play a key role in the level of safety. This point is in fact what is witnessed in the story regarding the Brescia-Edolo railway whereby a fully safe system experiences an accident due to its surrounding environment.

3.3.d System-Environment Interaction

The relationship between the system and the environment can either be physical or non-physical. Physical interactions often involve interfaces in terms of mechanics or transfer of energy but can also be non-physical through regulations, laws etc [6]. The take-away here is the background influence the environment can have on a system; in the story regarding AutoMotorSportief 2014, a threat related to small technical malfunction (which in an isolated context would not have been very problematic) gets enhanced by the environment in which this occurs leading to much greater levels of danger.

3.3.e Human-System Interaction

Since the human can assume numerous roles, the interactions between the human and system as a consequence can also be vast. These interactions are not limited to physical interactions either but can be of a more psychological nature. Within this interactions is also where we assess human performance [6]. Again, in this context humans play adverse roles on the attributed levels of safety. In the story regarding the Piper Alpha oil platform, the dangers related to a technical defect are largely enhanced by the addition of human error in interacting with the system and as a consequence levels of safety are drastically reduced.

3.3.f Human-Environment Interaction

This interaction is often not within the boundaries of the system during development, however, understanding this interaction might provide useful insight for the system. Furthermore, this dynamic can also indirectly influence the system, as a result of these interactions regulations may change, policies may be altered or introduced and these are all elements which can affect the system [6]. This interaction is often very hard to predict and anticipate as often times the contributing factors to danger are largely beyond the boundaries of the technical system itself but still hold great influence on Safety by Design considerations. In light of this last point, in the Tenerife Airport Disaster, all contributing factors to the accident were aside from the aeroplanes themselves but still very present in the background of the situation, therefore being able to predict and anticipate their presence and relation to the aeroplane becomes very difficult. And as such, large difficulty was also experienced in writing such a story as identifying and explaining the reasons as to the accident are far beyond the scope of the technical system itself.

3.4 Storytelling: What constitutes a good story

In a Ted Talk given by Andrew Stanton, a renowned American animator, highlights the details that a good story must incorporate in some manner, the creativity in which these are implemented is then what distinguishes masterpieces from good stories. The most important features are summarized below:

- Knowing the inside and outs of your story line, and understanding and implementing the fact that everything you are saying is leading to a singular goal [20].

- A story should engage and make your audience care. You want them to interact with the story and try to analyze the story without them perceiving this act, that's what a quality story does. People inherently are problem solvers and by nature try to piece things together to make sense of them, therefore, a story teller must use this inherent human trait to their advantage. Broadening on this concept, we may speak of the "Unifying Theory of 2+2", which Stanton mentions in his talk. In essence you do not give your audience "4" but you rather give them 2 and 2 and let them make 4. The argument here is that this holds attention through the story [20]. In writing the stories, the said theory of 2+2 has been followed whereby the first part of the story (title, picture, introduction) and the second part (technical descriptions, findings, recommendations) provide two separate inputs for the reader to be summed up to gain a learning message. The process followed in the stories is that the first part gives the reader the relevant information as to the cause of the accident and the second part provides recommendations, in line with Safety by Design and ISO 12100's risk reduction process, as to what could have been done to mitigate said accidents and it is then left to the reader to piece these two together to ultimately gain a learning message on Safety by Design.

- Another key element in a story is its dynamics. It's argued that change is fundamental in a story, if things become too static (fixed) a story loses value as in life things are rarely ever static [20].

3.5 Goal Evaluation

To test whether or not the goal of this research project has been achieved and to which extent, a questionnaire has been formulated and target students were asked to answer the questions after reading the 6 stories. The questions cover the following areas:

- Length of stories
- Titles
- Pictures
- Introduction of the scenario
- Description of events
- Understanding of events
- Anticipation of the cause of accidents and possible preventive measures from the introduction
- Understanding of the technicalities involved from the findings
- Relevance of Safety by Design principles and ISO 12100
- Enjoyment of story reading
- Storytelling as a means to raise awareness and understanding of safety

Each questions provided "yes" or "no" answers to gauge more concrete results in terms of understanding, as well as a chance for comments and additional remarks. The audience was comprised of bachelor students from the Mechanical Engineering Faculty of the University of Twente, with an age group of 21 (42.9%) and 22 (57.1%) year olds.

4 RESULTS AND DISCUSSION

Question	Yes	No	Comments
Did you find the story length adequate?	85.7%	0%	14.3%
Did you feel that the title is representative of the story?	85.7%	0%	14.3%
Did you feel that the pictures are representative of the stories?	100%	0%	0%
Does the Intro describe the scenario accurately?	85.7%	14.3%	0%
Did you find the description of events sufficiently detailed?	85.7%	14.3%	0%
Did you get a clear understanding of the events?	71.4%	14.3%	14.3%
From the initial description, could you anticipate/predict the cause of accident and what could have been done?	100%	0%	0%
From the findings, did you find it easy to understand the technicalities involved?	71.4%	28.6%	0%
Did the readings enforce the relevance of Safety by Design principles (ISO 12100, SbD, SCT)?	100%	0%	0%
Did you enjoy reading the stories?	100%	0%	0%
As an Engineering study, do you feel that readings on Safety by Design can be a useful tool to increase awareness	100%	0%	0%

Comments:

- Some stories are too long
- Some titles are not very representative
- Could have been more detailed for a better understanding

Fig. 5: Questionnaire with responses

Feedback from students who answered the questionnaire are going to be analyzed in order to develop results from the research methodology. Majority of readers found the length of the stories adequate with only 14.3% of students indicating certain stories were slightly too long. 85.7% of readers felt that the titles were representative of the stories being narrated, with the remaining 14.3% expressing a contrary opinion stating that the titles were slightly misrepresentative. In connection to the front page picture, all students found them representative of the stories. When asked if the introduction described the scenario accurately, a positive response was given by 85.7% of them, whilst a negative response was received by the remaining 14.3%. 85.7% of students also found the description of events sufficiently detailed enough whereas the remaining expressed potential for additional detail to further clarify the situation. A good amount of readers, 71.4% gained a clear understanding of events from the reading of the 6 stories. The remaining students (28.6%) expressed varying opinions with half of them claiming they did not get a sufficient understanding and the other half felt that the stories could have been further detailed in order to reinforce the intended message and goal. All students reported that from the initial description alone they had a sufficient anticipation of the cause of accidents and what could have been done to prevent said accidents. Additionally, more than half of the target group (71.4%) found it easy to understand the technicalities involved from the findings of the investigation whilst the rest (28.6%) expressed difficulty in this regard. Lastly, it is interesting to note that all readers gave full positive feedback to the last 3 questions: they all believed that the reading of stories enforced the relevance of safety concepts; they all enjoyed reading the stories; and they all felt that as engineering students storytelling on safety principles (such as Safety by Design, Safety Cube Theory and ISO 12100) can be a useful tool to increase awareness on Safety by Design. The questionnaire was sent out to 25 students and 21 of these accepted to participate in the experiment with curiosity. This alone is a rather encouraging result towards the answer of the main research question as it suggests the perceived interest raised by storytelling as a means of raising awareness of Safety by Design principles. Additionally, the complete positive reactions received on the last 3 questions (relevance of safety in the stories, enjoyment of reading and storytelling as a tool to increase awareness) confirms the encouraging feedback received by the audience. The reactions received on the manner in which the stories were written was also generally positive and what is most promising is the fact that all students could sufficiently understand/anticipate from the initial description the cause and possible prevention of the accident. The other responses received are still quite satisfactory in terms of length, title, pictures, introduction and description. Areas that could have had room for improvement and further details are the understanding of events and the technicalities involved: this is indeed in line with the fact that the readers were all engineering students therefore generally accustomed to highly technical and well detailed literature. Additional remarks received were supportive and appreciative of the experiment.

5 CONCLUSIONS

The findings of the research methodology - as presented in results and discussion - reveals that current engineering students do indeed have satisfactory level of knowledge and understanding with respect to safety principles as formalized by international standards such as ISO 12100, by Safety by Design principles as well as by the Safety Cube Theory. It can also be deduced that there is a good level of awareness of the importance of integrating the aforementioned principles when we tell stories about Safety by Design. The curiosity raised by the experiment also details that there is room to further increase such levels of awareness. The general positive feedback to the reading of the 6 stories (about accidents that actually occurred in real life) also proves that a technical argument can be successfully presented in the form of storytelling to engage and educate the audience through a dynamic path. The selection of the 6 accidents, covering the 6 fundamental aspects of the Safety Cube Theory, narrated in the stories has been experienced by both the author and the readers as a good means of passing on lessons learnt from experience.

Therefore, based on this experiment, it could be concluded that storytelling can be a viable means to integrate Safety by Design principles in engineering design in education at a university level, provided it combines qualities of a good story (creativity, engagement and dynamic) with a high level of technical notions and language in connection to the target audience. If written in a way that balances the above aspects they might have the potential to be used as a resource material to be integrated in education across engineering faculties.

5.1 Reccommendations for future research

Based on the encouraging outcome of this research paper aimed at testing how storytelling could be a means of integrating Safety by Design in design engineering, broader experiments could be carried out. It is suggested that the number of stories written are increased to further reinforce the message and concepts presented. With regards to the selection of stories, it is recommended to be attentive in keeping an integral view of the fundamental aspects of safety and their interactions. Furthermore, it is key to ensure that there is sufficient information available from expert opinion and unbiased judgement on the human, environment and technical system of the incident and particular attention should be paid on the human-environment interaction as this is often rather complex and difficult to find information on. Additionally, the questionnaire could be expanded to a larger group of readers to gain more representative responses of the target group and furthermore, the target group could be extended to students from different engineering courses to gauge how students/designers from different backgrounds perceive and react to safety principles and concepts.

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