AUTOMATED SAFETY-IN-DESIGN RULE-CHECKING FOR CAPITAL FACILITY PROJECTS

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ABSTRACT: *Safety-in-design (SID) reviews are mandatory for capital facility projects because they eliminate hazards before activities in the construction, operation, and maintenance phases take place. Existing SID review processes which many large corporations have in place, however, still rely mainly on manual input and judgment of experienced safety experts. Often very skilled humans make decisions based upon paper-based drawings or three-dimensional visualization models. As such, tasks in safety-in-design review sessions remain to be manual and thus are very much time-consuming, expensive. Furthermore, if not all hazards are detected and mitigated, they can be potentially error-prone. Unsafe design ultimately exposes workers at risk as it provides an unsafe work environment. It can also become very costly if unsafe design is detected outside of the design and construction planning phases of a capital facility project.*

The objective of this work was to develop a safety code compliance checking technology that does not replace human judgment, but supports human decision making of safety experts, designers, engineers, and field staff. The developed work applies novel safety code compliance checking algorithms on intelligent information models which are prepared during design and construction planning. The initial scope of the developed algorithms is limited to check for safe work access and egress requirements in existing information models. As existing safety rules and best practices are embedded in the developed code compliance checking system, they can be automatically executed on information models which exist for every capital facility project. A case study is presented to illustrate its practical implementation for an off-shore oil platform. Results show that the developed system generates automated reports that list the safety violations and furthermore, along with visual screenshots of the unsafe object in the information model, indicate the process of how these issues can be mitigated based upon established best safety practices. The significance of human-assisted decision-making in SID reviews and its potential to lead to safer designs early in a project is explained.

KEYWORDS: *Capital facility projects, design for safety, design reviews, information modeling, rule checking, 3D model, safety-in-design.*

1. INTRODUCTION

Major capital facility projects typically involve a large number of organizations and individuals over a long lifecycle. They are often built across the globe, in different regions and under different cultural contexts. Such complex projects are furthermore driven by very tight schedules and have limited resources available. As a consequence, the responsibility of who designs, plans, reviews, manages, and controls safety becomes unclear. However, it remains essential that such projects are designed and built in a safe way; otherwise cost and time overruns occur when safety issues are embedded in faulty project design and move forward to detailed planning and ultimately construction, operation, and maintenance. Therefore, safety-in-design (SID) emerged as a concept of involving safety requirement and risk management knowledge into the project design phase. Its goal is to eliminate workplace incidents (e.g., accidents that lead to injuries and/or fatalities) and provide a safe workplace. Expected other benefits are reducing the likelihood of changes in the field and associated cost and time overruns.

Safety engineering integrates risk management principles into the design and construction planning when: (1) owner, contractor, and other relevant project stakeholders are involved in the decision-making process, (2) associated risks and hazards inherently embedded in a design are systematically identified and eliminated/mitigated, and (3) the entire project team communicates and solves residual risks associated with the design and construction plans. To adopt and implement elements of the SID process, a regulatory push towards SID was established in United Kingdom in 1995. It required designers to perform Construction Hazards Prevention

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through Design (CHPtD). The approach was later adopted throughout the European Union. Australia has also moved towards mandating CHPtD practices and since then has demonstrated its leadership by making practical resources for designers and for CHPtD implementation available online (Toole and Gambatese 2008). The SID process has as such been detailed for application in the entire lifecycle of a project, including design, planning, construction, operation, maintenance, repair and demolition/refurbishment. Specifically, it is a designer's responsibility to prepare a safe design based upon understanding the range of work activities and work environment which are associated to building, maintaining, repairing, servicing, and cleaning a facility (Victoria 2005).

The current design review process in many capital facility projects, however, still relies mainly on safety expert opinions. These experts base their decision upon paper drawings or three-dimensional visualization models. Their task remains mostly manual and thus is very time-consuming, costly, and eventually error-prone. Proposed is an automated safe code compliance-checking system that supports humans in safety decision making early in a project phase by using intelligent information models.

2. BACKGROUND

2.1 Human factors engineering and requirements for a capital facility project

Human factors engineering is a multidisciplinary effort. It compiles and generates information about the capabilities and limitations of humans. It applies information to equipment, systems, facilities, procedures, environments, training, and personnel management to produce safe, comfortable, and effective human performance (Federal Aviation Administration 2005). When human factors is applied early in the acquisition process, it enhances the probability of increased performance, safety, and productivity; decreased lifecycle staffing and training costs; and becomes well-integrated into the program's strategy, planning, cost and schedule baselines, and technical tradeoffs. Otherwise, late changes in operational, maintenance or design concepts are expensive and involve high-risk program adjustments. For instance, design professionals need to provide adequate working distances in their designs for the various construction trades and common tools. An example inadequate clearance between steel bolts and adjacent steel members must be provided to allow the use of typical positioning and bolting or welding tools (Toole and Gambatese, 2008). Ergonomic issues may also be included in spatial considerations for constructability (Bello 2012). An alternative approach was developed by Gambatese and Hinze (1998) that focused on construction industry safety best practices as they relate to project-specific hazards.

2.2 Existing manual checking approach

Designers and construction planners are encouraged by most owners to specifically address worker safety in their work. Their involvement, however, has largely been a voluntary effort in the US (Gambatese and Hinze 1998). Another problem is that many times designers and planners have little to no background in safety rules and regulations, making it very difficult for them to apply advanced safety concepts or best safety practices in their work. For these reasons, Frijters and Swuste (2008) designed effective qualitative evaluation methods, e.g. panel discussions, which assist them in developing safer design alternatives and better construction methods. They also pointed out that administering such safety design review panels in practice is very resource intensive as it requires physical presence of many design, construction, and safety experts in one location and, depending on a project's size, for several days or even weeks.

The basic work flow of a SID implementation is illustrated in Figure 1. Since designers typically have very limited to no understanding of how their design influences construction and operational safety, owners provide SID training to all designers before the design phase starts. After the owner communicates the project objective and scope, designers create their first design of the facility. As the initial model of the design inherently includes unsafe design elements and other constructability issues, it is reviewed by the SID engineer for code compliance. Concurrently, construction experts look at constructability issues.

Communication of safety issues in the model review phase is mainly between the designers and SID engineers and through e-mail and conference calls. For that reason they frequently meet and review in teams. It is often the SID engineers who point out design flaws to the designers. Safety markups on two-dimensional drawings visualize the issues. These often do not explain clearly enough or solve issues as they relate to spatial constraints in a model. For many years 3D and information modeling have alleviated some of the visualization issues related to spatial objects. Clash detection tools in information modeling software has become one of the most popular applications as it automatically detects most the time and spatial conflicts. They often also indicate constructability issues, but may not provide methods on how they are solved. It is humans that then redesign the flawed model.

Sophisticated clash detection tools specifically for safety do not exist. As such, alternative design approaches that lead to a safer design are only then successfully integrated during the model review phase when a SID engineer detects a safety issue and points it out to a designer. It is then up to the designer resolving any such issue that originated from a mistake or flaw in the initial design. More importantly, mitigating unsafe design during model review ensures that less time and money is wasted downstream in the construction and operation phases. A model review session thus serves as an important and critical point in time for designing safer and more constructible models. The sooner it can be facilitated in the design process, the more efficient and effective will be the SID implementation workflow.

Fig. 1: SID implementation workflow.

2.3 3D information modeling for automate compliance checking

With the advance of visualization and information modeling technology, more and more attention has been put on checking the quality of design models. Existing commercial software such as Navisworks and Tekla BIMsight were designed for viewing 3D models and clash detection. Latter allows detecting clashes of objects as their spatial properties create a geometric conflict in a digital 3D model.

Zhang et al. (2013) developed the first safety-rule checking engine to detect and resolve fall-related safety hazards. Their work also estimates, visualizes, and schedules protective fall protection protective equipment in building information models (BIM). Building design code checking (Eastman et al. 2009) including circulation check (Lee et al. 2010) has also been explored. However, no existing application or research has been found on the topic of automated SID checking of design models.

3. RESEARCH METHODOLOGY

The developed safety code or rule-checking approach is illustrated in Figure 2 and further explained as follows:

(1) SID rule interpretation: An existing SID best practice, typically a text document with illustrations, is first examined and converted into a parameterized rule set. An example of the rule interpretation from (Chevron Corporation 2012) is shown in Table 1.

Table 1: Rule interpretation of SID rule of Main walkway.

Natural Language Rule	"Main walkway routes through plants, buildings, and topsides modules shall be a minimum clear width of 48 inches (1,219 mm)."

Interpreted rule	If (MainWalkway.Width >= 1219)
	Then pass;
	else
	fail;

(2) 3D model preparation: Before the start of the design model review process, the work of designers and engineers including MEP, structure, architectural from designers are typically integrated For the purpose of SID rule-checking, these model need to be prepared with correct geometry and attributes. The result is that the interpreted rule can be correctly mapped to the corresponding model object.

(3) Rule execution: The parameterized rules are applied to the geometry of the information model. The rule-checking is executed automatically on the entire model.

(4) Rule-checking reporting: The results of running the rule-checker are reported. Details are listed in a table format that is easy for humans to comprehend. The table contains the safety clash, the safety code or regulation that is violated, a visual snapshot of the 3D model objects or space that was violated, and finally and if available the recommended safety best practice on file to resolve the safety issue.

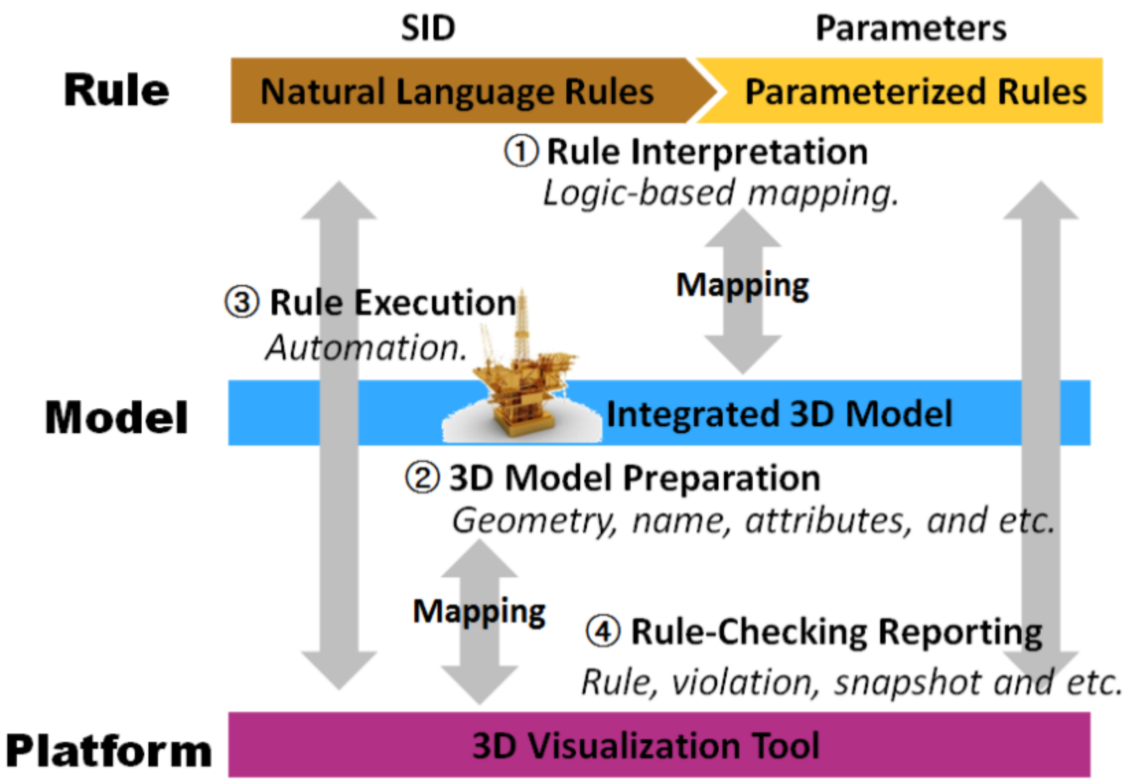

Fig. 2: Rule checking process for rule-based SID checking system.

4. IMPLEMENTATION AND CASE STUDY

The developed SID platform was implemented as a plug-in on an existing visualization platform (e.g., Navisworks). The interface includes three components next to a 3D model view (see Figure 3): (1) A box that allows checking of specific rule sets, (2) a box that displays the detected safety violation(s) according to the selection in (1), and (3) a box that provides a user with further information about the violation and an opportunity of leaving comments or personal remarks.

The developed approach was tested on a capital project model (e.g. off-shore oil platform) as shown in Figure 3. The rule-checking platform was tested for safe access/egress to work spaces on the platform. As recent and tragic events in the past have shown providing easy access/egress to work areas is important to maintain a safe and productive work environment. One research objective was to use the developed SID model review to find safety violations.

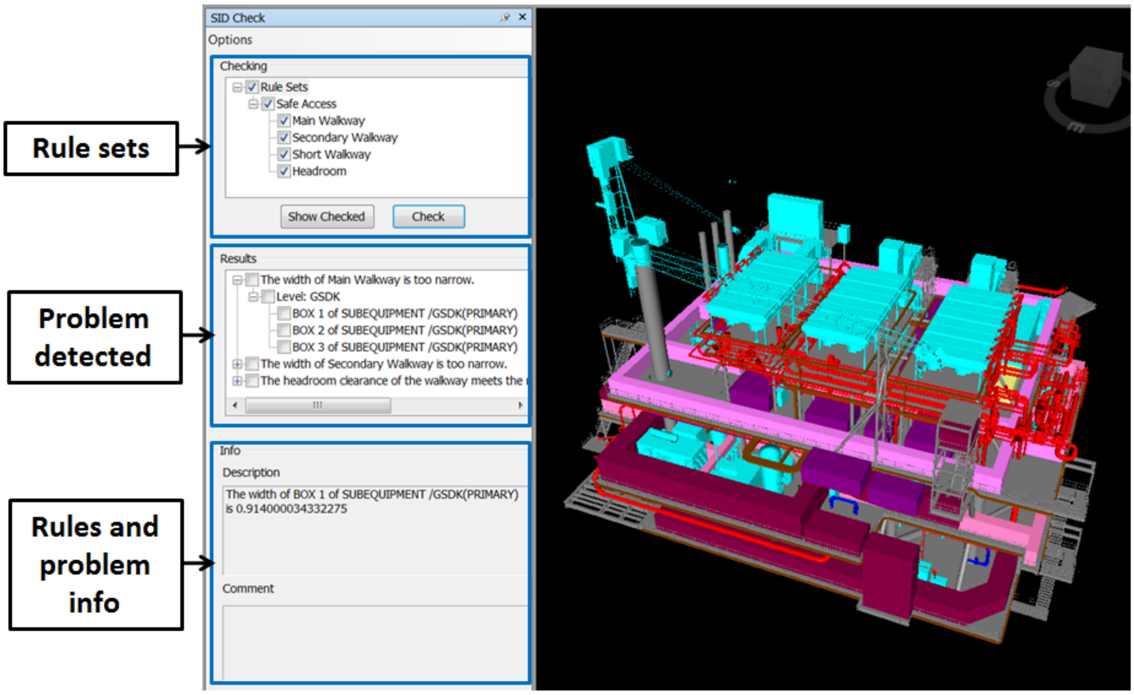

Fig. 3: Interface of developed plug-in on an existing 3D visualization tool.

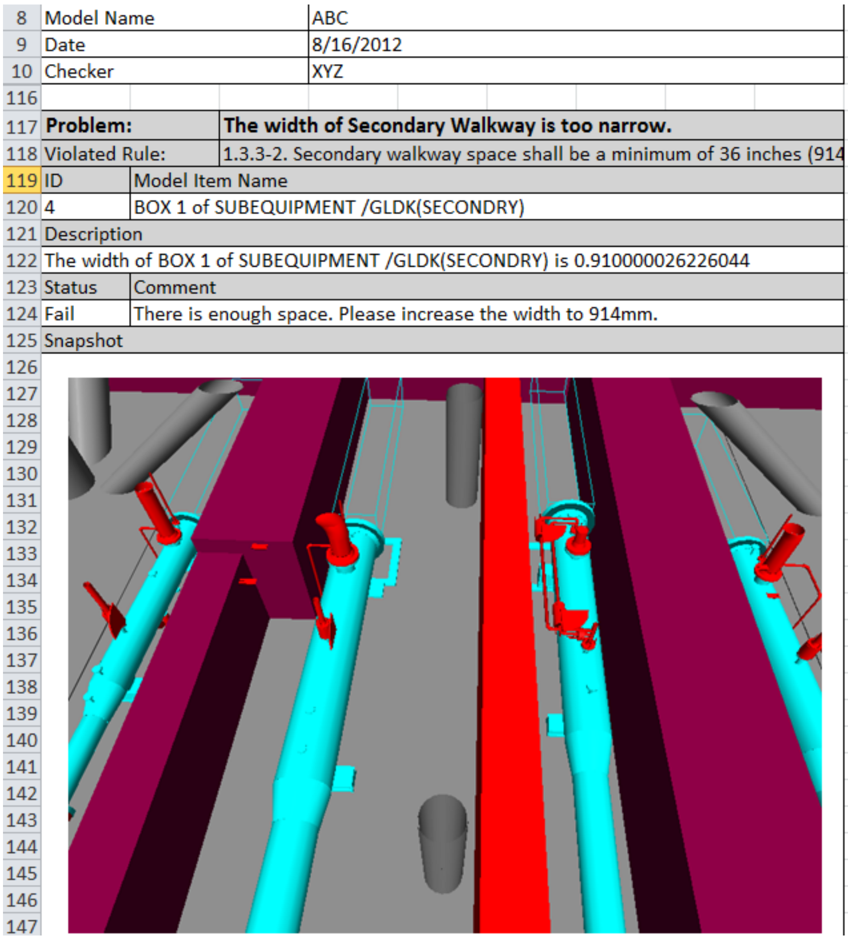

Fig. 4: Example checking report in Excel format.

43 violations were detected by the automated SID rule-checker. They were categorized according by the level of severity. Figure 4 shows an example of the safety-rule checking report that was automatically generated. The associated objects in the model which cause a safety issue are highlighted in red. The developed interface also

displays an automated recommendation how the safety issue can be resolved. The recommendation is based on historic events and has embedded solutions there were pre-determined by humans to have previously successfully resolved the same or a similar issue. A user finally has control to approve the recommendation, implement the design chance, pass it back to the designer for a required change, and/or send it off for final approval by a SID engineer. It is important to keep the human involved in the final decision making process. The human user ultimately stays involved in an automated safety review process. A human may find more complex safety issues that the current automated SID rule-checking engine may not be able to solve. A human finally approves it and has a chance to score whether it was successful or not. This ensures that the automated safety rule-checking platform increases its success rate. Another advantage of the automatically generated and human-approved reports are that SID violations can be easily conveyed back to the designer and help them understand what the issue is even without visualizing the problem in 3D modeling software.

5. DISCUSSION AND CONCLUSIONS

As an application for the design-for-safety (DfS) concept, a preliminary automated SID rule-checking platform focusing on safety access/egress was developed. An application was developed based on an existing visualization platform and tested on a design for a capital facility project. The potential benefits of the application include: (1) add to the traditional safety design review process as a supportive tool that helps make SID engineers make better-informed and faster decisions, (2) instead of relying solely on the SID engineers' experience, the automated SID compliance checker provides consistency especially in large models reducing the human error of finding most but not all safety issues, (3) allowing SID engineers to concentrate and spend time on safety issues that are too complex for an automated SID checker to find, and (4) the developed tool allows designers to identify and reduce potential design errors/unsafe design early in the design phase and even before it is handed off to SID engineers thus ensuring DfS concepts by empowering many project stakeholders as early as possible in the design and review process of projects. Future research will need to (1) to explore the requirements and feasibility of implementing many other SID rules based on the proposed methodology, and (2) to study the effectiveness of such system as an assistive system for designers and SID engineers in practice. As such, the reliability of any rule checking system largely depends on the correctness of the 3D model, e.g. object properties and naming (Eastman et al. 2009).

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