Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

DESIGN FOR SAFETY KNOWLEDGE-BASED BIM-INTEGRATED RISK REGISTER SYSTEM

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Safety is a major challenge in the Construction industry. Researchers have shown that many construction fatalities could have been avoided with proper design considerations. Design for safety (DfS) knowledge helps designers to identify how their design may pose a risk during the life cycle of a building facility. Hence, designers can use DfS knowledge to address these safety issues in the design phase. Nevertheless, identified risk and required mitigation of the risk must be noted in a risk register. Moreover, all the risks cannot be addressed or eliminated during design. Hence, residual risks must be addressed during actual construction, operation and maintenance. This study proposes a DfS knowledge-based risk register system that registers design deficient risk with mitigation action and the residual risks that must be addressed during actual construction. The risk register is integrated with the BIM so that the residual risks can be easily visualized in BIM compliant 3D model for further action in later phases. A structure of risk identification procedure incorporating DfS knowledge is described. Identified risks are stored in a database. Mitigation action along with residual risks and responsible persons/parties for a design element are linked with the BIM model. Such early identification of hazard would be very useful to be prepared for any potential risk in advance which can save significant time and cost for the constructor.

Keywords: Construction safety, DfS rule, Knowledge library, Risk review, Building information modeling, Risk visualization, Residual risk, Risk mitigation.

1 INTRODUCTION

Designers can significantly contribute to reducing risks to those involved in construction works (HSE 2012). As stated by Behm (2005), 42% of 242 fatalities were linked to design. However, designers have limited knowledge regarding how their design can affect construction safety (Toole 2005). Hence, researchers have been working in developing knowledge-based safety library, in other words, design for safety (DfS) library, in order to help designer to take necessary action in addressing construction hazards in their design (Gambatese *et al.* 1997, Nguyen *et al.* 2014). Moreover, Building Information Model (BIM) has been used to check and visualize safety issues during design and construction. For example, Zhang *et al.* (2013) used a table-based rule to automatically check BIM model against risk of falling from height and suggest design solution. Benjaoran and Bhokha (2010) presented a rule-based 4D CAD model to detect hazards related to working at height along with necessary safety measures. Nevertheless, all the risks cannot be addressed or eliminated with design and these remaining risks are known as residual risks. Therefore, identified risk, required mitigation measures and the residual risks must be properly

documented in a risk register for further action during the actual construction, operation and maintenance. This study presents a DfS knowledge-based risk register model that records design deficient risk with their mitigation action and the residual risks. The risk register is then integrated with BIM compliant 3D model so that all the residual risks can be visualized for further action in later phases.

2 MODEL DEVELOPMENT

Figure 1 depicts the framework of risk register model that consists four main parts. The first is a DfS knowledge library which covers design related risk that may arise during construction, operation and maintenance. The second is a BIM compliant 3D model that can be parsed against the safety rules built in DfS knowledge library. The third is a reasoning engine that uses safety knowledge for safety review/assessment using BIM. Finally, the fourth is a BIM-integrated risk register that facilitates the management and control of the safety issues identified in design stage. The following sub-sections briefly elaborate different parts of the risk register model.

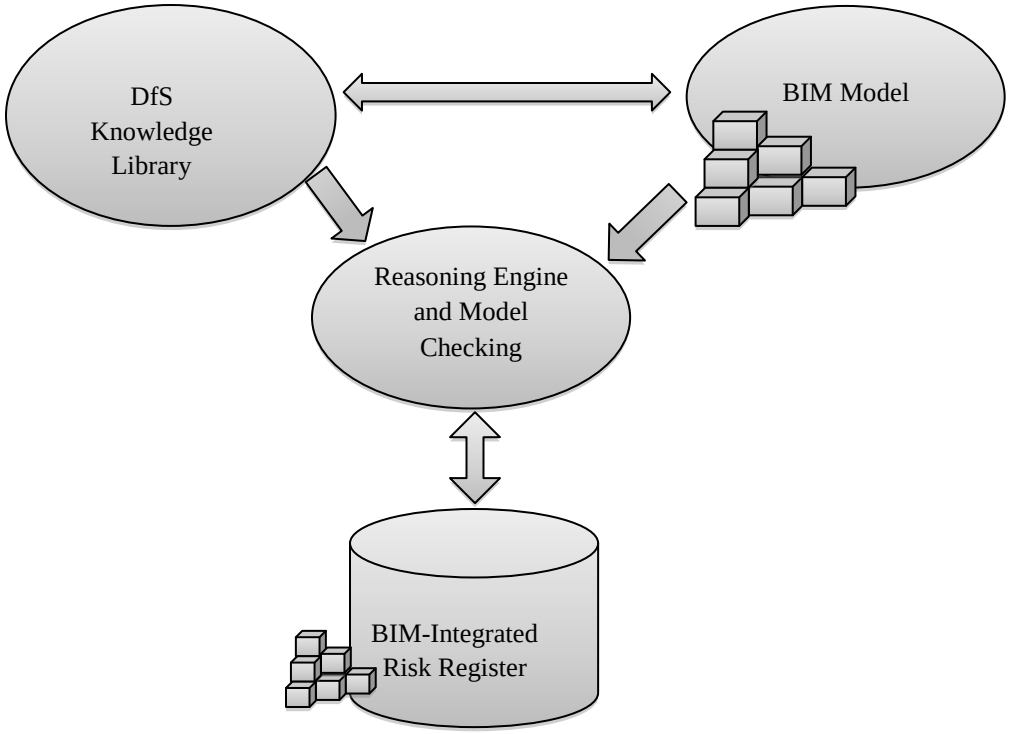

Figure 1. BIM-Integrated Risk Register model.

2.1 DfS Knowledge Library

In order to help designers with design related hazards to be considered in their design, a rule-based DfS knowledge library is necessary. After Gambatese *et al*. (1997) who developed checklist-based "ToolBox" to assist designer in identifying project specific hazards, some researcher established few rule-based DfS features to automatically check hazards of deficient design in BIM model (Benjaoran and Bhokha 2010; Zhang *et al*. 2013; Jia *et al*. 2014). Nevertheless, these DfS features are particularly meant to prevent hazards of fall from height and

the rules are hard-coded into the algorithms. The authors have developed a comprehensive DfS knowledge library with safety rules that can be used to check against safety issues for any design element in the BIM model and working in a separate paper. For example, a precast beam can pose risks of "Transportation and breakage issue" and "Falling object" if length of the beam is too large or no lifting point is provided for safe lifting, transportation and installation of the beam. The designer often misses these requirements of beam length and provision of lifting point. To help the designer with DfS knowledge, two rules can be set as "Length≥5m" and "NoLiftingPoint". If a precast beam in the BIM model is found with length more than 5 m and with no lifting point, it will be identified as a hazard with possible risks of "Transportation and breakage issue" and "Falling object", as mentioned earlier.

2.2 BIM Model

BIM becomes the core of any building facilities starting from design, construction, operation and maintenance. Safety issues are also linked with the BIM model that can be easily visualized and addressed (Wetzel and Thabet 2015). Next part of the risk register system is a library of design elements with their physical properties for BIM compliant 3D model. Since the knowledge library is to be used by the designer for his/her design elements, the list in the library must be rigorous enough to be picked by the designer. IFC elements have been stored in a library with some inferences since these are ISO recognized unified elements.

2.3 Reasoning Engine

The next part of the risk register system is a reasoning engine that compares physical parameters of design facility in BIM model against the safety rules set in DfS knowledge library. The reasoning engine sets the platform for model checking and a design element will be highlighted along with risk and possible mitigation measures if it fails any safety rule. The designer can then take necessary corrective action to address the risk.

2.4 Risk Register

Risk register is the core of the system that is to be passed from design phase to the constructor to deal with the residual risk. When a designer checks a design element through the reasoning engine, all the identified risks/hazards are tagged and visualized for the respective design elements in the BIM model and stored in risk register.

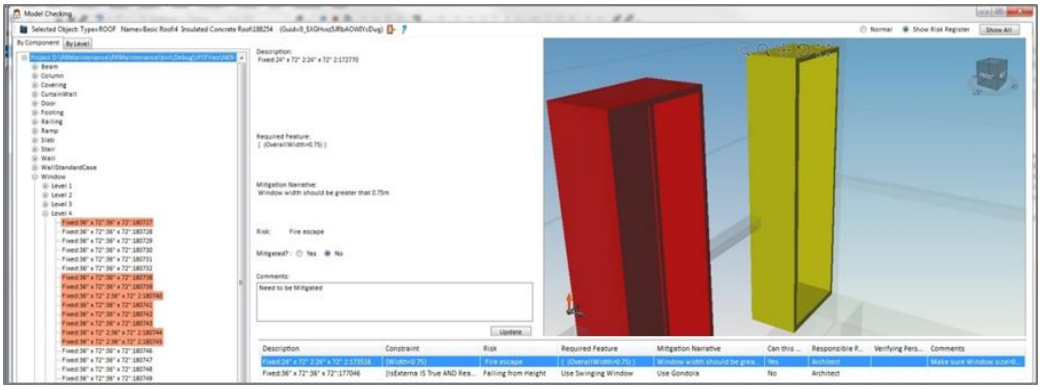

Figure 2. A view of BIM-Integrated risk register.

It also stores information about action taken to mitigate the risks and any other suggestions with responsible persons in order to follow up on the residual risk. For example, a window can pose a risk of "Fire escape" if the window width is less than 0.75 m. To help the architect (designer of the window) with DfS knowledge, a rule can be set as "Width≤0.75m". If any window in the BIM model is found with width less than 0.75 m, it will be identified as a hazard with possible risk of "Fire escape". Figure 2 shows a snap shot of risk register where design element "Window" is highlighted in the BIM model because it fails the safety rule "Width≤0.75m" and it will pose the risk of "Fire escape", as mentioned earlier.

3 CASE EXAMPLE

A BIM model of 5-storey building has been used to illustrate the effectiveness of BIM-integrated risk register system. For illustration purpose, only windows have been checked with safety rules from DfS knowledge library and are shown in risk register system. Other design elements have not been included in the check in order to avoid the crowdedness. Nevertheless, all the design elements for the building can be checked and shown in risk register.

In the BIM model, a few windows have width less than 0.75 m and windows on one side of the building have a property of "NotSwinging". It is to be noted that a window with the property "Swinging" enables easy cleaning and maintenance from inside the building. If the glass of window cannot swing it means that it will pose a risk of "Fall from height" during operation and maintenance. The risk can be mitigated in numbers of ways. Firstly, it can be address by design with selecting window system that has swinging property. Alternatively, cleaning should be done using gondola and the constructor should install hooks for gondola operations on the roof or building frame. This is to be done during construction.

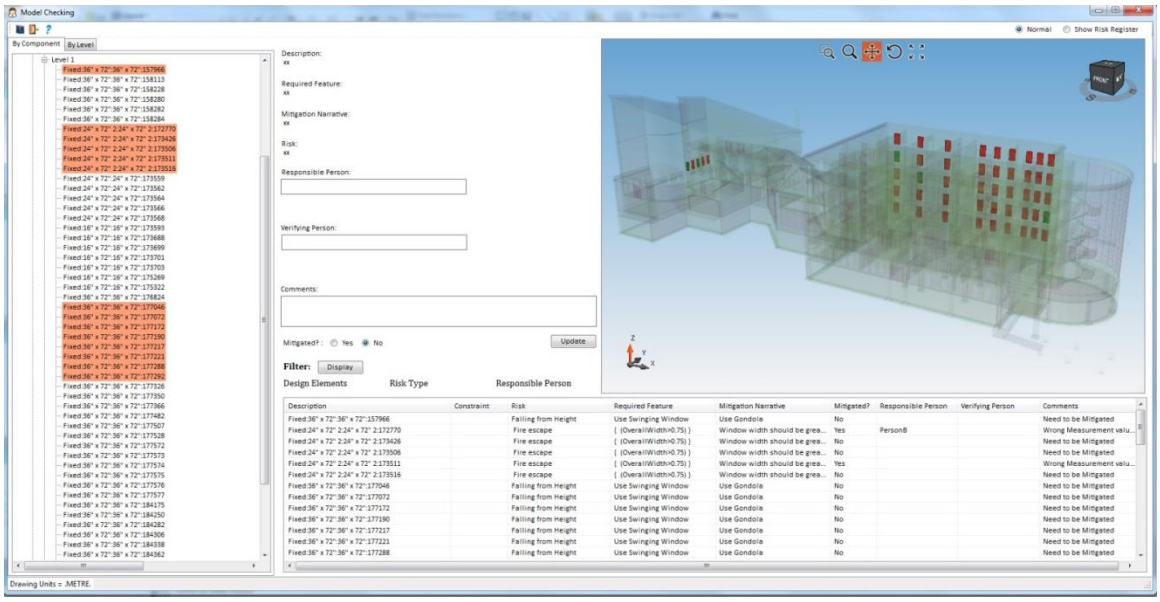

Figure 3. Risk register for the case example BIM model.

Figure 3 shows the risk register after checking the 3D model of the building. The model is displayed transparent and the design elements with errors are highlighted as Solid. The same elements are highlighted in the Tree view at the left side. As can be seen, five windows are

highlighted since their widths are less than 0.75 m. On the other hand, windows at the backside of the building are highlighted as well since those windows have property of "NotSwinging". Corresponding risks, possible mitigation measures are displayed in a list. The object with an error is viewed "zoomed fit" when selected by the user as shown in Figure 2. The user can assign responsible and verifying person for the risk and can track the mitigation status. Once the error of an element is mitigated, it will be highlighted in green and objects that are yet to be mitigated are highlighted in Red. The user can also enter few comments corresponding to the picked up object for future reference.

Figure 4 shows one example of mitigation status and further suggestions for design element slab. For example, when a slab designer designs his slab, he may not be aware of the location of material stockpile and the necessity of heavy equipment movement for construction. Consequently, the potential risk could be "Failure of slab" if it is not designed for material stockpile and heavy equipment movement. The risk register suggests designer about possible mitigation. However, during design stage, the designer may not have knowledge about the location of the material stockpile. In most cases the constructor decides about construction sequence and in-house arrangement of materials. In order to follow up for the risk of "Failure of slab", the designer could put a note in the risk register "Design loads are to be provided to the constructor. The constructor shall check with the designer for material stockpile location and heavy equipment maneuverability". In this way, the risk register could help step by step mitigation of hazard from design to construction, operation and maintenance.

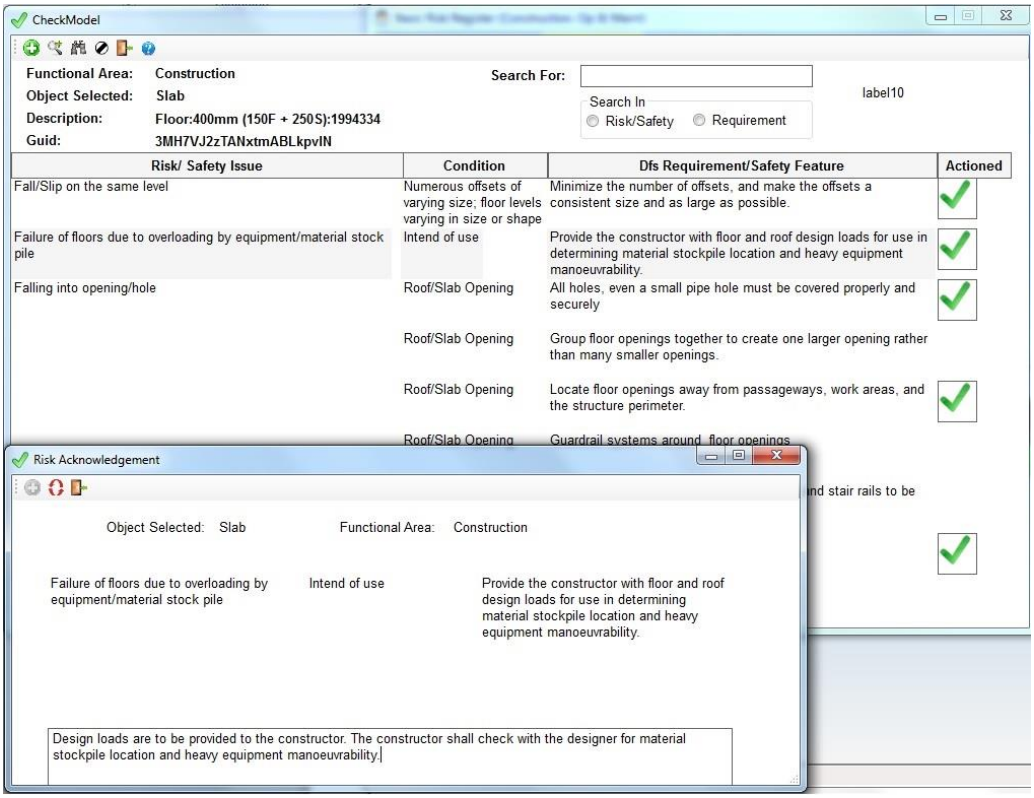

Figure 4. Action taken and suggestion for further action.

4 CONCLUSION

Early identification of hazard before the commencement of actual construction work has found to be very effective to prepare for any potential risk in advance. As can be seen from the illustrative case example, DfS knowledge library greatly help designer to identify any potential hazard during design phase with possible mitigation measure. The proposed BIM-integrated risk register build the database for identified risk, action taken, and residual risks to be taken care of in the later stages of actual construction, operation and maintenance. Visualization of objects with errors in the 3D model helps constructor to better understand the risk and prepare accordingly. The risk register also facilitates to keep record of responsible person, verifying person and any suggestions to follow up the risk. Such risk register will help constructor to prepare for the risk in advance and hence, avoid any surprise situation that may cause potential delay of work which could be very costly.

Acknowledgments

We would like to acknowledge Workplace Safety Health Institute, Singapore, for providing funding of this project under WSHI RPF call number MOMOSDETT12000007.

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