Ontology-based Representation of Implicit and Explicit Knowledge for Job Hazard Analysis: Focusing on Water Infrastructure Jobs

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Abstract:
Given that each construction infrastructure project is unique, it is necessary to perform a Job Hazard Analysis (JHA) for all high-risk activities in every construction project. Due to the dynamic nature of construction sites, JHA needs to be conducted before the job and then updated when new information is added. In most cases, JHA is performed manually, and it is challenging to reflect the changes in the construction plans or schedules in JHAs. Considering these challenges associated with JHA practices, previous researchers attempted to automate the JHA process by building ontology-based solutions. However, most of these studies have only considered the explicit knowledge of JHA and ignored the implicit knowledge for hazard identification and control, which is considered as one of the most important knowledge components in the process of JHA. Thus, this research attempts to represent the JHA knowledge based on both the explicit and implicit knowledge of JHA in a form of ontology, focusing on water infrastructure jobs. To achieve this goal, a document analysis on JHA documents and a qualitative Delphi method were adopted to identify the implicit and explicit concepts and relationships regarding the identification and control of various hazards from the practitioners. This paper provides the concepts related to JHA and the relationships among them that can be mapped onto an ontology for automating JHA processes.

Keywords:
Conceptualisation, Job Hazard Analysis, Ontology, Safety Management, Water Infrastructure

1 Introduction

The construction industry is considered as a high-risk industry which has one of the most risk-oriented working environments that accounts for about 20% of occupational fatalities in the world. The increased numbers of workplace injuries and fatalities create irrevocable damage to the industry and its stakeholders (Asadzadeh et al. 2020). Hazard identification, as the initial step in safety planning, is very critical since if hazards are not recognized during the early stages, they cannot be eliminated, reduced, or controlled and could cause injuries. Moreover, the process of hazard identification in the construction industry is subject to a larger number of variables and unknowns compared to other industries (Mihić 2020). Therefore, as the standard process used to identify construction hazards, Job Hazard Analysis (JHA) is a risk assessment exercise which is heavily influenced by the experiences, knowledge, and biases of safety personnel.

Automation is a new and trending research area of construction safety management. Considering the inherent limitations in the traditional JHA, many researchers have tried to automate hazard identification and analysis. Some of these studies directly contributed towards the automation of JHA (Chi, Lin & Hsieh 2014; Wang & Boukamp 2011; Zhang, Boukamp & Teizer 2015) while others created an indirect contribution (Ding et al. 2016; Goh & Chua 2009, 2010; Kim et al. 2016; Kim et al. 2013; Lu et al. 2015; Rahman et al. 2018; Xiong et al. 2019; Zhong & Li 2015). However, knowledge sources used in most of these studies is limited to the explicit knowledge and they failed to incorporate implicit knowledge which is a critical knowledge component for JHA. Because of this limitation, these studies failed to develop important relationships between the hazards, causes and risks which should be determined by a safety expert's experience. Considering these limitations of the past studies, the current research aims to acquire explicit and implicit knowledge of the safety experts and develop an ontology to develop an automated JHA process which can assist work planners during the safety planning phase of a project.

2 Literature Review

2.1 Causality of Construction Accidents

Many researchers tried to understand accidents in the industrial settings by introducing accident causation models. In general, the ultimate objective of these accident causation models is to provide tools to prevent industrial accidents (Abdelhamid & Everett 2000). The different models are based on different perception of the accident process. Some of the most influential accident causation models and methodologies are: single event concept, determinant variable concept, domino theory, fault tree analytical methodology, management oversight and risk tree, Petersen's multiple causation model, Reason's 'Swiss Cheese' model, and system model of construction accident causation (Department of Energy 1992; Heinrich 1936; Mitropoulos, Abdelhamid & Howell 2005; Petersen 1971; Reason 1990). All these accident causation models attempt to identify the factors and process contribute towards an accident. For example, the system model of construction accident causation considers a system view of accidents and identify the production factors and conditions that create hazardous situations. Thus, these accident causation models can be really useful during the JHA process as the process try to recognize contributing factors, causes, and sub causes of possible accidents.

2.2 Job Hazard Analysis

A safety management system is an important mechanism to assist accident prevention and reduction by employing appropriate and consistent safety management programs including planning, education, training, and inspection (Bunn et al. 2001; Labour Department 2002; Moorkamp et al. 2014; Yoon, JS et al. 2013). JHA has been identified as one of the most important elements of a safety management system (Crutchfield & Roughton 2019). JHA is an efficient, proactive method for identifying, evaluating and controlling safety risks before the work takes place (OSHA 2002). In the Australian industry context, completing a JHA is required for any high-risk construction and maintenance work activities and is regulated by WHS authorities (Safe Work Australia 2019).

JHA is usually performed by a JHA team, which usually comprises a JHA manager, a safety representative, the leader of the work team and the people undertaking the work (Rausand

2011). JHA is a risk assessment method for analysing hazardous operations and concerns all risks relevant to a specific work task. JHA can help minimise WHS risks especially when the type of task or the work environment is new (ISO 2009). Generally, the JHA is performed through six main steps (Albrechtsen, Solberg & Svensli 2019): step 1 - Decomposing the job into functions, tasks, and steps, step 2 - Identifying potential hazardous events and conditions that can occur during the execution of each sub-task identified in previous step, step 3 - Assessing the potential consequences of the identified hazards, step 4 - Assessing the expected probability of occurrence of the identified hazards, step 5 - Assessing the risk of each sub-task based on the assessed probability and consequence with the use of risk matrix, step 6 - Identifying risk reduction measures that improve safety of the sub-tasks that have an intolerable risk.

As a systematic method for loss prevention, JHA has several advantages (Glenn 2011). When the JHA process is identified as a main element of the safety management system, it provides a methodology to bring reality to discussions about the quality of work being performed by employees. Since tasks are properly assessed, the control of hazards and associated risk is better defined and communicated. This will result in improvements in procedures, methods, protocols, quality of materials, equipment, tools, standard of training of employees and the identification of environmental problems and issues (Crutchfield & Roughton 2019). If the results of the JHA is properly applied, it delivers so many advantages by increasing the efficiency through proper control of hazards. A study conducted by Zheng, Shuai and Shan (2017) proves that a systematic JHA has the capacity to reduce the number of recordable injuries considerably. Crutchfield and Roughton (2019) and Yoon, IK et al. (2011) identify JHA as a simple instrument that helps to highlight the hazards of risky operations. Both managers and non-managerial level workers gain insight into task-specific risks by performing a JHA. The JHA gathers the team who are responsible to complete the work activity, and the process. Therefore, a JHA is not only making plans for safety, but also functioning as a planning tool for the productivity and quality of the task to be completed (Albrechtsen, Solberg & Svensli 2019).

2.3 Risk Assessment of Hazards

Mitigating risks as early as possible in the project life cycle is one of the main principles in any construction project. Despite undertaking risk management in the early stages of the project, residual risks will always be there which needs to be prudently handled during the construction phase. JHA process provide effective results in situations where the safety is not guaranteed by adherence to standard procedures or plans or by established barriers. Therefore, JHA is considered as one of the successful methods which has the ability to deal with this residual risk (Kjellen & Albrechtsen 2017). Evaluating the relative risk level of sub-tasks is considered as one of the most important steps in the JHA process (OSHA 2002). Risk is usually defined as the severity of an event combined with the probability or likelihood of that event occurring. The two measures, probability of occurrence and consequences place the risk in a standard scale from most negligible to the most severe to determine the priority order of treatment (Rozenfeld et al. 2010). Statistical analysis of historical accident data, which could provide the numerical probabilities and severity levels for accidents, would be a straightforward way to assess the risks. However, Albrechtsen, Solberg and Svensli (2019) has identified that the risk of hazards is often evaluated without expressing the values for probability of occurrence and consequences. The reason behind this is the extremely small likelihood of occurrence of most potential accidents, and the high rate of incident under-reporting. Thus, very large sample sizes would be required to achieve statistical significance of the distributions obtained. Fortunately, although evaluation of risk level of hazards is critical to improve safety management, precise assessment is not certainly necessary (Jannadi & Almishari 2003). As per Rozenfeld, Sacks and

Rosenfeld (2009) an estimated predicted risk level will be sufficient for the safety manager to take decisions.

3 Research Methodology

Ontology is a formal information model that explains and describes knowledge of a specific domain that can be communicated and shared by people and computer applications (Batresa et al. 2014). Thus, ontology development required sufficient understanding of the targeted knowledge domain. Knowledge can be acquired through the acquisition of explicit knowledge (knowledge that is easier to access and verbalize) and implicit knowledge (knowledge an individual acquired through experience, in an incidental manner, without awareness of what has been learnt) (Ettlinger, Margulis & Wong 2011; Hélie, Proulx & Lefebvre 2011). The development process of JHA ontology was supported by both explicit and implicit knowledge to increase the reasoning capability of the JHA ontology.

Water facility infrastructure projects consist of high-risk construction activities which involve dynamic interaction between workers, heavy plants and equipment, materials, and complex surrounding environment. Given the execution complexity and high potential risk involved in the infrastructure projects, the number of safety research conducted is significantly low (Altawil 2017). Considering these aspects, the research was conducted focusing on water infrastructure industry and the methodology was designed to acquire both explicit and implicit safety knowledge relevant to water facility construction.

The research was conducted in two stages. In the first stage, a thorough document analysis was conducted to identify the hazardous activities, hazards and control measures. The second stage comprised of three rounds of expert interviews to identify the relationships in the targeted domain. Research tools used during the development of JHA ontology is demonstrated using a flowchart as shown in Figure-1.

3.1 Document Analysis

A total of 115 JHA documents from 10 different contractors were analysed to identify hazards that are commonly found in the water infrastructure industry. These JHA documents represented the common construction activities such as excavation, concreting, welding, compaction, plumbing, drilling, lifting construction elements etc. The analysis also included 12 Australian codes of practices that are relevant to the construction work. The codes represented excavation work, hazardous manual tasks, welding work, abrasive blasting etc. From the document analysis a list of construction hazards was created and categorised based on the factors/causes of hazards identified from the literature. Moreover, a comparative analysis of multiple JHA documents produced for the same activity revealed some dissimilarities in the hazard's risk level and associated control measures. Thus, it was identified that there are some factors which are not depicted in the JHA documents influencing the risk level of hazards. Based on this information, a semi-structured interview guideline was prepared to identify relationships between causes, hazards, and risks.

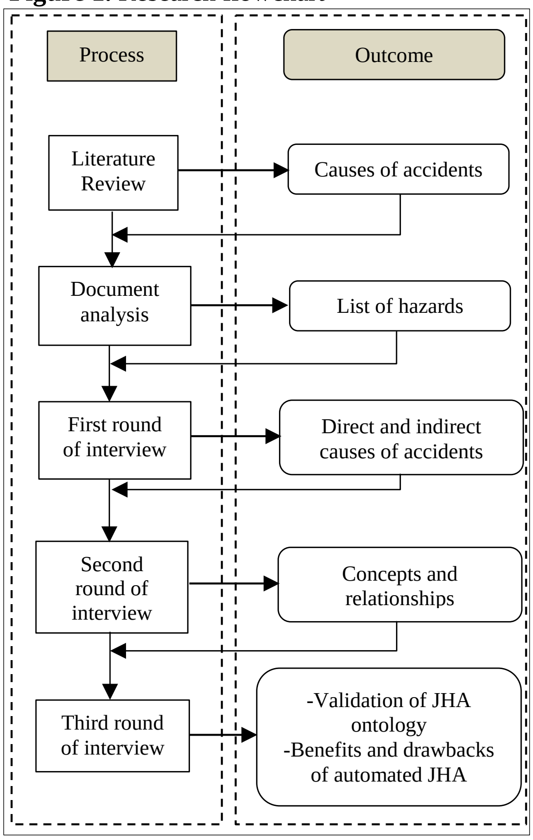
3.2 Delphi Study

Delphi methodology is known to be an effective technique for collecting and synthesising informed opinion on a specific topic and the information collected from the experts remain anonymous preventing participants from dominating others in the process (Whitehead & Day 2015). The purpose of adopting Delphi in this research is to identify the concepts and the relationships in the construction safety domain to develop an ontology. 18 construction professionals from 5 different companies were selected using purposive sampling technique based on their involvement in the JHA process of water facility construction activities. Participants' experience ranged from 5 – 34 years, with an average of 20 years. Table 1 shows the composition of interviewees who participated in this research study. SUP denotes the experts with a direct involvement in the JHA process and SAFE denotes the experts with an indirect involvement. During the first round the hazards and their causes identified from the document analysis were presented to the experts and asked to consider two broad questions – "How these causes could lead to an accident" and "What are the factors influence the risk level of hazards at the stage of JHA". Additionally, the experts were asked to identify any causes that were not recognised from the literature review. Content analysis of the collected qualitative data has resulted a list of direct and indirect causes of hazards and these direct and indirect causes were further categorised based on the nature of the origin and relationships exist between them. At the start of the second round, the categories resulted from the previous round were presented to the interviewees to obtain their consensus. The second round was mainly focused on risk analysis process of hazards done at the stage of JHA. Interviewees were asked to consider two broad questions – "How the risk level of hazards is determined during JHA" and "How control measures are selected to mitigate the hazards" – as a stimulus for generating relationships for the ontology. Moreover, during this round, the interviewees were informed about the automated system for JHA and asked them to identify the factors that can be successfully incorporated into the system based on their predicting capability. The content analysis of the qualitative data collected from this round resulted in a set of relationships between direct causes, indirect causes, hazards, risk, and control measures. This has resulted in a list of concepts and relationships that are needed build the JHA ontology. The third round was mainly focused on validating the findings of the two rounds and finding out the benefits and drawback of automated JHA process.

Table 1. Composition of interviewees

Interviewee ID	Designation	Experience
SUP1	Supervisor	28
SUP2	Supervisor	24
SUP3	Supervisor	32
SAFE1	Safety consultant	27
SUP4	Supervisor	15
SUP5	Supervisor	5
SUP6	Supervisor	18
SUP7	Site safety advisor	12
SAFE2	Senior safety advisor	21
SAFE3	Safety manager	27
SAFE4	Health and safety consultant	14
SUP8	HSEQ advisor	7
SAFE5	Safety manager	23
SAFE6	HSEQ administrator	12
SAFE7	HSEQ manager	34
SUP9	Supervisor	14
SAFE8	Safety consultant	30
SUP10	Field operation implementation manager	22

Figure 1. Research flowchart



4 Findings and Discussion

4.1 Risk Analysis for hazards

Risk assessment of hazards is the most important step that has to be done once hazards are identified. During the JHA process, risk analysis is performed at two stages. Initial risk is assessed with the existing conditions and the residual risk is assessed considering the impact of implementing mitigating strategies. According to the interviewees, a hazard by itself do not provide enough information to decide the suitable control measures. Hazard has to be expressed with its associated risk level to decide what control measures need to be undertaken. Therefore, risk analysis plays a vital part in the JHA process.

4.1.1 Initial risk analysis

The initial risk of a hazard varies with numerous factors. Document analysis revealed that risk level of a hazard depends on the nature of job step and the conditions presented during the execution of job step. According to the interview data all the interviewees who were directly and indirectly participate in the JHA process undertakes qualitative risk assessment due to the lack of statistical data presented in the field. Moreover, the interviewees highlighted the difficulty of relying on previous accident data to predict the risk level of hazards.

> "Even though the probability of a particular accident is 0.001%, no one can say that the same accident will not be repeatedly occurred within a small period of time". *(SAFE4)*

Historical analysis of safety data can be resulted in number of valuable features, which can be very useful for performing risk assessment and formulating risk mitigating strategies (Casal & Darbra 2013)). Numerous researchers have used multiple methodologies to determine accident probabilities using historical data (Bilir & Gürcanli 2018; Jannadi & Almishari 2003; Jocelyn, Chinniah & Ouali 2016; Lee & Halpin 2003; Nowobilski & Hoła 2022). However, some interviewees argued about the possibility of assigning a probability value for a particular hazard. These values could be precise for a system or for a plant. But applying these figures in the construction industry which has a dynamic environment may not be successful to assess the risk of hazards as in other industries.

> "It is impossible to give a numerical value as the probability of a particular hazard. Probability of hazards depends on various external conditions that present during the execution of an activity. Predetermined probability values do not represent those conditions. Thus, using quantitative method for risk assessment during JHA process wouldn't give much valuable input for decision making". *(SUP3)*

Determining severity of hazards is less problematic compared to determining probability or likelihood (Leveson 2015). Hazards that arise during a job vary based on the executing method and material or component associated with that particular job. When material or component and the executing method of the job step is known it is easier to determine the severity of hazards. Therefore, if it is possible to define a job step using the execution method and material or component associated, a severity value can be easily assigned to the hazards. As mentioned by interviewees if all the external conditions that presents at the working environment keep unchanged and workers are competent, the risk level of hazards won't change for a job step if it is executed using the same method and material or component. This revealed a relationship between the severity and the nature of the activity.

4.1.2 Residual risk analysis

Risk is expected to be remained even after implementing risk mitigating strategies. Thus, complete elimination of risk from the workplace is hard to achieve. Since risk can be mitigated by either controlling severity or probability, control measures can be broadly divided into two main categories. When it comes to the phase where JHA process is undertaken the control measures that are aimed to control the severity have already been implemented. Because the execution method and material are finalised at the early stages of risk management process. Therefore, at the moment of performing JHA, it’s all about dealing with probability of hazards.

> “Out of the five hierarchies of controls, elimination and substitution are implemented at the early stages of risk management process. Elimination and substitution of hazards is achieved by changing the executing method or materials. When it comes to the JHA stage, it may not be cost effective to implement those control measures.” *(SAFE5)*

Lower four rungs of the hierarchy of control: isolation, engineering controls, administrative controls, and Personal Protective Equipment (PPE) are used to control the probability of hazards. Isolation, engineering controls and PPE reduce exposure to hazard and thereby control the probability. Administrative controls help to regulate the behaviour of worker to reduce the probability of occurrence of hazards. During the assessment of residual risk, impact of each of these control measures in terms of controlling the probability, has to be taken into the consideration. Interviewees also flagged the importance being knowing the emergence of new hazards as a result of implementing risk mitigating practices. Sometimes hazards that were not originally identified during the hazard identification stage can become aggravating condition due to the execution of risk control measures.

4.1.3 Concepts and their relationships in the JHA ontology

Through the analysis of data collected from the first and second rounds of the expert interviews, concepts and the relationships for the JHA ontology were determined. In order to enable automatic reasoning over the represented JHA knowledge, concepts and relationships were categorised into distinct types and this created the foundation for the semantics of the JHA ontology. Using these data semantic rules were developed to enable the automatic risk evaluation of hazards over the external factors. Thus, each and every concept and the relationship in the JHA ontology support two inference mechanisms; “type inference” and “rule-based inference”. Table 2 shows the list of relationships and the main concepts of the JHA ontology. All together these concepts and the relationships represent the main elements of the schema of JHA ontology which will later become the blueprint of the Knowledge Graph for JHA process.

Table 2. Relationships and concepts of the JHA ontology

No	Relationships	Associated concepts	Denotation
1	1A. primary_hazards_relationship	job_step, primary_hazards	These relationships exist between causes of hazards and hazards
	1B. workplace_hazards_relationship	workplace, workplace_hazards	
	1C. weather_hazards_relationship	weather, weather_hazards	
	1D. proximity_hazards_relationship	proximity, proximity_hazards	
	1E. atmospheric_hazards_relationship	atmosphere, atmospheric_hazards	
2	2A. primary_hazards_cm	primary_hazards, cm_ph	These relationships exist between hazards and their control measures
	2B. workplace_hazards_cm	workplace_hazards, cm_wph	
	2C. weather_hazards_cm	weather_hazards, cm_weh	

	2D. proximity_hazards_cm	proximity_hazards, cm_proh	
	2E. atmospheric_hazards_ cm	atmospheric_hazards, cm_ath	
3	3A. high_risk_relationship_wp	primary_hazards, workplace	High risk relationships exist between primary hazards and risk increasing external conditions to demonstrate the increased risk situations
	3B. high_risk_relationship_we	primary_hazards, weather	
	3C. high_risk_relationship_pro	primary_hazards, proximity	
	3D. high_risk_relationship_atm	primary_hazards, atmosphere	

4.2 Benefits of automated JHA

Each construction project is unique, due to the continuously changing nature of work activities, labour force and work environments. Therefore, JHA need to be conducted not just at the commencement of an activity but every time when a risk influencing external factor changes. Moreover, safety personnel identify JHA as a challenging task due to its labour intensive, complex and time-consuming nature. This makes it hard to quickly respond to the changes in the construction plans while maintaining the appropriate safety standards. Thus, a computer-based system could assist the safety personnel to execute the JHA process in a timely and accurate manner. Risk of construction hazards depends on numerous factors. Therefore, person who conduct JHA must consider many variables for each hazard in order to assess its risk. This makes the process more complex and time consuming. Consequently, there is a great chance for analysts to obliterate some important variables. Moreover, inaccurate risk analysis could lead to implement unnecessary control measures which could become a cost to the builder. Further, assessment of risk highly depends on the knowledge of the personals who perform it. Consequently, the process could be biased and inaccurate. A computer-based system would allow the analysts to largely incorporate historical data into the JHA process and to reduce the bias during risk analysis. Construction sector progressively becoming sustainable and because of that, organisations try to minimise the paperwork. With the recurrent nature of JHA process the involvement of paperwork is considerably high. Thus, a computer based JHA process could assist the creation and storing ability of JHA documents and reduce the paper waste largely. Interviewees also said that a computer-based system would attract the analysts and they may be more interested to engage in a computerised JHA process rather than in a paper-based system.

4.3 Drawbacks of automated JHA

Even though a computer based JHA process is developed with the hopes to increase its efficiency, it has some drawbacks as well. Traditional JHA process encourage worker participation and it is vital for the quality of JHA process. By incorporating the workers in the JHA process, they get a chance to share their valuable knowledge and promote greater ownership of the decisions taken. Further, it also enhances safety communication between workers and managers. Computer-based JHA process do not encourage worker participation in the process as traditional process and reduces situational awareness of workers. As construction can happen at anywhere in the world, there can be situations where the analysts have no access to the internet. This could limit the development of JHA documents and sharing it with workers. Since the risk analysis of the JHA process depend on numerous variables and the relationships are complicated, it is impossible to automate the entire JHA process. Thus, the analysts still have to put some effort to the process. Work health and safety standards change regularly. Thus, the computer-based system may need to update quite frequently in order to incorporate these new changes. Computer-based applications could force its users to rely too much on technology. Since JHA process is responsible for the safety of workers during the entire activity, possible inaccuracies could be ended as to injuries or accidents.

5 Conclusion and Further Research

Traditional JHA process has its own limitations due to lack of computer integration in the process. With the dynamic nature of construction industry, manual execution of each and every step make it harder to conduct necessary updates in the process. Considering this inherent drawback in the process, this research aimed to develop an automated method to execute the JHA process. An ontology-based method was adopted to achieve the aim of research. The developed JHA ontology covers comprehensive domain knowledge by incorporating codes of practice documents and previous JHA documents. Moreover, the integration of implicit knowledge of safety personnel, resulted in emergence of new concepts and relationships which facilitated the risk evaluation of hazards. During subsequent stages of the research, a Knowledge Graph will be developed on top of this JHA ontology and will be validated through case studies. As limitations, the proposed JHA ontology can only perform risk evaluation to the hazards that arise through the execution of the activity. No risk evaluation could be performed for hazards that arise from external conditions. Moreover, no residual risk evaluation is performed for the hazards after the implementation of suggested control measures. However, the system will still provide all the necessary information for analysts to determine the residual risk level of hazards.

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