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Prevention through design and construction safety management strategies for high performance sustainable building construction

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Recent studies have found that Leadership in Energy and Environmental Design (LEED) buildings have a higher injury rate than traditional non-LEED buildings and that 12 of the LEED credits increase risks for construction workers. The objective was to identify and describe risk mitigation strategies that reduce the safety risk associated with the design and construction of high performance sustainable projects by conducting extensive interviews with experienced designers and constructors. Fortunately, feasible prevention techniques through design and construction safety management strategies exist and can be used to mitigate the safety risk associated with the design features and means and methods of construction used to achieve LEED certification. Most commonly, designers and contractors identified prefabrication, effective site layout and alternative products as methods to prevent injuries that specifically relate to the hazards of each sustainable element. The results of the interviews and results from previous research were organized into a decision support tool built in Adobe LiveCycle. Practitioners may use the findings and the tool to enhance safety for construction workers, an aspect of sustainability that is not currently addressed in the LEED Program. Researchers may also use the techniques described as a starting point for lifecycle safety analyses for sustainable buildings.

Keywords: Safety, sustainability, design for safety, LEED.

Introduction

The rate of occupational fatalities in the construction sector is disproportionate relative to the number of employees in the industry. In 2010, the US construction industry consisted of 7% of the workforce but accounted for 22% of all work-related injuries in the US. The Bureau of Labor Statistics (2010) stated that workers in construction incur more fatal injuries than any industry in the private sector. Furthermore, a report from the Center for Construction Research and Training (2007) has shown that: construction accounts for 21% of all fatal work injuries; construction workers experienced 135 350 injuries and illnesses; there are over 1100 fatalities in the industry; and the overall recordable injury rate is 190 per 10 000 employees.

Though the US construction industry's injury rate has improved following the inception of the Occupational Safety and Health Act of 1970, improvement has decelerated over the past 10 years (Bureau of Labor Statistics, 2010). There are significant concerns that high performance sustainable building construction involves higher risk work environments that are not being properly managed or controlled. In fact, Rajendran *et al.* (2009) recently found suggestive evidence that Leadership in Energy and Environmental Design (LEED) certified buildings have a recordable injury rate that is 9% higher than traditional, non-LEED projects using case studies and statistical tests of empirical data. In a follow-up study, Fortunato *et al.* (2011) conducted case studies to compare LEED and traditional building strategies and found that workers on LEED projects tend to have more work at height, in trenches and excavations, and near energized electrical systems. Additionally, workers enter unfamiliar, high-risk work environments when installing vegetated roofs,

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photovoltaic (PV) panels, atria, skylights, or enter dumpsters to retrieve recyclable materials. Managing and controlling these hazardous work environments will become even more important as the number of projects involving construction of high performance sustainable buildings continues to grow.

Increased adoption of the US Green Building Council's (USGBC's) LEED Green Building Rating System for new construction is an emerging trend in the construction industry. Since its inception in 1998, LEED has grown to encompass more than 14 000 projects covering 3.6 billion square feet of developed space (United States Green Building Council, 2009a). In the next decade, the USGBC expects that approximately 10% of commercial construction starts will be LEED certified and the value of green building construction projects is expected to increase to $60 billion (United States Green Building Council, 2009a). Though this rapid growth is exciting, the architecture, engineering and construction (AEC) industry must identify and implement design interventions and construction management strategies that mitigate LEED safety risks. The importance of safety considerations for sustainable projects has recently been highlighted by the National Institute of Occupational Safety and Health's (2011) 'Green, Safe, and Healthy Jobs' initiative, which focuses on ensuring that safety and health are not overlooked as components of environmental and social sustainability.

Managing construction hazards has long been viewed as an essential component of effective project management. According to a recent Delphi study, preventing injuries can be achieved by hundreds, if not thousands, of different strategies (Rajendran and Gambatese, 2009). However, several researchers have identified the 'essential' elements of an effective safety programme such as worker orientation and training, project-specific safety plans, substance abuse programmes, recordkeeping, and employee involvement in safety management and planning (Liska, 1993; Jasleskis *et al.*, 1996; Hinze, 2006; Hallowell and Gambatese, 2009; Rajendran and Gambatese, 2009). Among these strategies prevention through design (PtD) is regarded as one of the most effective. In order to facilitate adoption of this technique, Gambatese *et al.* (1997) developed a tool for designers that provides design suggestions that improve the ability of workers to construct the design elements safely. Unfortunately, this tool was created before green building became common and, therefore, does not include design suggestions for sustainable design features.

The research objective was to identify and describe risk mitigation strategies that reduce the safety risk associated with the design and construction of high performance sustainable projects by conducting extensive interviews with experienced designers and constructors. This original contribution explores new avenues in the area of safety and sustainability because it is the first comprehensive analysis of injury prevention for sustainable buildings. Because the focus is on the welfare of the construction workers who have traditionally been ignored in the definition of a 'sustainable building', it also introduces the concept of social sustainability as a component of the delivery of these projects. Thus, the findings can be used as a foundation for researchers who analyse multidimensional sustainability and practitioners who wish to adopt a lifecycle approach to sustainability that includes the welfare of construction workers. For example, the findings can also be used to integrate with the LEED rating system as requisite strategies for LEED certification.

Because LEED is the most common and most standard method of certifying sustainable projects, the LEED credit system was used to develop the research framework. Also, special attention was paid to methods of risk mitigation that can be incorporated into design because (1) many of the risks identified by previous researchers were directly connected to specific design features; and (2) PtD has been shown to be a very effective injury prevention strategy because it occurs early in the project development process. Once the new knowledge was created, the results, along with data from previous studies, were organized into a decision support tool that facilitates integration of the findings with design and safety planning.

Literature review

In order to develop context for the study and effectively structure the research framework, literature related to sustainable building design and construction, the relationship between these projects and safety, and effective methods of injury prevention is reviewed.

High performance sustainable buildings

The USGBC was formed to promote the construction of buildings that are environmentally responsible, profitable and healthy (United States Green Building Council, 2009b). The USGBC developed a green building rating system called LEED, which was first introduced for new construction in 1998. This system is a voluntary consensus-based US national standard used to develop high performance sustainable buildings. The LEED rating system was developed through an open consensus-based process that included a diverse group of practitioners and experts from the building and construction industry. The most commonly used of the nine different versions of LEED is the LEED-NC for new construction, a credit-based system with 69 total possible credits in the following six categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, Indoor Environmental Quality, and Innovation in Design (United States Green Building Council, 2009b). LEED was used as the basis to measure and evaluate different green building initiatives as this is the most widely accepted green building accreditation programme in the US.

Green building's popularity has grown rapidly due to experts' perceptions of the benefits from decreased impact on the environment (Eicholtz *et al.*, 2008) and empirical data that show monetary savings through decreased utility costs (Fuerst and McAllister, 2008; Miller *et al.*, 2008). Though there are apparent benefits to the LEED Program, general contractors have explained that LEED projects tend to be more involved and can take extra time to complete (Schaufelberger and Cloud, 2009). Past research on green design has typically focused on the health of the final occupants and not the health and safety of the workers who build the facility. As Rajendran *et al.* (2009) argued, to be truly 'sustainable' a building's impact on the health and wellbeing of the public should be considered not only for the final occupants but also for the individuals that construct, operate, maintain and decommission the facility. Despite apparent benefits from building high performance sustainable buildings, these types of projects have also had enough safety-related accidents to raise concern.

LEED and safety

Several recent studies have been performed to investigate the relationship between the LEED certification and construction worker safety and health. These studies were prompted by Rajendran *et al.* (2009) who found moderate statistical evidence that the recordable injury rates are higher for LEED certified projects through analysis of empirical injury data and the Center for Construction Research and Training's (2008) case study of the Las Vegas City Center Project that found preliminary evidence that safety may be compromised when attempting to achieve LEED certification. Following this study, Rajendran and Gambatese (2009) developed a sustainable construction safety and health rating system to rate projects based on the level of safety management on the project. Recently, Fortunato *et al.* (2011) identified specific hazards that resulted from individual LEED credits using case studies of projects located in the US. Out of the 55 applicable credits (some were removed because they did not involve specific design features or construction methods) it was shown that 16 credits had an impact on construction worker safety and health when compared to traditional design and construction. Twelve of these credits involved additional hazards that increase safety risks, two *decrease* hazardous exposures, and two credits involved design elements or construction methods that had mixed impacts. Subsequently, Dewlaney *et al.* (2011) conducted interviews with experts to quantify the perceived increase or decrease in safety risks for the credits highlighted by Fortunato *et al.* (2011). These results are included in Table 1, which shows that the three credits with the greatest safety impacts are the heat island effect—roof, onsite renewable energy, and construction waste management. The results presented in Table 1 were the results of interviews with practising professionals and case studies on active projects. This table was organized by reference to the US Occupational Safety and Health Administration (OSHA) injury classification scheme and highlights the injury prevention classifications that were shown to have the highest incident rates. All other classifications in the OSHA system such as transportation incidents, caught-in, and struck-by were combined into one 'other' category. For more information on the data and the analysis techniques, refer to Dewlaney *et al.* (2011). The present study builds directly on this previous work.

Safety management strategies

Of all the parties involved in construction, contractors typically take the lead role in addressing worker safety and health (Rajendran and Gambatese, 2009). Though this is primarily due to the mandate of OSHA regulations, several studies have identified elements that are effective for safety programmes. Findley *et al.* (2004) reported various elements of an effective safety programme, including: a written, comprehensive safety and health programme; safety and health responsibility and accountability clearly established and implemented; employee involvement in design and operation of the safety and health programme; and frequent worksite inspections. Similarly, Hinze (2001) developed the following nine best management practices to make zero accidents realistic for contractors based on interviews with leading contractors: demonstrated management commitment; staffing for safety; safety planning; safety training and education; worker participation and involvement; recognition and awards; subcontractor management; injury reporting and investigations; and drug testing. Finally, Liska (1993) studied the practices of Construction Industry Institute members and found that pre-task

Table 1 Percentage increase in risk associated with LEED credits (after Dewlaney *et al.*, 2011)

	Risk classifications					
LEED credit	Falls to lower level %	Falls to same level %	Overexertion %	Exposure to harmful substances %	Other %	Total %
Brownfield redevelopment	0	0	0	4	8	12
Stormwater quality control	6	0	0	0	0	7
Heat island effect—roof	4	5	13	0	19	41
Innovative wastewater technologies	0	0	3	14	4	22
Optimize energy performance	9	9	0	1	4	22
Onsite renewable energy	24	9	3	0	2	37
Enhanced commissioning	0	0	0	0	11	11
Construction waste management	0	0	0	0	36	36
Outdoor air delivery monitoring	1	2	0	0	2	5
Construction IAQ management plan	5	10	1	–1	2	16
Low-emitting materials—adhesives/ sealants	0	0	0	–1	12	11
Indoor chemical and pollutant source control	0	7	1	0	6	14
Controllability of systems—lighting	2	8	0	0	1	10
Daylight and views	16	12	4	0	0	32
Total	67	60	24	16	107	

planning; safety orientation/training; safety incentives; alcohol and substance abuse programmes; and accident or near miss investigations are the most effective safety strategies. It should be noted that these studies are only a small sample of safety studies that have attempted to identify the most effective injury prevention techniques. Since the writers aim to identify PtD and safety management strategies for sustainable building elements, the discussion of general safety management methods will remain brief.

Prevention through design (PtD)

The technique of designing a facility in such a way that it is safe and healthy for construction workers to build goes by many names including designing for safety, safety constructability and prevention through design. The strategy typically involves identifying and mitigating hazards during the design phase by changing the design of the permanent structure so it is safer to build. According to experts, eliminating the hazard is far more effective than simply reducing the hazard or providing personal protective equipment to workers (Gambatese *et al.*, 2005).

There are many existing examples of how designers can improve construction site safety through the design process. One example is specification of higher parapet walls. Since designers tend to specify parapet walls that are relatively short in height, fall protection is still required by OSHA. If designers were to specify parapet walls to a height of 42′′ falls may be prevented. In an early publication, Gambatese *et al.* (1997) used interviews to identify over 100 such examples that can be reliably employed to remove hazardous work conditions and organized them into a user-friendly software system called the Design for Safety Toolbox. This tool was created before the hazards associated with LEED were identified; consequently, PtD strategies specific to LEED projects remain unidentified. More recently, Cameron and Hare (2008) used a group and individual interviews to develop seven tools for integrating health and safety across multiple phases of project development. These tools include: (1) a responsibility chart, (2) option evaluation chart, (3) workshops, (4) safety in plans, (5) red-yellow-green risk feedback, (6) health and safety milestones, and (7) design change protocols. Although these tools are likely to improve the delivery of high performance sustainable projects, none focused specific attention on sustainable building projects.

Using the Delphi method Behm (2005) confirmed that PtD is a viable strategy that can have a significant influence on construction safety. Through interviews with architects and engineers, this study found that a large percentage of design professionals are in fact interested in implementing the PtD practice in their design. The results from this initial study on the topic are indicative that this is a viable intervention for construction. These findings were validated by three studies. First, Atkinson and Westall (2010) found that increased safety communication during design was linked to strong safety performance using a combination of statistical analysis of empirical data and interviews. Second, Trigunarsyah (2007) analysed survey results and found a strong link between safety performance and safety consideration during design. Finally, the European Foundation for the Improvement of Living and Working Conditions (1991) found that, based on injury statistics, 60% of all fatal accidents on construction sites were related to decisions made prior to the construction phase.

Owing to several significant barriers such as fear of liability, lack of safety knowledge, and typical safety roles and responsibilities assigned by the Occupational Safety and Health Act of 1970, the PtD strategy has not diffused through the US architecture, engineering and construction industry. In fact, when designers were recently asked to rate the importance of six aspects of their design work, it was found that construction worker safety ranked the lowest behind quality, end user safety, cost, schedule and aesthetics (Gambatese *et al.*, 2005). Fortunately, the increased use of integrated project delivery (e.g. design-build) and owner representatives' recent interest in PtD is likely to increase the adoption of the strategy. The writers believe that the use of the technique will also increase during the design of high performance sustainable buildings as new knowledge of the hazards and viable design interventions improves.

Research contribution

After reviewing current literature, it was clear that there is a need to establish safety risk mitigation techniques for high performance and sustainable construction. Though researchers have identified the safety issues with the design techniques and construction methods implemented to achieve LEED certification, no research has been performed to identify potential mitigation strategies. The present study aims to address this gap in knowledge.

Research methods

In order to identify techniques for construction management and prevention through design that can be used to mitigate identified construction risks for high performance sustainable buildings, interviews were conducted with highly experienced design and construction professionals. Interviews were selected as the data collection method because (1) the research was highly exploratory because specific construction methods and design interventions have yet to be identified for sustainable building elements; (2) the interviewer could provide context by describing the hazards identified in previous research and ask follow-up questions and obtain rich responses; and (3) the data could be gathered in a relatively short timeframe with the resources available. Though the majority of the interviewees worked and resided in Colorado, all of the interviewees had completed projects outside the state.

It was of the utmost importance that the interviewees were highly experienced and had been involved as key members of the design or construction of several LEED certified projects. In total, 11 contractors, 13 designers, and two subcontractors were interviewed. The individuals selected for participation were highly qualified. On average, each interviewee had been involved in the design and/or construction of 103 traditional projects and four LEED certified projects and had 18 years of experience in the architecture, engineering and construction (AEC) industry. It was also important to ensure that the interviewees were not employed in a position where their input might be biased by their role. For example, during previous research, the writers have noticed that LEED professionals and safety professionals often have views that are biased towards their primary function, which can lead to invalid and unreliable results (Fortunato *et al.*, 2011). Thus, interviewees who were employed as superintendents, project managers and lead designers were targeted. Because such individuals have broad perspectives and are able to recognize the needs of multiple organizational functions, their suggested safety risk mitigation strategies are likely to be more viable. Furthermore, the findings should be applicable to a large base of LEED construction projects as the data collected were based on participants with extensive background on mostly large-scale projects.

The researcher opened each interview with a brief description of the objectives and the hazards associated with the 14 LEED credits under investigation that had been identified in past research. As previously indicated, the LEED rating system was used as a framework for the questionnaire because it is the most standard and commonly used sustainable building certification system. The scope was limited to the 14 credits that Fortunato *et al.* (2011) found *increase* safety risk when compared to traditional building design and construction. Once the context for the study had been established, interviewees were asked to identify construction management strategies and design interventions that could be implemented to mitigate the safety risk associated with specific hazards caused by the means and methods achieved to earn specific LEED credits. Interviewees were encouraged to identify both design and construction interventions rather than focus solely on the techniques that could be employed by their function. That is, contractors were asked to identify potential design interventions and vice versa. This strategy was employed to encourage innovative ideas and an integrated approach to safety. When interviewees were asked to identify construction interventions, they were instructed to focus on the *specific* strategies that can be used to mitigate the *specific* hazards previously identified (e.g. prefabrication of a specific component) rather than describe commonly used strategies that apply to construction in general (e.g. job hazard analyses, written safety plans, and employing a safety manager). Because each credit was addressed individually, the results can be applied not only to projects attempting to achieve LEED certification but to any project that incorporates the sustainable elements or practices encompassed in the 14 LEED credits. This is important because many local governments have sustainable building programmes that are unique to their geographic region.

Interviews were conducted in a structured fashion where the interviewer introduced a credit and its associated safety hazards, then solicited safety management strategies. Interviews were conducted until no new prevention through design or construction safety management strategies were identified. This replication was observed after 26 interviews. This strategy ensured that the results were complete, the process could be easily replicated by future researchers, and the results were both internally and externally valid.

Results

This results section describes the aggregate results obtained from the 26 interviews. The strategies identified are discussed credit-by-credit. It is expected that these strategies can be easily incorporated on site; however, some strategies may not be cost-effective for all projects. The hazards discussed for each credit are those identified by Fortunato *et al.* (2011) and Rajendran *et al.* (2009) and were confirmed and elaborated upon by the interviewees. For further reading on how designers and contractors can achieve LEED certification, refer to United States Green Building Council (2009b).

Brownfield redevelopment

Though this credit was not highlighted by previous researchers, many of the interviewees discussed health and safety hazards resulting from the construction activities required to develop brownfield sites. Interviewees felt that handling and disposing of contamination is a very hazardous activity because of exposure to harmful chemicals. Additionally, workers may be more likely to be exposed to fall, collapse and transportation hazards because of the extensive earthwork operations typically involved in removing subsurface contaminants. Interviewees noted that using impermeable plastic liners in the beds of heavy equipment and completely washing all equipment at the end of each workday could help prevent the spread of contamination throughout the worksite and would reduce exposure. Additionally, contractors may consider adding training and safety planning for construction tasks that involve chemicals and providing breathing apparatus and other personal protective equipment.

Stormwater quality control

Most commonly, detention ponds are used to achieve this credit, which have been found to increase the risk of falls due to increased excavation and trenching. Typically, these ponds will be constructed in the first phase of the project when several trades are working concurrently. The risk of falls due to detention pond excavation can be mitigated by designing the detention ponds without vertical cuts similar to a zero-entry pool (i.e. edge or entry that gradually slopes from the deck into the water in the manner of a natural beach), and by ensuring a proper slope to avoid steep embankments. During pre-construction planning, construction managers should avoid concurrent activities near the excavation during sequencing and site layout planning. For example, scheduling the excavation when there are fewer concurrent tasks can help to limit hazardous exposure. During construction, hazards should be identified, highlighted and described using a combination of flagging, barricades and signage.

Heat island effect–roof

The hazards associated with this credit are a result of using thermoplastic polyolefin (TPO) single-ply roofing membranes or other white roofing options rather than traditional black ethylene propylene diene monomer (EPDM) rubber roofing. TPO membrane material is slightly heavier and is more slippery than EPDM, which can increase overexertion injuries and falls. Additionally, TPO has been described as, 'blindingly bright' and causes eye strain and an increase in slips, trips and falls because of decreased visibility. First, these risks can be mitigated by specifying tan or light grey membranes. Though these alternative colours decrease the reflectivity of the materials, the solar reflectivity index required for certification can still be achieved. Second, during the fabrication process, TPO membranes could be designed to include a dull peel-off cover that could be prefabricated on to the TPO material to lessen the brightness and provide traction. Such a cover could be made of recyclable material and removed upon completion of roof work. Third, interviewees suggested that surfaces could be texturized to aid in traction and rubber walkpads could also be placed on the higher traffic areas for traction. To reduce the potential for eye strain, contractors can mandate tinted eyewear and provide signs at the entrance to the roof warning about brightness. Lastly, contractors can purchase a higher number of smaller rolls from the supplier, if available, to reduce the weight and, consequently, overexertion injuries. This strategy may increase the cost of the roofing materials and would likely require a design change on the part of the manufacturer. However, with an increase in customer demand, such products could become mainstream.

Innovative wastewater technologies

This credit can be earned through a variety of different design techniques including a dual wastewater system, purple piping or roof cisterns. Researchers found that there is an increase in the risk of working at heights and exposure to hazardous chemicals when constructing a dual wastewater system compared to a traditional single wastewater system because there is an increase in piping material handling and installation duration. Furthermore, workers may be exposed to chemicals used in the onsite filtration process. To mitigate these risks, the construction management plan can employ extensive quality control measures beyond the typical due diligence to monitor the additional installation and utilize prefabricated piping that can be pre-assembled to eliminate excessive connections. The time spent working with hazardous chemicals could be minimized by keeping the system isolated and contact with chemicals could be prevented by requiring non-polyester gloves and respiratory protection. The specifications drafted by the architect or owner may also include a requirement for the contractor's installer to have met certain training requirements with the related chemicals.

Optimize energy performance

Energy performance may be optimized by using energy-efficient window systems and mechanical systems, high efficiency heat wheels and exchangers, LED light fixtures, mechanical window shades, advanced automation systems and double caulking. For this credit, there is typically an increase in time required to install wire and controls, which increases the time spent on ladders. Interviewees suggested that designers could specify prefabricated panels of the exterior skin system, framing, structure and vapour barrier. This strategy would involve offsite fabrication and the use of a crane to place the panels during construction. Before implementing this design technique, however, it would be prudent to perform a comparative lifecycle risk analysis to ensure that using a crane would not actually increase safety risk. For the case of double caulking to improve energy performance, workers tend to spend more time on scaffolding and ladders. To reduce the amount of time spent at height, contractors may double joint and caulk from the interior of the building prior to installing finish materials.

Onsite renewable energy

Inclusion of onsite renewable energy most commonly involves installing photovoltaic (PV) panels or the infrastructure for the future installation of PV panels. The California Department of Public Health (2011) recently reported four fatalities associated with the installation of solar panels. When installing these components, workers face an increased exposure to falls because PV panels are often installed on the roof and an increased frequency of overexertion injuries because the panels are heavy and unwieldy. If possible, designers should consider locating the PV panels on the ground to protect both construction and maintenance workers from exposure to work at height. If the panels must be placed on the roof, they should be located as far from the edges, skylights and vegetation as possible. Additionally, panels that are pre-assembled (i.e. 'plug-and-place') may be specified as long as they are not cost prohibitive and are of a size and weight that can be easily placed with available workers and equipment. The use of higher parapet walls and designed tie-off points could also be considered to help reduce the risk of falls. Finally, as the sustainability market continues to flourish, photovoltaic panels have taken new forms such as being incorporated into the roof membrane, roof shingles, wall panels and windows. These new products should be considered during the design if there are apparent safety benefits to the construction or maintenance crews.

Enhanced commissioning

This credit can be achieved by beginning the commissioning process early in the design phase and executing additional activities after systems performance verification has been completed. These processes tend to involve personnel on site who are not familiar with construction means and methods or safety protocol. The presence of these individuals on site is distracting and has been shown to result in more frequent falls, strains, abrasions, and workers being struck by equipment or materials. To mitigate these risks, all commissioning agents should receive a site-specific orientation and obtain appropriate personal protective equipment. Interviewees also suggested that these agents pass an OSHA 10-hour course before being permitted on site. Finally, designers should optimize the access to mechanical, electrical and plumbing (MEP) equipment for inspections and maintenance.

Construction waste management

A LEED credit is awarded when contractors divert waste and demolition debris from disposal in landfills and incineration facilities by recycling materials and producing less waste. When material is being recycled, both Fortunato *et al.* (2011) and Rajendran *et al.* (2009) observed 'dumpster diving' where workers climb into dumpsters to retrieve and sort recyclable materials when materials have been erroneously placed in the incorrect receptacle. These activities result in a significant increase in the frequency of lacerations, strains and sprains. Interviewees offered several innovative solutions that would prevent this hazardous activity. First, throughout many areas of the United States, smaller, local waste management companies are developing programmes where they will receive commingled materials from construction sites and sort the recyclable materials at an offsite facility. Interviewees suggested that such a strategy may actually save the construction firm money because the cost savings associated with fewer injuries and time spent recycling on site would outweigh the estimated $100 per standard 30 yard dumpster for offsite recycling. Second, contractors could use multiple, smaller trash receptacles throughout the site. Smaller dumpsters (5–10 yards or clamshells) can be distributed around the site and then when full, they can be hoisted to the main dumpster area. Clamshells are dumpsters where the complete cover assembly is mounted on a subframe and hinged from the rear of the container so that when emptied, the whole assembly spreads open like a clamshell allowing the refuse to dump freely. Second, interviewees recommended having well-labelled dumpsters including bilingual text and images to encourage proper sorting. One interviewee also suggested initiating an industry-wide receptacle colour-coding system. Third, manufacturers of recycling bins could install a 'window' on the side of each dumpster made out of a clear polycarbonate material so that workers could actually *see* the type of material in each bin. Finally, many interviewees suggested having a specific worker who oversees waste management and monitors the recycling efforts.

Outdoor air delivery monitoring system

The construction activities required to install a permanent monitoring system for outdoor air delivery were found to have a minimal impact on worker safety. Nevertheless, workers face a slight increase in exposure to fall hazards because of the increased time spent on ladders when wiring and mounting air delivery systems. Several interviewees suggested that incorporating the monitoring equipment into the prefabrication process would eliminate these observed risks.

Construction indoor air quality management plan

The indoor air quality management plan involves maintaining covers over open ducts during construction, not running diesel equipment indoors, proper ventilation, dust mitigation, housekeeping, and protection of onsite stored materials and installed absorptive materials from moisture damage. Risks associated with these activities include increased exposure to fall hazards because of an increased time spent on ladders maintaining covers on the ductwork and overexertion. Interviewees noted that it is becoming more common for subcontractors to prefabricate 'caps' on to the ends of the ducts; however, this practice does not necessarily reduce the increased time spent on ladders because workers must still ascend and descend ladders to remove caps and work with cellophane that is easily punctured and awkward to install. Interviewees suggested changing the material used for the caps such as using a magnetic 'universal' cap. Such an investment would be a one-time cost as the caps could be used on subsequent projects. Unfortunately, such caps are not commercially available at this time. Also, several interviewees suggested offsite fabrication of longer sections of ductwork to decrease the time spent at height.

Low-emitting materials–adhesives and sealants

To achieve this credit, all adhesives and sealants must comply with South Coast Air Quality Management District Rule #1168 (e.g. the VOC (volatile organic compounds) limit of wood flooring adhesives is 100 g/L less water) (United States Green Building Council, 2009b). Though it is known that using low-emitting adhesives and sealants is a health benefit to workers and occupants, these products have been found to be of lower quality and require significant rework. This rework typically involves work at height, overhead work, and exposure to dusts from grinding and sanding. Interviewees suggested that designers and contractors research the available products and verify that they will withstand expected temperatures and are compatible with other construction materials. The use of mock-ups can often mitigate future problems with these products and enable the contractor or designer to select a different product before installation. Designers may also wish to specify natural flooring systems on a sweeper system (i.e. a floating floor with wood planks resting on resilient spacers or rubber pads) or finished concrete to eliminate the need for adhesives.

Indoor chemical and pollutant source control

Minimizing building occupant exposure to potentially hazardous particulates and chemical pollutants can be achieved by designing and constructing carpet tiles that are at least 10 feet long in entranceways and exhaust systems that are separated from spaces that could include harmful chemicals (e.g. coffee rooms or janitor's closets). Safety risks for these building elements include increased exposure to fall hazards because of overhead work and work at height when installing additional piping and ductwork. To mitigate these risks, interviewees noted that designers can implement PtD strategies including designing a floor plan with access to fresh air thereby minimizing the total amount of overhead ductwork needed. Designers may also choose to design the HVAC (heating, ventilating, and air conditioning) systems to be housed under the floor making them easier to install and maintain. During construction, a permit system should be established if workers must work on top of or within ducts.

Controllability of systems–lighting

To meet the requirements for the LEED lighting controls credit, 90% or more of the multi-occupant spaces must have occupancy sensors or timing controls. The hazards associated with these elements include more complex wiring that increases workers' exposure to electrical shock and work at height. As with many other sustainable elements, the interviewees believed that elements of the lighting controls could be prefabricated or simplified to avoid onsite electrical work where energized systems are common. Interviewees also suggested that designers locate the sensors at a reachable height from the floor, instead of the ceiling, so that electricians may construct or maintain them without working at height.

Daylight and views: daylight 75% of spaces

Daylighting requires that 75% or more of all regularly occupied spaces achieve daylight illuminance levels of a minimum of 25 footcandles and a maximum of 500 footcandles in a clear sky condition on 21 September at both 9 a.m. and 3 p.m. (United States Green Building Council, 2009b). Daylighting has been shown to be one of the most hazardous aspects of the LEED system because the credit is achieved by installing skylights, large windows and atriums, all of which involve work at height or near exposed openings. Interviewees suggested that designers include a courtyard or minimize the depth of the building to enhance daylight rather than use atriums and skylights. Additionally, increasing the ceiling height to allow light to penetrate deeper into the building, orienting the building to appropriate cardinal directions, opening floor plans, and specifying solar tubes, automated shade systems and daylight concentrators all help to achieve the requisite daylighting without subjecting construction workers to extremely high risk tasks. If skylights or atriums must be included, they should be designed with tempered glass to prevent severe lacerations; and contractors should block off all areas below overhead work, use man-lifts and scissor lifts when possible for overhead work, and ensure proper tie-offs and barriers around openings. Finally, contractors may wish to purchase commercially available equipment that is designed to aid in the handling of heavy glass.

Decision support tool

In an effort to organize the aforementioned PtD and construction safety management suggestions, a decision support tool was created using Adobe LiveCycle®. The resulting system is a portable document file (PDF) that utilizes a USGBC LEED v2.2 checklist for new construction as the user input interface. The tool was built in the same format that has been used for similar purposes, where the design elements are selected and customized reports are provided to the user by automatically accessing the full database of safety strategies (Gambatese *et al.*, 1997). In fact, the tool was developed to integrate with the output and format of Gambatese *et al.*'s (1997) 'Design for Safety Toolbox'. To operate the system the user simply selects the LEED credits that apply to their project by checking boxes next to appropriate credits. Once the credits are selected, the tool provides a risk report that summarizes the safety risks identified by Rajendran *et al.* (2009) and Fortunato *et al.* (2011). Second, in two separate reports, the tool provides a summary of the PtD and construction management strategies that decrease the safety risk associated with the selected credits. The purpose of this tool is to aid in injury prevention for high performance sustainable building construction. By quickly and easily obtaining safety information early in the project lifecycle, designers and contractors can identify and evaluate safety risks for a specific project and select the mitigation strategies that are the most effective. It should be noted that the research objective was to identify and disseminate new prevention through design and construction safety management strategies that specifically target the risks posed by high performance sustainable building components. Thus, the discussion of the development and testing of Version 1 of the tool will remain brief.

After the tool was created, it was distributed to the original interviewees. A subset of eight participants (three contractors, three designers, one subcontractor and one industry consultant) provided detailed feedback on the tool's performance and efficacy. On average, this subset of the original interview group had 24 years of experience and had completed 112 traditional projects and 31 LEED certified projects. Once the tool was distributed, participants were asked to pilot test the tool and complete a brief 13-question survey. For each question, participants were asked to rate the extent to which they agreed with a statement on a modified Likert scale where 0–2 represents 'disagree', 3–7 represents 'neutral' and 8–10 represents 'agree'. The survey included simple statements such as, 'The program is easy to use' and five open-ended questions.

The responses from the survey results are summarized in Table 2, and indicate that the tool is clear, easy to use and self-explanatory. Overall, 74 out of 104 responses fell in the 'agree' category, 27 in the 'neutral' category and only three in the 'disagree' category. The overall average rating of the program was 8.0. The lowest rating was related to the program being accepted by safety personnel as standard practice with an average of 6.5 and the highest rating was 9.0 for the graphical capabilities.

Open-ended questions focused on the quality of the output of the tool, the training needed to effectively and efficiently use the tool, the impact that the tool would have on preconstruction safety management, and potential pitfalls of the tool. All respondents believed that the easy-to-use graphical user interface and accessibility of PDF will enhance the diffusion of the tool and increase implementation when introduced to the industry. All respondents also believed that the operations of the tool are easy to understand and that the output is concise but complete. In fact, one respondent commented that,

> the provided risk reports would be very effective in properly training and discussing the hazards that are increased with the selected LEED credits for a project. Because the reports pinpoint the hazards that have increased across the industry, it would be very helpful in preventing similar injuries.

Another respondent believed that the tool will enhance preconstruction management on high performance sustainable projects and will serve as a catalyst for safety discussions during design and planning. Similarly, another respondent believed that the output

Table 2 Survey results for safety risk mitigation tool

Evaluation criteria	Disagree			Neutral					Agree			Average
	0	1	2	3	4	5	6	7	8	9	10	
The displays are easy to understand	0	0	0	0	0	0	0	2	5	1	0	7.9
The program is easy to use	0	0	0	0	0	0	0	0	5	2	1	8.5
The amount of work required to use the program is acceptable	0	0	0	0	0	0	0	2	2	1	3	8.6
This program reduces the amount of work required to do similar analysis	0	0	0	0	1	0	0	0	3	1	2	7.1
The user interface is appropriate	0	0	0	0	0	0	0	0	5	3	0	8.4
The graphical capabilities are appropriate	0	0	0	0	0	0	0	0	1	6	1	9.0
The program will be accepted by safety personnel as standard practice	0	0	1	0	0	2	1	1	0	3	0	6.5
The safety risk mitigation techniques provided by the program are quite useful for improving the current safety management programs	0	0	1	0	0	0	0	3	2	1	1	7.3
The safety risk quantification techniques provided by the program are quite useful for improving the current safety management programs	0	0	0	1	0	0	0	3	1	2	1	7.5
If the program became available for the company, it would be used for most high performance sustainable projects (or LEED projects)	0	0	1	0	0	1	0	1	1	3	1	7.4
Using the program is not time consuming	0	0	0	0	0	0	0	1	1	4	2	8.9
The program is a valuable tool for improving safety	0	0	0	0	1	0	0	3	0	2	2	7.9
I recommend continued development of the program for operational use	0	0	0	0	0	0	0	3	1	1	3	8.5

could be used to enhance job hazard analyses and toolbox talks during construction.

Several pitfalls of the system were also discussed. Two respondents believed that a brief tutorial would be required for a participant to read and interpret the results correctly and one respondent said that the tool needs to have a welcome screen with a brief description of how the results are organized. A single participant explained that though useful and effective, the program could be adjusted for better functionality and to provide more description for the output. Four of the respondents asked for more detail in the risk reports; they believed the reports would be effective in properly training and discussing the hazards that are increased with the selected LEED credits, but that a description of what the percentages on the risk reports represent would be beneficial. The most significant negative comment came from a designer who believed that this tool will be most useful to contractors since they are responsible for safety and less useful to designers. Though this response indicates a resistance to prevention through design rather than a true pitfall of the system, it is an important perspective that may be shared by other designers in the AEC industry that would limit implementation.

Limitations

The primary limitation was that the data were obtained solely through interviews with project participants and, therefore, the results are not based on empirical data. Additionally, the majority of the participants were located in Colorado at the time of the interview, which limits the external validity of the results. However, because most of the interviewees have completed projects outside this limited geographic region, the writers believe that the results can be extended to the US AEC industry. The results are also limited to the common design elements and means and methods of construction used to achieve 14 specific LEED credits described by United States Green Building Council (2009a), Rajendran *et al.* (2009) and Fortunato *et al.* (2011). As new technologies are introduced to the industry, their safety impacts and methods of managing new risks or exposures must be independently evaluated. Furthermore, the viability and utility of the decision support tool were only tested through interviews with eight industry representatives. This small number limits the external validity of the results. Thus, extensive testing with a large and diverse population of active professionals is warranted. Lastly, this inquiry did not evaluate the cost of the design and construction interventions or their impact on safety risk. Rather, the focus was on identifying potential injury prevention strategies that may be considered by practitioners and evaluated by future researchers. Therefore, some strategies may not be cost-effective or realistic for some projects.

Conclusions and recommendations

The research study aimed to identify and describe risk mitigation strategies that reduce the safety risk associated with the design and construction of high performance sustainable projects without compromising the building's performance. Data collection efforts specifically focused on methods that mitigate safety risk rather than strategies that simply transfer risk from one project participant to another. Rajendran *et al.* (2009), Fortunato *et al.* (2011) and Dewlaney *et al.* (2011) found that 14 credits increase the safety risk for the following injury types: falls to lower level, falls to the same level, overexertion, and 'other' injuries such as scrapes, lacerations, eye strain and muscle sprains. The interviews conducted with contractors and designers revealed that each of the 14 credits has at least one construction method or PtD strategy that can be used to mitigate the identified risks. This is the first known attempt to identify such strategies, which are likely to have a positive impact on worker safety and health on high performance sustainable building construction projects.

A common trend in the design suggestions was that the designer has the option to specify alternative design features or construction materials that have minimal impacts on safety risk. Since there are multiple methods to achieve the LEED credits, safety can be preserved by strategically selecting the methods used to earn each credit. Furthermore, designers have the opportunity to use different spatial layouts that remove hazardous conditions. For example, the hazards associated with indoor chemical and pollutant source control could be eliminated by ensuring that each room has openings for air flow.

Prefabrication is another PtD technique that was suggested for six of the credits. By completing work in an offsite controlled environment, risks associated with construction at height, overhead, with energized electrical systems, and in confined spaces can be reduced. It should be noted that the suggestion to prefabricate some elements was made not in an effort to transfer the risk from the contractor to vendors and subcontractors but, rather, to move high risk tasks from dynamic and complex construction sites into a controlled environment where they can be more effectively managed and controlled. Similarly, interviewees also commonly suggested that work be performed on the ground surface whenever possible thereby reducing the time that workers are exposed to work at height and near exposed edges.

Several common construction safety management strategies that go above and beyond typical methods of safety management (e.g. job hazard analyses, written safety plans, etc.) were also suggested. For example, contractors can sequence the activities on a project to prevent crowding and concurrence of incompatible tasks. Proper sequencing can also minimize exposure to dangerous equipment and hazardous materials. Additionally, purchasing and enforcing the use of specialized personal protective equipment and incorporating new technologies (e.g. specialized equipment for transporting large glass units) was also suggested for specific high risk tasks.

The writers expect that the results presented and organized into the decision support tool can be used to enhance PtD and construction safety management on high performance sustainable buildings. The results can also be integrated with the design for safety suggestions obtained and organized by Gambatese *et al.* (1997). Similarly, the specific construction safety management strategies described can be combined with general safety programme elements to create a comprehensive and effective plan that addresses common safety issues and the unique challenges of high performance sustainable building elements. Such integration will promote a holistic approach to sustainability that includes worker safety and health as suggested by Rajendran *et al.* (2009).

The writers suggest that future researchers conduct a lifecycle safety assessment that tracks and quantifies safety impacts for high performance sustainable projects and includes material and product suppliers, subcontractors, contractors, occupants and maintenance workers. The findings presented may also be used to develop hypotheses for rigorous empirical testing and longitudinal studies of safety and sustainability as injury prevention practices are implemented and tested. They can also be used as a database for testable models that facilitate cross-discipline communication and proactive safety decisions.

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