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Prevention through Design (PtD) of integrating accident precursors in BIM

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Abstract: Construction workers are engaged in many activities that may expose them to serious hazards, such as falling, unguarded machinery, or being struck by heavy construction equipment. Despite extensive research in building information modeling (BIM) for safety management, current approaches, detecting safety issues after design completion, may limit the opportunities to prevent predictable and potential accidents when decisions of building materials and systems are made. In this respect, this research proposes a proactive approach to detecting safety issues from the early design phase. This research aims to explore accident precursors and integrate them into BIM for tracking safety hazards during the design development process. Accident precursors can be identified from construction incident reports published by OSHA using a text mining technique. Through BIM-integrated accident precursors, construction safety hazards can be identified during the design phase. The results will contribute to supporting a successful transition from the design stage to the construction stage that considers a safe construction workplace. This will advance the body of knowledge about construction safety management by elucidating a hypothesis that safety hazards can be detected during the design phase involving decisions about materials, building elements, and equipment. In addition, the proactive approach will help the Architecture, Engineering and Construction (AEC) industry eliminate occupational safety hazards before near-miss situations appear on construction sites.

Key words: Prevention through Design (PtD), accident precursors, text mining, Building Information Modeling (BIM), construction safety

1. INTRODUCTION

Although the construction industry accounts for 5% of total U.S. employment, fatal occupational injuries in construction recorded about 20% (976) of the total fatalities (4,764) in 2020 [1], [2]. Construction workers are engaged in many activities that may expose them to serious hazards, such as falling from rooftops, unguarded machinery, or being struck by heavy construction equipment. In addition, as construction injuries and fatalities incur immense societal costs, totaling approximately $171 billion in 2019 [3], measuring construction safety performance has been considered an important part of construction project management. The Experience Modification Rate (EMR) has been used as a popular indicator of contractors' safety performance during the bidding stage [4], but it has limitations that cannot reflect the likelihood of construction-related on-site injuries and accidents at a project level. Driven by a system safety engineering theory in which elimination of hazards through design selection should be prioritized for safety [5], a proactive approach is required to detect safety issues before construction execution.

The concept of Prevention through Design (PtD) has encouraged ‘safety by design’ or ‘design for safety’ in the construction industry [6], [7]. The PtD concept can be applied to Building Information Modeling (BIM) to detect possible threats to occupational health and safety using 3D modeling from the planning stage [7]. For example, BIM can support identifying and preventing potential fall hazards on construction sites by detecting floor edges, holes, and unsafe areas using model information such as floor elevation and dimensions [8]–[10]. BIM also provides a platform for visualizing near-miss data for assessing the safety performance of construction workers [11]. Current approaches detect safety issues using building models after the design stage is completed. However, in that design choices can largely dictate construction safety performance [12], current approaches may limit the opportunities to detect potential accidents, which can be predicted when decisions about building materials and systems are made. Given that building component information allows designers and construction managers to extrapolate potential accidents, BIM can provide a designing platform to integrate each building component with hazard issues, avoiding potential hazards which are intrinsic to building components.

This research aims to provide a proactive safety management system that can evaluate construction safety for design alternatives and selections and track safety risks during the design development process. The proactive system will be devised by integrating hazard precursors into BIM. By providing a practical solution for managing construction safety throughout the project life cycle, this research envisions the future AEC industry process where construction safety risks are identified during the design phase. With the solution, in BIM environments, design decisions are made and evaluated by forthcoming construction risks nested in building models. With integration of safety detection systems into BIM, architects can track safety risks in the progress of developing building models. Owners can choose a building design that is expected to offer a safe construction workplace, and construction engineers and managers can identify the models’ potential hazards and safety concerns. The proposed proactive approach will eliminate occupational hazards even before near-miss situations appear on construction sites. This research will contribute to a successful transition from the design to construction stage by which a construction workplace can prevent potential accidents. This study will also advance the body of knowledge about construction safety management by shedding light on what causes construction site accidents.

2. RESEARCH BACKGROUND

2.1. Accident precursors

According to the US National Academy of Engineering [13], accident precursors are building blocks of accidents which can be designed as any conditions, events, and sequences leading to accidents. The precursors include both internal factors such as human errors and external factors of unforeseen circumstances such as hurricanes. Many efforts have been made to learn from incidents to prevent future injuries and hazard precursors were inferred from historical accident reports. Wu et al. (2010) presented a systematic model for improving construction safety by tracking a list of precursors and immediate factors and continuous reporting near misses [14]. Tixier et al. (2016) used a natural language processing (NLP) system to extract precursors from injury reports [15]. The NLP system was devised to quickly and automatically check injury reports and ameliorate the experts’ safety knowledge. To predict safety outcomes using extracted precursors, Baker et al. (2020) proposed a machine-learning-based predictive model and showed advanced predictive power [16]. Despite substantial previous research to better understand and prevent safety risks, the efforts to connect safety factors into the project life cycle have been fragmented since identified hazard precursors are not considered in the planning and designing phase in a proactive manner. Rather, most studies are solely focused on extracting hazard factors in an automatic manner. Although a few studies have provided a good starting point to link construction hazard factors to design development [17], hazard precursors inherent in diverse design decisions have not specifically been discovered. In this respect, this research presents a preventive rather than reactive strategy against hazards precursors by proposing a further expansion of the safety management scope to the early design stage.

2.2. BIM and construction safety

The implementation of BIM in the AEC industry has transformed construction safety and health management by allowing automatic hazard detections [10]. An automated rule-based checking system was developed and integrated in BIM for safety planning and simulation to prevent fall hazards [10]. According to the need for safe management throughout construction progress, 4D-BIM has also been utilized to improve occupational safety by providing more information such as site layout and safety plans and visualizing the plans and site information [9], [18], [19]. Based on the models throughout the construction phase, activities related to scaffolding work were also identified and risk factors based on the survey for industry professionals were coded in different colors in the BIM model [19]. BIM can often be employed to provide realistic site layouts for onsite safety management. For example, cloud-based BIM with sensors provides location information of workers and real-time alerts can be provided to workers near potential incidents [20]. When optimizing safety surveillance camera installations, BIM can provide construction phase layouts to consider horizontal and vertical safety monitoring on the construction sites [21]. Current approaches are still challenging in that a completed building model including installed building elements and their building process will be needed to evaluate incident risks on site.

Although there were approaches to evaluate the safety risk of a model itself, previous studies have required extremely high levels of detail in the model that often make the project become computationally large, as well as hazard detections become too late. For example, we need models throughout construction phases in which architectural elements are divided by construction parts; construction workflows (e.g., activity sequences) are in detail; and temporary structures and equipment are also included as objects. A research effort has been conducted for proactive safety management at the design stage to support safer design alternatives for architects and structural designers [22]. However, it is still challenging that users identify construction processes and associated elements, which may discourage designers who have little construction experience.

3. RESEARCH METHODOLOGY

This research employed text mining for identifying hazard precursors, and parameter query using visual programming (Dynamo) to integrate risks into BIM workflows as shown in Figure 1. Construction fatality reports published in Occupational Safety and Health Administration (OSHA) were collected from 2009 to 2017 [23]. Using the OSHA dataset, text mining was conducted using the R programming language. Hazard precursors were investigated based on term frequencies and their correlation. By comparing correlation of texts in the fatality reports with ifcBuiltElement defined by buildingSMART [24], we explored a dependency structure matrix (DSM) to investigate dependencies between hazard precursors and BIM elements. Based on the matrix, preliminary conditional statements were established to assign risk factors in BIM, and the risk parameters were assigned to a test BIM project model in Revit by developing a dynamo script.

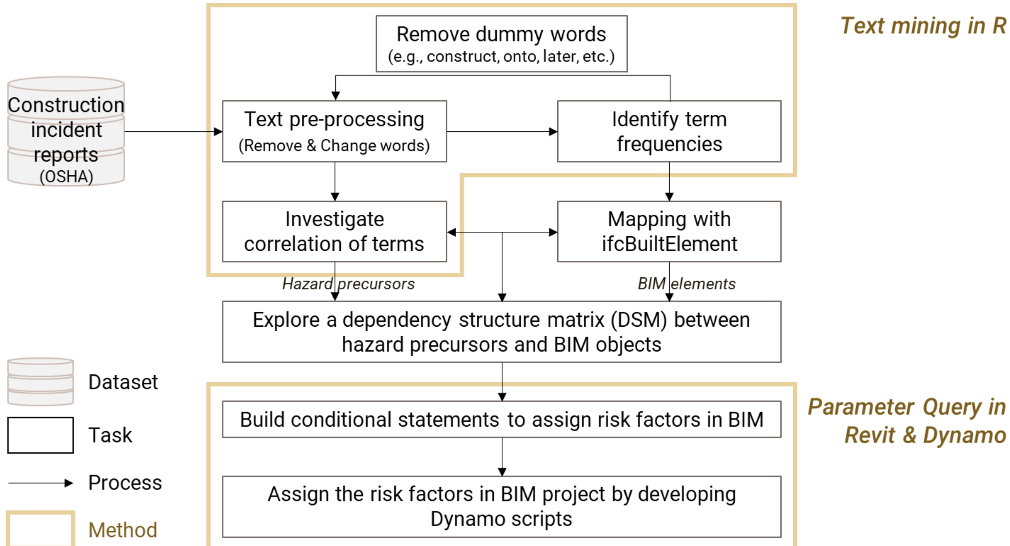

Figure 1. Proposed methodology for integrating hazard precursors in BIM using text mining and parameter query in BIM

4. PRELIMINARY APPLICATION OF THE PROPOSED METHODOLOGY

4.1. Analyzing text-based safety data

We collected 9,005 construction fatality records from 2009 to 2017 from OSHA. The preliminary description of the incident was extracted for text mining analysis. Text pre-processing was conducted to remove redundant and unrecognizable text or change all terms into lowercase and word stem to increase analysis accuracy. Term frequencies, the frequencies of the terms occurring in the incident reports, were identified and this will guide us to investigate the importance of accident risks. In that we used construction fatalities in which the impacts of the incidents are high; a higher frequency of the incidents was assumed to be more critical based on the risk matrix approach [25]. According to the term frequencies in Figure 2, among ifcBuiltElement, ifcRoof, ifcSlab (floor), ifcWall, ifcDeepFoundation (trench), ifcBeam, ifcDoor, and ifcEarthworksElement (trim and excavation) were shown frequently in sequence in the construction fatality reports. In addition, the list of tools and equipment indicating higher impacts was in the order: truck, vehicles, ladder, trailer, forklift, tracker, crane & boom, scaffolding, bucket, loader, rig, and drill (it might be the drilling rig). The impacts of building materials and methods on fatal injuries were also shown as follows: pipe, concrete, tank, metal, steel, wire, gas, paint, and cable.

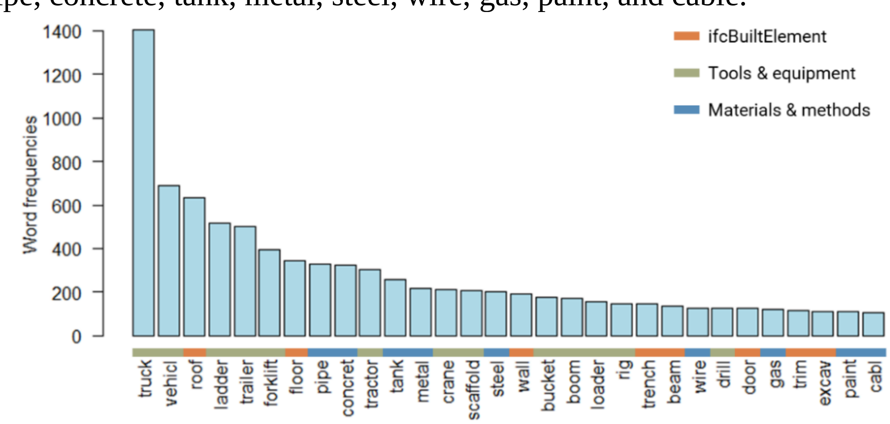

Figure 2. Top 30 most frequent words of ifcBuiltElement, construction tools & equipment, and materials & methods

The list of ifcBuiltElement can be considered elements containing accident precursors. To derive the precursors inherited in the BIM elements, we analyzed correlated terms of each element which were discovered in Figure 2. For example, correlated terms with "wall" elements are shown in Figure 3. Fatality reports including "wall" elements can include materials such as concrete, steel, and masonry; locations of work such as tops, feet, etc.; and properties such as structure elements or not.

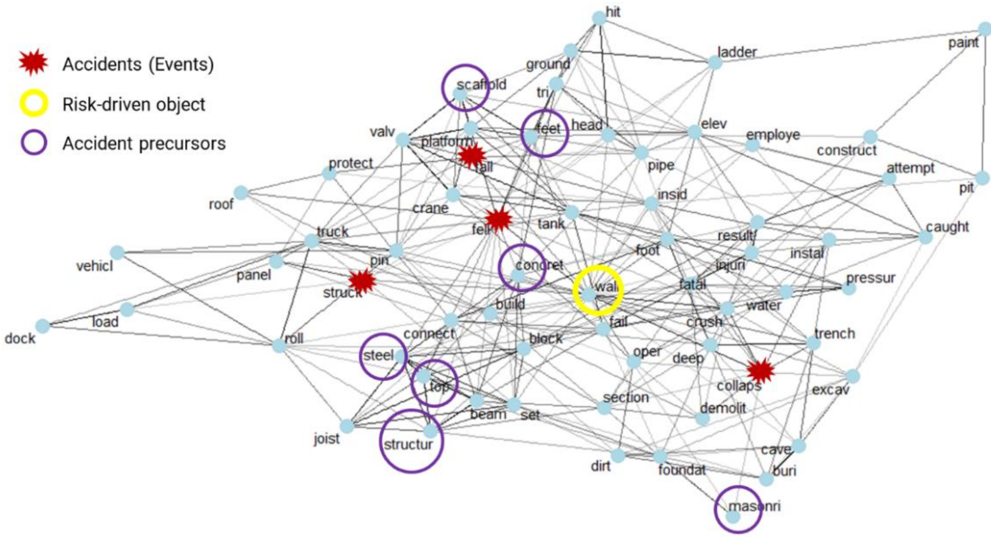

Figure 3. Correlated terms with "wall" in the construction fatality reports

4.2. Identifying dependency structure of BIM elements and hazard precursors

As the wall elements are one of the major building components and are involved in many types of accidents (e.g., fall, struck by, collapse, etc.), a dependency structure matrix (DSM) centered on the wall elements was explored and identified in Figure 4. DSM has often been used for activity sequencing and construction scheduling [26]–[28]. In that DSM can present attributes such as the strength of task dependency [28], the correlated terms centered on wall elements were utilized to create a DSM. The DSM shows that interconnection of accident events, risk-prone elements (i.e., walls, in this case), and accident precursors.

	Events			Risk-prone element	Precursors					
	Fall	Struck by	Collapse	Wall-driven risk	Height	Structural or not	Steel	Masonry	Concrete	Scaffolding
Fall		X								
Struck by										
Collapse										
Wall-driven risk	X	X	X							
Height	X			X		X	X		X	X
Structural or not				X	X		X		X	
Steel				X	X				X	
Masonry			X	X						
Concrete	X			X	X					X
Scaffolding	X			X						

Figure 4. Dependency structure matrix (DSM) of wall-driven risk

4.3. Assigning safety factor in BIM projects

To assign safety factors to BIM projects, we first created a project parameter named "Risk Factor" in Revit 2020 that can be listed and kept track of throughout design development. The values of risk factors can be assigned by multiple conditional statements that can be formulated based on elements' parameters indicating hazards precursors. A dynamo script was used to get parameters' values indicating precursors of the risk-prone elements, evaluate the risk quantifiably, and assign the risk factors in the BIM elements. Figure 5 presents an example of a dynamo script setting risk factors for wall elements based on their height and structural usage. This script can be expanded to the entire BIM project by selecting different elements and changing evaluation parameters and conditions. Additional script fors visualizing risks in colors will help us track the project's overall safety as shown in Figure 6.

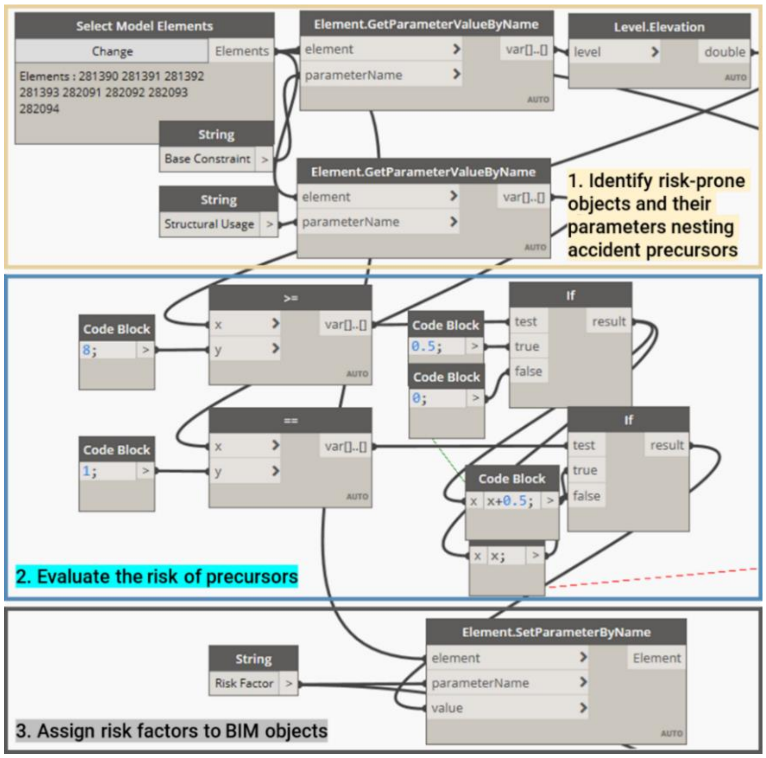

Figure 5. Example of dynamo script setting risk factors by model elements' elevation and structural usage (in this case, the risk factors were assigned into wall elements)

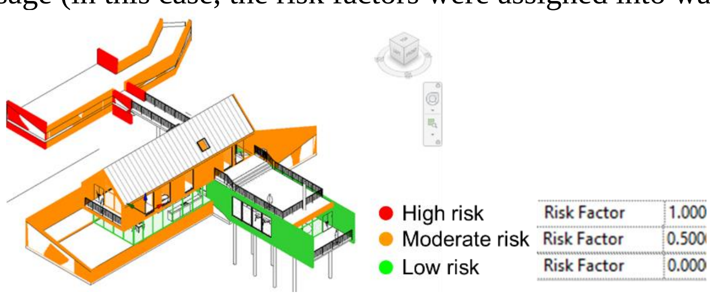

Figure 6. Example of tracking risk factor for walls in Autodesk Revit sample project using the dynamo script (semi-automatic assignment based on the elements' parameters)

5. CONCLUSION

This research proposes proactive safety management in the AEC industry by integrating the evaluation of hazard precursors in BIM. Text analytics of fatality reports enabled us to identify accident precursors related to ifcBuiltElement in BIM projects. Based on the correlation of the terms, the dependency structure matrix among accidents, BIM elements, and precursors was discovered. The DSM was the basis for formulating multiple conditional statements that could impose quantifiable risk factors on BIM elements. Then, by leveraging parametric modeling features, accident potentials can be evaluated based on the elements' placement and attributes in a project, and risk factors can be measured and assigned to the elements. The risk factors can be traced in the BIM schedule (a written list of elements) or in color mapping in a visualized 3D model.

The proposed research methodology and approach can transform the paradigm of construction safety management by providing predictable and avoidable occupational risk factors. Also, it expands the method of quantifying construction hazards by employing text mining and parameter querying. BIM projects with safety scores can support a smooth delegation of safety management features from the design stage to the construction stage. Architects can consider construction site safety without preliminary construction experience. Owners can be informed of design alternatives being projected as a safe construction site, by selecting a safer construction site; facilitate quality and daily production; and ultimately improve onsite productivity. Contractors can identify potential hazards and safety concerns before construction and plan for safety activities.

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