Designing a Knowledge-Based System to Facilitate the Process of Fall Risk Assessment in Construction

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Background

Globally, with an annual budget of $10 trillion, the construction industry corresponds to 13 percent of the gross domestic product (GDP) (Barbosa et al., 2017). It also offers more employment opportunities for many young individuals globally (International Labour Organization (ILO), 2017). Despite its benefits, the construction industry contributes to poor safety performance (Safe Work Australia, 2019). According to global accident rates, compared to other sectors, construction fatalities and injuries were higher (Sousa et al., 2014). In both developed and developing countries, fall from height (FFH) is a prominent cause of fatal accidents on construction sites. In India, the construction industry plays a key role in economic growth (Singh et al., 2021). Vigneshkumar et al. (2019) found that FFH accounts for 50% of overall construction accidents in India by analyzing accidents in the Indian construction sector during 2019-2020 using right to information (RTI) reports and local police records. Although the government has enacted several safety regulations and recommendations, fall accidents in Indian construction (Chellappa and Salve, 2018) and in other developing nations construction sector continue to rise at an alarming rate (Awwad et al., 2016).

Enhancing safety performance by preventing accidents is the current mantra in the construction industry worldwide (Zwetsloot et al., 2013). Hence, several approaches were proposed globally to prevent falls. Though such studies proposed different methods of fall prevention, they were either too complicated to put into practice or didn't offer a clear plan for enhancing construction safety performance (Sanni-Anibire et al., 2020). Hence, there is currently a shortage of practical approaches to improve construction safety performance. The industry most likely lacks a straightforward, comprehensive, and still successful method. This can be achieved by using a fall risk assessment (RA) method. "The most critical safety process in construction is RA, since if it fails, all other procedures are likely to fail" (Manuele, 2013). RA is a continuous holistic process at the core of construction safety planning and needs adequate planning, monitoring, and feedback (Celik and Gul, 2021). According to Bansal (2011), safety planning entails identifying and assessing potential safety risks associated with construction activities and drawing steps to control the risks via the RA process during the pre-construction phase. Considerable practical and theoretical knowledge is needed to execute the RA process (Ding et al., 2016). Nevertheless, RA faces significant challenges. For instance, RA heavily relies on the site members' experience. The fragmented nature of construction sites makes it difficult to draw on the expertise of different site members (Carter and Smith, 2006). Indeed, safety experts conduct the RA process based on their skills and safety knowledge, engineering drawings, standards, and regulations. (Chellappa et al., 2020). It is documented that such a process does not imitate real-life construction operations (Hadikusmo and Rowlinson, 2004; Ding et al., 2016). The conventional method of RA frequently fails to detect risks associated with an activity, either due to inadequate knowledge or a lack of time (Gadd et al., 2004), resulting in accidents (Albert et al., 2013).

According to Carter and Smith (2006), challenges in construction safety could be eliminated by incorporating knowledge management (KM) into safety planning. Hallowell (2012) stated that proper safety KM could improve the companies' ability to respond to safety challenges. According to Dong et al. (2018), safety knowledge is a justified belief that increases firms' ability to manage hazards to effectively attain an acceptable risk level. Some researchers (e.g., Mohammed et al., 2019) proposed different approaches to integrating KM into construction safety planning. Unfortunately, there has been limited research on KM and safety in construction because most construction firms limit the minimum enforcement of their safety efforts (Hallowell, 2012). Given the above, this study focused on integrating KM into the safety planning to facilitate the process of RA, focusing on preventing falls in the Indian construction industry.

Construction involves numerous tasks and trades. Due to time constraints, it was practically difficult to include all the trades in this study. Therefore, this research was presented in the context of traditional vertical formwork (wall and column). Formwork is used as a mould and shaped into desired dimensions for concrete tasks. Formwork used in construction often involves working at heights (Amrutha et al., 2014), and a high level of fall incidents are associated with its operations (López-Arquillos et al., 2014). It is evident from the literature that preventing falls during formwork operations through RA from a KM perspective is an uncharted area. Hence, the goal of this research work was to collect evidence to answer the following research questions:

1. How are safety KM strategies employed in construction companies during the fall RA process?
2. What are the challenges encountered during fall RA and what knowledge do the users require for fall RA?
3. How should safety knowledge be represented while developing a knowledge-based system to facilitate the RA process focusing on preventing falls during vertical formwork?
4. How effective is the proposed system to perform fall RA?

Aim and Objectives

This research study aims to design a safety knowledge-based system to facilitate the process of RA, focusing on preventing falls during vertical formwork in construction projects. The following objectives are set to achieve this aim:

- To identify the safety KM strategies employed by construction companies during the fall RA process
- To identify the challenges faced by the users during fall RA and understand the safety knowledge needed by them for fall RA
- To develop a knowledge-based system for representing safety knowledge by
    - Identifying the activities that pose the risk of falls in vertical formwork

    - Analyzing the fall trends in formwork operations
    - Capturing the safety knowledge of formwork activities for fall RA
    - Developing a system to store and reuse safety knowledge
- To test and evaluate the knowledge-based system by potential end-users

Methodology

A mixed-method approach was adopted, and the data collection and analysis were carried out in different stages to accomplish the research objectives.

First, to identify the safety KM strategies employed in construction companies during the fall RA process for fall prevention, interviews were conducted. Eight safety professionals (heads/managers) with relevant experience in the RA process in Indian construction were participated.

Face-to-face oral interviews were conducted. The interview guide had two sets of questions. The first set targets gathering background information from interviewees. The second set targeted to identify the KM trends in fall RA with questions: “Could you elaborate on the process of fall RA in construction? - How do you identify fall risks? How do you assess fall risks? How do you choose control measures to prevent falls? How is safety knowledge stored and re-used for fall prevention? What tools are used to store safety knowledge?”. These questions were asked to understand better the interviewees' profiles and organizations that adopt safety strategies. The duration of data collection was for three months (November 2019 to January 2020), with each session lasting approximately one hour.

To ensure the interview results, the research team again contacted the companies and requested to be a part of their safety meetings after the interviews. During safety meetings, research-related documents such as data sources used for fall RA, RA worksheets, and tools used to share data were shown to the researcher that companies use during fall RA. Using this method, the researcher took experts' input, verified the interviews, and added meaning to the definitions of safety KM in fall RA. This increases and ensures the validity of this study's results. The interview analysis was carried out by transcribing the recorded interviews and coding the transcripts to conclude the raw data gathered. The data was first transcribed and verified against audio recordings to make them ready for analysis. The researcher thoroughly examined the transcripts before beginning to interpret the data. Then, a thematic analysis was conducted to analyze interview data, facilitated by a Computer Assisted Qualitative Data Analysis Software (CAQDAS) known as ATLAS.ti.

To achieve the second objective, a mixed-method approach - interviews followed by surveys were adopted to collect data. Same as previous phase, the interview was conducted with the same individuals to identify the challenges faced by users and the safety knowledge required for fall RA. The researcher used an interview guide to conduct the interviews. There were two sets of questions in the interview guide. The first set targets gathering background information from interviewees. The second set targeted understanding the users' challenges during the fall RA process and their opinions to enhance it. Eight full interviews were conducted. The interviews lasted between 1 hr and 1.5 hrs. All interviews were tape-recorded with the interviewee's

permission and transcribed later. Over four weeks in March and April 2020, the interviews were conducted. The interview analysis was carried out by transcribing the recorded interviews and coding the transcripts in ATLAS.ti to conclude the raw data gathered.
Once the interview data was analyzed, the identified challenges and requirements were subject to a survey as a variable on a Five-point Likert Scale (1=Strongly Disagree to 5=Strongly Agree). There were 15 scale items (variables) derived from challenges and user requirements. A web survey was built on a specified site to collect participants' responses and made available to participants via LinkedIn. At the start of the questionnaire, a filtering question was added to ensure that the participants were experienced in the RA process. Based on experience, participants were requested to rank the challenges and requirements for improving the fall RA process. Over nine weeks between April and June 2020, 84 questionnaires were returned. Of these, 33 were discarded due to invalid or missing data given by respondents. As a result, the analysis was conducted using 51 valid responses. The response rate, in the end, was 60.71%. Internal consistency was checked among the variables. The mean statistics were employed to identify the most critical challenges faced by the users and their needs and compared them with interview results. A descriptive analysis was conducted on the usable returned survey using IBM SPSS Version 22.0.

Next, to develop a knowledge-based system, the activities that pose fall risks during formwork operations were identified through observation and surveys with construction practitioners. The field observation's main goal was to produce a preliminary list that would subsequently be validated in a survey by construction experts. Four projects in the southern part of India were visited for field observations. The projects ranged from Rs 50 crores to 150 crores in multi-story buildings. The formwork construction methods differed from one site to the other, while all projects entailed new construction. All projects used traditional form components, i.e., plywood. In total, the research team observed 192 working hours, resulting in the documentation of 12 different formwork activities, four of which pose a risk of falls. The observation phase was completed when no new activity was observed within stipulated working hours. It was considered that adequate repetition had been attained once this requirement was reached. A sample size of 8 industry experts currently employed in South India was invited in person by the researcher to participate in the survey with the list of four fall risk activities and descriptions. Three practitioners refused, and five accepted the invitation and agreed to participate. All the experts had more than five years of experience in construction and were engaged in formwork activities.

Then, the riskiest activities and fall trends in formwork were analyzed using the OSHA database. First, the database containing vertical formwork fall incidents information was to be identified. The data from OSHA Fatality and Catastrophe Investigation Summaries (FCIS) database was used first due to its reliable source. Some data were missing and not updated in the OSHA database after 2016. Hence, the documented reports from OSHA between 1995 and 2015 were used in this study to analyze and understand the fall trends, such as the severity of activities, the height of falls, and their causes in formwork activities. The accident reports were retrieved from the database using the keyword “concrete formwork.” Initially, 526 reports were found, and with a further filter using keywords such as “vertical formwork” and “fall from height”, 203 reports were retrieved from the database.

In five different criteria, the retrieved data are summarized: (1) injuries severity, (2) the activity of the formwork being carried out at the time of the occurrence, (3) trade workers involved in each activity when the fall occurred, (4) height of fall, and (5) causes of fall. Based on the severity level set forth by Dharmapalan (2011), the severity of the incident was classified. Dharmapalan (2011) established four severity levels: Near miss: no injuries; low severity: temporary pain; medium severity: results in medical action; and high severity: fatality or permanent disability. Based on studies conducted by Amrutha et al. (2014) and Hallowell (2008), the formwork activities that pose the risk of falls, the formwork activities are classified, namely assembly, erection, concrete pouring, and stripping.

A Delphi research technique was adopted to capture the safety knowledge for fall RA associated with four formwork activities. The researchers employed a three-step method to select a highly qualified panel of experts for the current study. The selection of participants relied on each participant's job and position within their firm regarding human resources management and their education, profession, and engagement in the industry. The only individual who worked and was in India during the study period was selected for participation. Following a thorough search for suitable participation, a list of 53 experts was produced. The researchers contacted the 53 individuals who had been identified, explained the study to them, and invited them to participate. Twenty-four of the 53 participants volunteered to join the panel if they were judged to be qualified experts.

Second, an email was sent to the 24 individuals interested in participating in the study. The email requested information on their qualifications, education, and work experience, among many other items. The goal of gathering this information was to decide if the individuals were qualified to participate on the panel as experts. For this purpose, Hallowell and Gambatese’s (2010) point-system qualification approach was used. The qualification point-system process includes criteria for the year of professional experience, educational background, professional registration, committee membership, research publications, and overall contributions to the profession, all of which are used to decide whether an individual is a construction expert. According to previous researchers' recommendations (e.g., Lopez-Arquillos et al., 2014), if an individual scores 11 points or more across multiple criteria, they are supposed to be an expert. Out of the 24 people who initially expressed an interest in participating in the study, the information was provided by 16 (66.67%) relating to the qualification criteria. All participants scored more than 11 points after gathering and evaluating the information provided and were thus regarded as qualified experts. A panel of 16 experts was within the recommended range indicated by prior studies (Karakhan et al., 2021).

As part of the Delphi process, a questionnaire was created as the data collection tool. The experts were given access to a web survey produced on a specific site to collect expert responses. Four rounds of questionnaires were used, and the panelists were unaware of the identities of the other panelists. The research team managed the survey independently and preserved confidentiality throughout the procedure.

The panelists were asked to indicate the causes of falls and the population at risk during formwork activities in the first round of the Delphi process to analyze and improve workplace safety. All indicated causes of falls and population risks were given to the panelists during the second round. They were asked if they agreed that the causes of falls and the population at risk stated in the first round were essential constructs for RA. The panelists were asked to weigh the probability and severity levels using the previously provided scales in the third round. In the fourth round, the panelists were asked to list each activity's fall risk control measures to prevent falls in the construction workplace.

The data were merged to achieve these objectives with each activity. The overall data from this study were combined for each activity using MS Excel to give a fall RA worksheet for vertical formwork to prevent falls at the site. The Delphi results were validated through face, construct, empirical, and external techniques to examine the goal of determining the degree to which the findings are relevant to reality.

Following the safety knowledge acquisition of vertical formwork for fall RA from experts, the safety knowledge for vertical formwork was also captured through document analysis to identify best safety practices for formwork operations. Working at height regulations, guidelines in India and other published articles internationally related to formwork operations were rigorously examined. These include the Factories act, 1948 (GOI, 2017), Guide to the Safety, Health and Welfare at Work (General Application) Regulations 2007, part 4: Work at Height (HSE, 2008), Industry Guide for Formwork (Safework, 2012), and Guide to Safety Procedures for Vertical Concrete Formwork (SSFI, 2016), Hallowell and Gambatese (2009), Amruta et al. (2014), López-Arquillos et al. (2014), and Barbosa et al., (2014).

A prototype was developed by using a content management system (CMS). Justinmind was used to create a prototype of the proposed fall RA system. The prototype was named SAFEFORM and its usability was evaluated utilizing the cognitive walkthrough (CW) evaluation method at construction companies in southern India. Five evaluators were selected from different educational backgrounds through random sampling. The evaluators have included two junior safety engineers, one graphic designer, one project engineer, and one construction engineering and management faculty with an average experience of 6.4 in years. The evaluators had a 1-hour session to determine the usability problems in SAFEFORM. Using the SAFEFORM user interface, the evaluators individually conducted tasks sequentially to perform the evaluation. Therefore, based on users' experience, evaluators put themselves in real users' positions. If a problem emerged after a task was completed, evaluators were allowed to report back from the users' perspective. As an observer, the researcher was present next to the evaluators during the evaluation period and made notes on the evaluators' comments, queries, understanding of the exact location of usability problems in SAFEFORM, and detailed explanations of usability problems. After completing the evaluation procedure, assessors evaluated their lists and, if necessary, updated or revised a comment.

Based on evaluators feedback, the interface design of the prototype was improved, and a web-based KM system was developed using PHP language programming. Then, to accomplish the last objective, the evaluation exercise was conducted through a survey with 20 potential end-users with experience in construction safety.

A demonstration of a live presentation to potential end-users would benefit the proposed systems' features and functionality. Next, they would be asked to fill out a questionnaire in which they would be able to express their thoughts on various systems aspects. It is noteworthy to mention that out of eight individuals who participated during the interview phase, five validated the proposed system. There were four sections to the questionnaire. The participant's information was gathered in section 1. The effectiveness of the system was evaluated in section 2. System benefits and organizational learning were examined in section 3. Finally, section 4 attempts to evaluate how the proposed knowledge-based system could help address the challenges faced by the users during fall RA.

Results and discussion

For the first objective, the data collected was represented in word tables, which helped identify the KM strategies across construction firms. The findings demonstrate that systematic safety KM was not commonly applied in construction firms. It was found that most organizations found an ineffective KM system for managing safety knowledge, especially tacit knowledge. Legislation and regulations were the primary explicit knowledge gained by organizations. Contracting organizations were responsible for developing their safety plans and safety management systems. In most companies, such methods were prepared by explicit knowledge sources such as accident reports, regulations, etc. For instance, some interviewees stated that the safety head conducted fall RA for any new project using the company's safety work method statement. Based on their experience, they choose the risk levels and control measures for any activities. This result relates with the past study conducted by Hadikusumo and Rowlinson (2004) that safety experts carry out the RA based on their own experiences with sources such as regulations and standards, which could not be adequate to prevent safety risks (Dong et al., 2018). Usually, tacit knowledge is held in an individual's mind, and transferring it to other employees in the organization is quite difficult. Effective safety KM could improve the organization's safety performance (Hallowell, 2012). According to Hon and Chan (2014), construction practitioners (i.e., site engineers or managers) have the potential to recognize possible safety risks in the projects that will arise. However, there was no systematic method to capture the knowledge from site professionals. More often, site professionals are not loaded with site safety jobs. Other aspects of the project have to be addressed by site professionals. They cannot allot time to share tacit knowledge because of the tight project schedule. However, they are individuals with excellent knowledge of project safety to share.

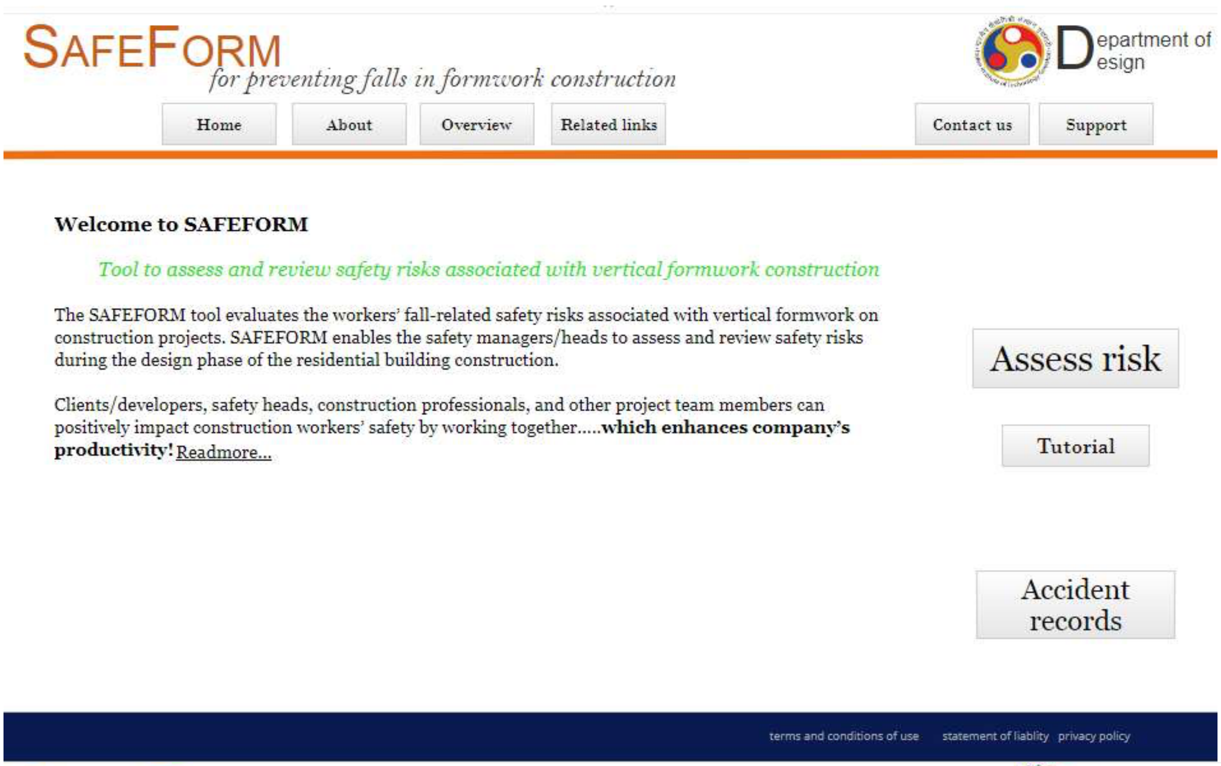
Another key finding was that safety KM strategies should be implemented effectively and constantly applied across the firms and should contain various elements that support capturing, storing, and transferring. During safety storage, the elements that the interviewed companies typically ignored were tacit knowledge. It was recognized that continuous improvement requires effective safety knowledge storage and that even if knowledgeable employees leave the company, the safety knowledge can be transferred to new employees. Tacit knowledge is essential in height work operations due to unexpected height works. ICTs have been used in construction projects to manage safety knowledge effectively (Hadikusumo and Rowlinson, 2004); however, such technologies are not widely designed for specific activities (Hon and Chan, 2014). Therefore, there is a need to design an effective safety KM to manage safety knowledge for fall RA. But before implementing such strategies, it is essential to understand the challenges that safety heads/managers face during RA and how the safety knowledge should be represented to users to facilitate the entire process of fall RA.

In order to so, the second objective was set to understand the challenges faced by users during the fall RA process and their opinions on facilitating it. Using interviews and surveys, 15 variables were identified as the challenges faced by the users during RA (6 variables) and users' requirements to facilitate RA processes (9 variables). It was found that identifying significant hazards and the steps involved in each activity are the major challenges users face during RA, which correlates with the results of Carter and Smith (2006). In most cases, users had to prepare RA with insufficient information about the activity. This is one of the major reasons that users could not address any significant hazards. Selecting appropriate control measures for risks was also one of the users' challenges. Safety professionals do not have experience handling site activities compared to site professionals and, thus are unaware of the risks involved in construction activities (Chellappa et al., 2020). The result also indicates that the risk evaluation scoring system was challenging to understand and perform. This is because different companies follow different risk scoring systems. It was also evident from the survey results that users face challenges when they work with insufficient data and time. One interviewee reported that they were supposed to conduct RA with insufficient technical data provided by the engineering team. During this stage, users had to conduct RA based on their experience, which is hard to list the potential hazards and preventive measures.

To facilitate the process of fall RA, users' requirements were gathered. The findings show that adequate technical details about a particular activity, such as a list of activities, causes of accidents, control measures, safety guidelines, past accident records, and safety practices-case studies, could facilitate the process of RA. The results also indicated that users were looking for some online system where they could access and share safety knowledge for RA. It could be either a closed system where only company employees can access it or an open system where anyone can access it. Therefore, it is evident from this phase that adopting an online system involving technical details on particular activity with a simple risk rating system that contains practitioners' safety knowledge could facilitate the RA process. However, it is essential to understand how safety knowledge of particular activity should be represented in an online system before proposing it.

To achieve this, the next phase was aimed to design a knowledge-based system to represent safety knowledge for fall RA focused on vertical formwork activities. First, the activities that pose fall risks during formwork operations were identified through observation and surveys. The results indicated that panel assembly, erection, concreting pouring, and stripping are the four activities that pose a risk of falls during vertical formwork operations. Then, the riskiest activities

and fall trends in formwork were analyzed using the OSHA database. Followed by the knowledge of formwork for fall RA was captured from construction experts through the Delphi survey. The findings show that panel erection and stripping were the high-risk activities related to falls and in terms of individuals, carpenters and laborers were at high risk of falls. Best safety practices for formwork operations were also captured through thorough document analysis. The captured knowledge was combined for each activity in MS Excel, and a framework was developed to store and re-use the knowledge. Then, based on the framework, a prototype was developed using CMS, and its interface design was evaluated
through CW. Based on experts' feedback, the prototype's interface design was improved, and a web-based KM system was developed using PHP language programming.



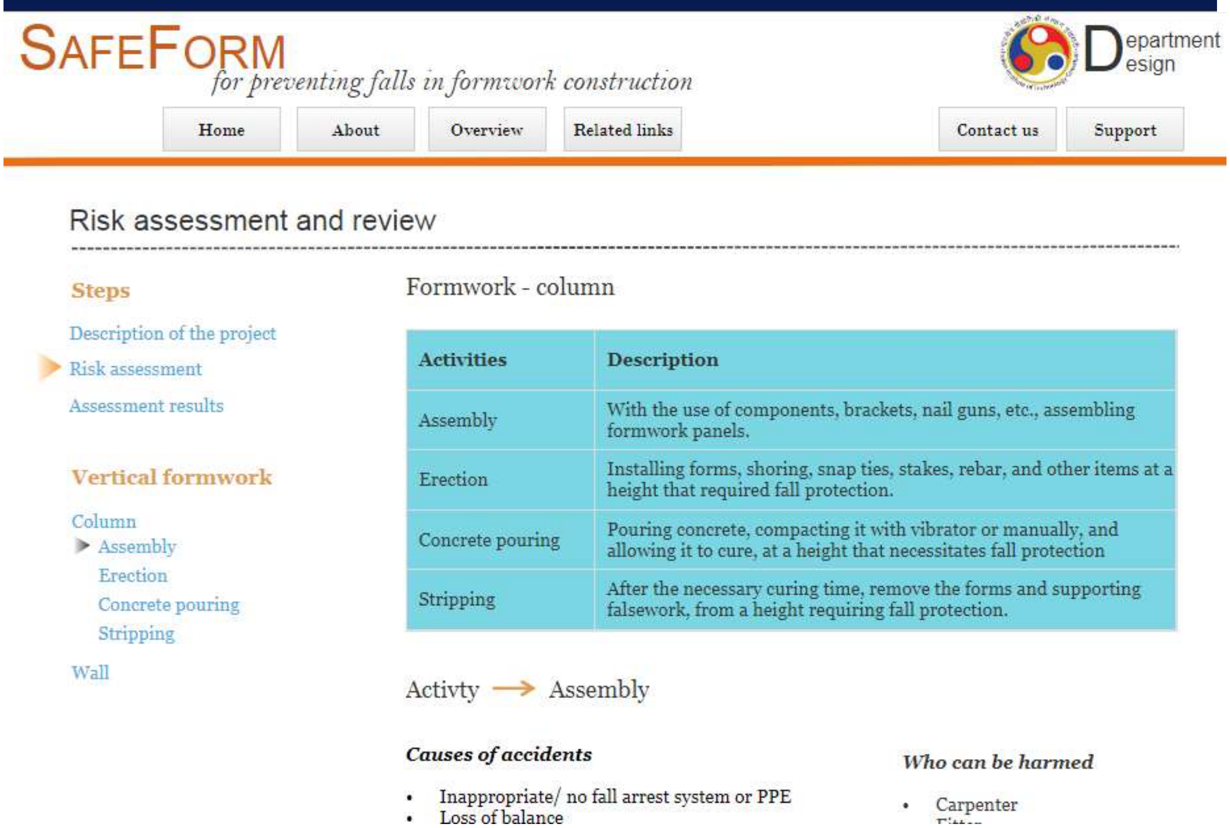
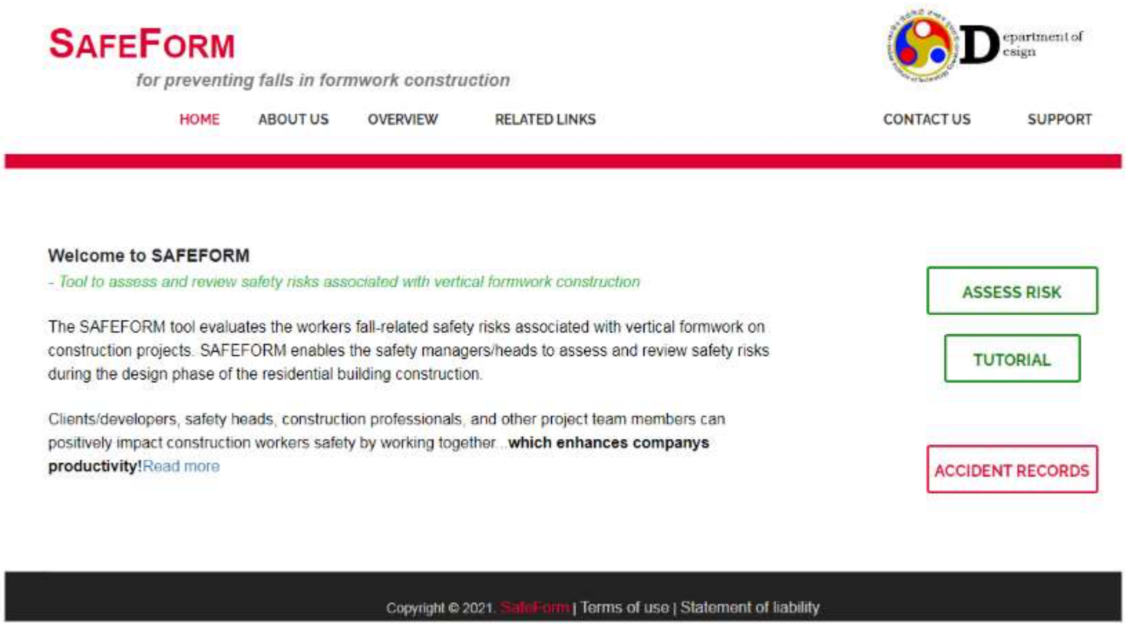


Figure 1. Front-end of the prototype
Figure 2. The back-end of the prototype



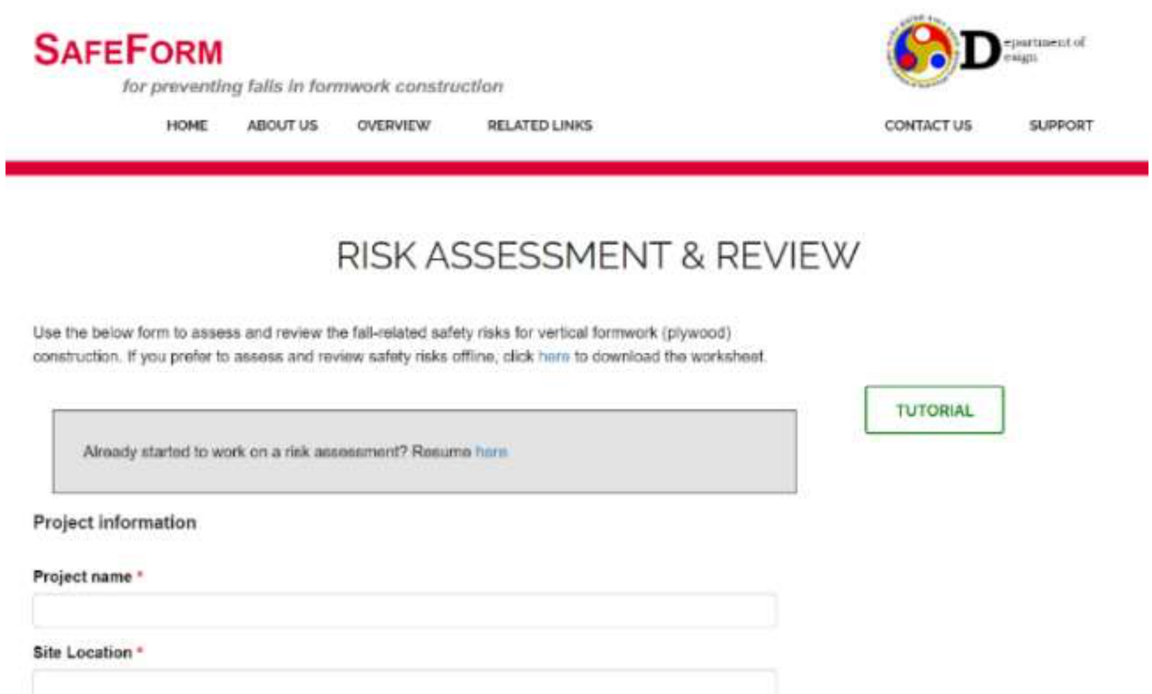
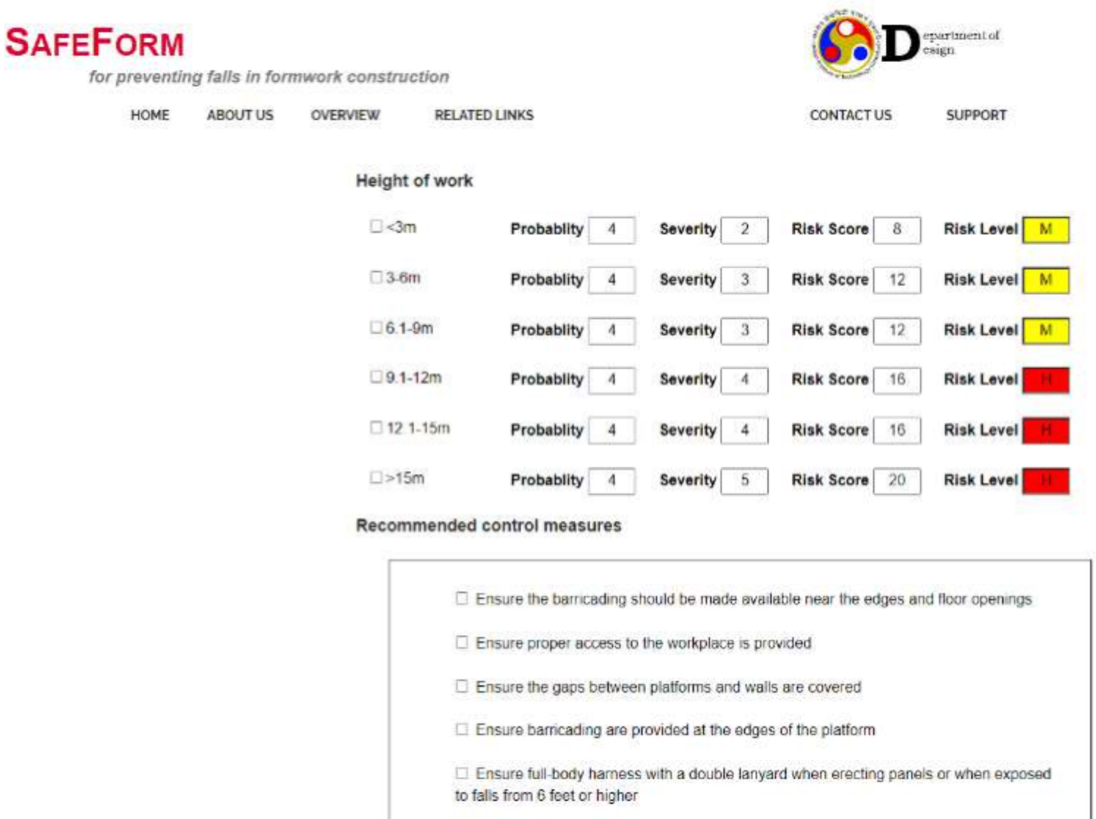


Figure 3. Front-end of the knowledge-based system
Figure 4. The page display of fall RA



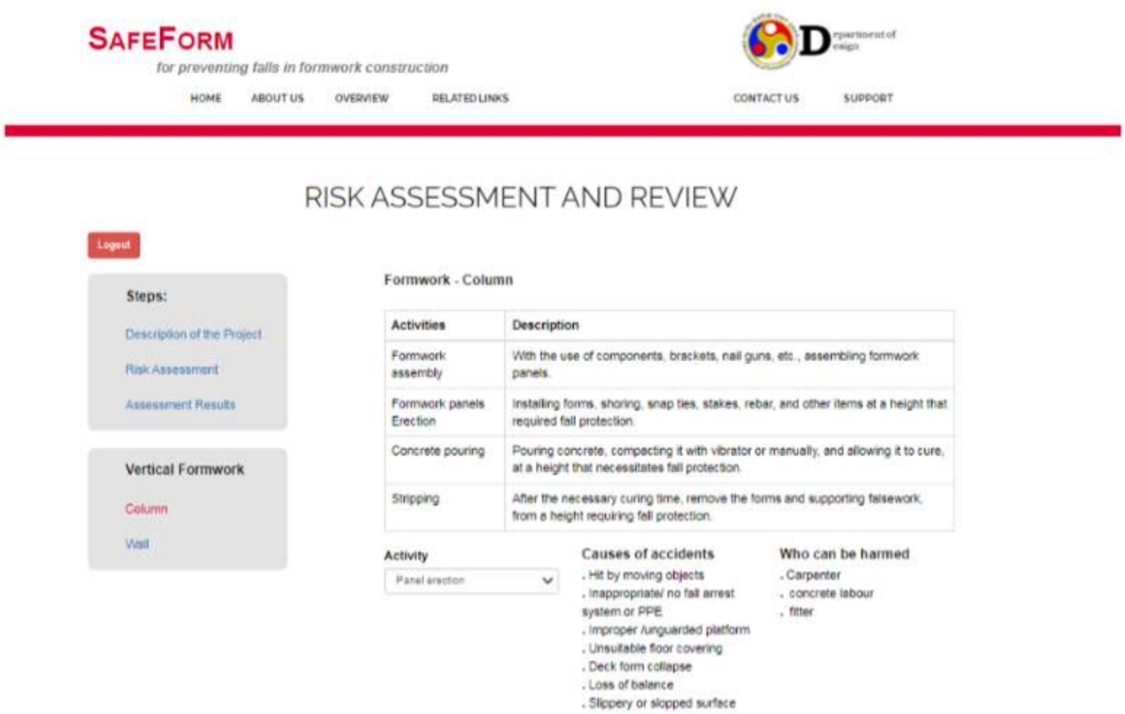


Figure 5. The page display of trade (column) for vertical formwork activities
Figure 6. The page display of risks scores and control measures for panel erection

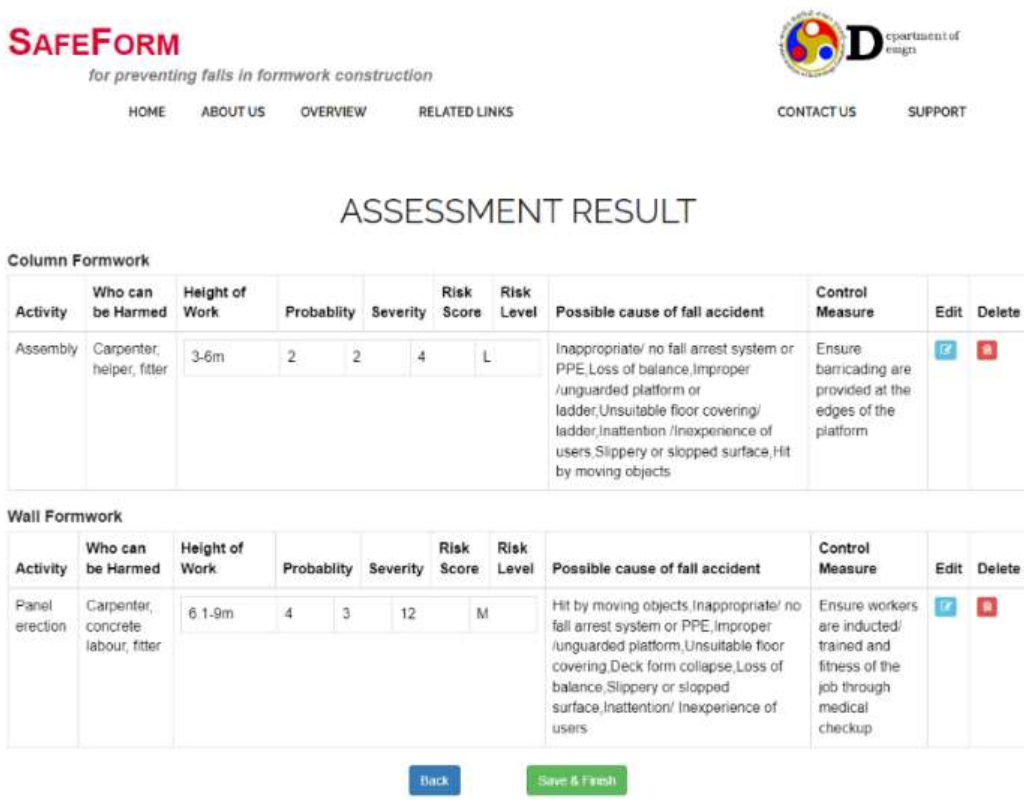


Figure 7. The page display of fall RA results

Evaluation of the final knowledge-based system was conducted through a survey with 20 potential end-users who had experience in RA in Indian construction projects. The respondents were asked to rate the system based on three criteria: features, benefits, and challenges, using dichotomous variables. The statistical analysis of the responses revealed that the raters' inter-reliability was rather high. Based on the findings, it can be determined that the proposed system offers numerous benefits to builders in (1) ensuring that end-users, regardless of their site location, have easy access to vertical formwork safety knowledge; (2) helping users with job site learning of safety RA skills; (3) effectively sharing safety knowledge; (4) facilitating the fall RA process on-the-job for safety heads; (5) helping to improve safety performance; (6) saving time that is spent on RA, and (7) assisting in developing better fall prevention plans.

Impact

The proposed system has several impacts as follows:

1. Reduces the time taken to complete the fall RA in construction projects.

2. Easy access and effective to acquire and share safety knowledge related to formwork activities. 3. Expected to reduce work loss at construction sites and project delays.

4. Expected to reduce financial damages to individuals and society caused by accidents.

Limitations and future scope

This study includes several limitations. First, the proposed system focused on traditional vertical formwork (i.e., plywood) in the context of residential building projects in India. Second, the study targets fall risk activities involved in vertical formwork in construction, and the study findings focused on the RA process to prevent them in Indian construction projects. Next, the proposed system focused only on the end-users, i.e., safety heads/managers of construction projects involved in the RA process. Finally, the safety knowledge of vertical formwork activities represented in the proposed system was designed in a static way.

Although this research work developed a knowledge-based system for preventing falls in Indian construction organizations, it could be applied in a similar context in other countries to increase its usefulness and enhance the performance of overall construction safety worldwide. Also, safety knowledge of other formwork activities, such as slab or beam focusing on FFH and other formwork materials, including aluminum and steel, could be incorporated into this system to develop a systematic RA tool for formwork operations targeting falls in construction. Such a system should be evaluated against the real-life environment to enhance the overall safety performance of formwork operations in India and other countries with similar environment.

Most important reference

• Hallowell, M. R., and Gambatese, J. A. 2008. "Quantification and communication of construction safety risk." In Proc., 2008 Working Commission on Safety and Health on Construction Sites Annual Conf., 572- 584, Gainesville: International Council for Research and Innovation in Building and Construction.