

# Safety Risk Quantification for High Performance Sustainable Building Construction

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**Abstract:** A recent study found that Leadership in Energy and Environmental Design (LEED) certified buildings have a recordable injury rate that is 9% higher than traditional, non-LEED buildings. A follow-up study showed that there are distinct aspects of the design elements and means and methods of construction used to achieve LEED certification that have negative impacts on worker safety. The research described in this paper builds on previous knowledge by quantifying the percent increase in base-level safety risk resulting from the design strategies and construction methods implemented to earn specific LEED credits. A total of 26 interviews and 11 validation interviews were conducted with designers and contractors who had completed an average of four LEED projects, 100 traditional projects, in their average of 18 years of experience in the architecture, engineering, and construction industry. The results indicate that design elements and means and methods of construction implemented to achieve 12 of the 49 LEED credits increase the frequency of injuries or exposure to known, high risk environments. The most significant impacts are a 36% increase in lacerations, strains, and sprains from recycling construction materials; a 24% increase in falls to lower level during roof work because of the installation of on-site renewable energy (e.g., PV panels); a 19% increase in eye strain when installing reflective roof membranes; and a 14% increase in exposure to harmful substances when installing innovative wastewater technologies. These results can be used to understand the safety impacts of sustainable building design, will enhance designer awareness, and help contractors to better prioritize safety resources. DOI: [10.1061/\(ASCE\)CO.1943-7862.0000504](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000504). © 2012 American Society of Civil Engineers.

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## Introduction

The U.S. Green Building Council (USGBC) was formed to promote the construction of buildings that are cost-efficient and energy-saving (USGBC 2009b). The USGBC developed a green building rating system called Leadership in Energy and Environmental Design (LEED), which was first implemented in 1998. LEED is a voluntary, consensus-based national standard that is used to certify high performance sustainable buildings. Currently, there are nine different versions of the LEED rating system. Of these, LEED for new construction is the most commonly used point system and has the following six categories: (1) Sustainable Sites, (2) Water Efficiency, (3) Energy and Atmosphere, (4) Material and Resources, (5) Indoor Environmental Quality, and (6) Innovation in Design (USGBC 2009a). Buildings are formally certified at four levels, depending on the proportion of the 69 possible credits that are achieved.

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The U.S. Green Building Council has projected that the value of green building will increase by \$60 billion over the next decade, resulting from the construction of over one million LEED certified buildings. The popularity of the LEED program has grown rapidly from a perceived decrease in negative environmental impact and monetary savings through decreased utility costs (Eicholtz et al. 2008; Fuerst et al. 2008; Miller et al. 2008). Though there are apparent benefits to the program, general contractors claim that LEED projects tend to be more complex and require additional time to complete (Schaufelberger et al. 2009). Additionally, Rajendran et al. (2009) and Fortunato et al. (2012) found that sustainable building design and construction has significant safety impacts as well. In their study of 74 projects, Rajendran et al. (2009) found that LEED certified projects had a mean recordable injury rate (RIR) of 6.12 injuries per 200,000 worker-hours while non-LEED projects had a mean RIR of 5.63. This 9% increase in RIR applies to the entire project, not just to the construction of the sustainable elements. Fortunato et al. (2012) built upon this research by conducting case studies to identify the new safety risks resulting from the design and construction strategies implemented to achieve LEED certification. The case studies revealed that a total of 12 credits increased safety risks when compared to traditional projects. For example, to achieve the LEED credit for material recycling, construction workers on several projects entered dumpsters to retrieve and sort recyclable materials. Such work was found to result in an increased frequency of lacerations, strains, and sprains. The results reported by Fortunato et al. (2012) and Rajendran et al. (2009) provide compelling evidence that sustainable high performance buildings are more dangerous to construct than their nongreen counterparts.

Though the rapid growth in LEED is exciting, it is essential for designers and constructors to identify, analyze, manage, and

respond to the increased safety risks associated with sustainable design and construction. The objective of this present research was to quantify the increase or decrease in base-level safety risk resulting from the design elements and construction means and methods implemented to achieve LEED credits. In this study, base-level risk is defined as the typical safety conditions that exist with traditional designs and construction means and methods. The influence of sustainable design and construction methods were quantified as direct multipliers (positive or negative) against base-level conditions. For example, a 20% increase in falls associated with the construction methods implemented to achieve a particular LEED credit would be defined as 20% greater than the traditional construction method (i.e., 20% greater than the base-level condition). The authors expect that this increase in knowledge is essential for identifying the highest risk design elements and construction activities and for prioritizing safety resources that must ultimately be allocated to respond to these risks.

## Literature Review

### Safety Risk Assessment

The research framework for this study was established on a strong foundation in risk quantification. The most common method of safety risk quantification involves separately measuring the following three components: (1) frequency, (2) severity, and (3) exposure. The relationship among these variables is illustrated in Eq. (1). In this relationship, frequency is the number of events per unit of time, severity is the magnitude of the potential outcome of an event, and exposure is the duration of contact with a potentially hazardous condition. This risk quantification strategy has been used as an analytical technique in several safety studies [e.g., Jannadi and Almishari (2003); Barandan and Usmen (2006); Hallowell and Gambatese (2009)]

$$\text{Safety Risk} = \text{Frequency} \times \text{Severity} \times \text{Exposure} \quad (1)$$

Quantifying frequency, severity, and exposure values can be a difficult task because data can be difficult to collect because of underreporting, poor recordkeeping, insufficient archival databases, and liability concerns with sharing incident data (Hallowell and Gambatese 2009). Data are also rarely collected for low-severity outcomes such as near misses, persistent pain, and first-aid injuries. To address this limitation, relative risks have been quantified using expert opinion surveys and interviews. Previous studies have shown that highly qualified industry professionals are capable of accurately quantifying relative safety risks for specific tasks and work environments (Hallowell and Gambatese 2010). Several researchers have used Eq. (1) and input from experienced professionals to perform comparative risk analysis for various work environments and trades. For example, Barandan and Usmen (2006) compared safety risks for various trades, and Larsson and Field (2002) and Zou and Zhang (2009) compared industry practitioner's recognition of safety risk factors to pinpoint the risk with the most impact. In the present study, a comparative risk assessment was performed by directly comparing the design and construction strategies employed to achieve individual LEED credits with the traditional building strategies identified by Fortunato et al. (2012).

### Risk Categories

To categorize the risk comparisons, the research team utilized risk classification schemes developed in previous studies. The Bureau of Labor Statistics, the Occupational Safety and Health

Administration (OSHA), and Hinze and Russell (1995) have developed and refined a construction-specific accident classification system. The 10 mutually exclusive and all-inclusive safety risk classifications described by these studies are as follows: (1) struck-by; (2) struck-against object; (3) caught-in or compressed; (4) fall to lower level; (5) fall to same level; (6) overexertion; (7) repetitive motion; (8) exposure to harmful substances; (9) transportation accidents; and (10) other. The "other" category encompasses all miscellaneous safety risks including, but not limited to: muscle sprains, eye strain, lacerations, and abrasions. During a comprehensive review of literature, the writers identified many publications that utilized this classification system (Hinze and Russell 1995; Jannadi and Almishari 2003; Zou and Zhang 2009; Hallowell and Gambatese 2010).

### Safety and LEED

The body of literature that describes the relationship between safety and LEED is extremely small despite the significant impacts discussed. As previously indicated, Fortunato et al. (2012) conducted a series of case studies on LEED projects to identify and describe the safety risks associated with the design and construction strategies implemented to achieve specific LEED credits. The study revealed that there are 12 credits that cause an increase in safety risk when compared to traditional methods. Because the present study builds directly upon this work, the salient credits, the common design and construction strategies used to achieve them, and the risks identified by Fortunato et al. (2012), Gambatese et al. (2009), and Rajendran et al. (2009) are highlighted in Table 1.

### Point of Departure and Contribution to Body of Knowledge

The objective of the present research was build upon previous knowledge by quantifying the relative percent increase or decrease in base-level safety risk for each of the LEED credits highlighted in Table 1. Though safety risks associated with LEED design and construction strategies have been previously identified as noted in the literature review, there has yet to be a formal study that quantifies their impacts on various types of safety risks during the construction process. The present study is important from both scientific and practical perspectives because it provides insight to the magnitude and relative impact of various sustainable design and construction methods on the safety environment. Practitioners can use this knowledge to enhance job hazard analyses and pretask plans, structure training and project orientations, and identify potential high-risk environments. Future researchers can build upon this study as it provides insights and data needed (1) to include safety as a component of lifecycle sustainability analyses, (2) to determine the expected risk profile for a high performance sustainable project, and (3) to evaluate future sustainable designs and construction methods. As with previous studies, LEED was used to develop the underlying framework for this study because it is clear, standardized and is the most commonly used green building certification program. Because each credit in this study was addressed individually, the results can be practically applied not only to projects attempting to achieve LEED, but to any project with sustainable designs or construction methods discussed. This is important because many local governments (e.g., City of Boulder, Colorado) have their own green certification programs that supplement LEED.

**Table 1.** Safety Hazards Associated with LEED Credits

LEED credit	Design and construction strategies employed to achieve LEED credit (USGBC 2009a)	Increased hazards when compared to traditional designs and means and methods of construction (Fortunato et al. 2012; Gambatese et al. 2009; Rajendran, Gambatese 2009)
Sustainable sites		
Storm water quality control	Reduce impervious cover, promote infiltration, and capture/treat storm water runoff from 90% of the average annual rainfall using pervious pavers, rain gardens, rainwater recycling, detention ponds, wetlands, and/or vegetated filters.	Increased exposure to on-site excavation and trenching, which may increase the number of falls and trench collapses.
Heat Island effect—roof	Specify thermoplastic polyolefin (TPO) materials that have a solar reflectance index (SRI) equal to or greater than 78 for low-sloped roofs (slope less than or equal to 2:12) or 29 for steep-slope roofs (slope greater than 2:12).	TPO membranes tend to be heavy, slippery, and “blindingly” bright when compared to ethylene propylene diene monomer (EPDM) These material properties were found to lead to slips, trips, falls to lower levels, and eye strain
Water efficiency		
Innovative wastewater technologies	Reduce the use of potable water building sewage by 50% through water-conserving fixtures or the use of nonpotable water (e.g., captured rainwater, recycled gray water, on-site treated wastewater)	These methods increase in the time that workers are installing electrical and mechanical systems at height, which increase the exposure to falls from working at height and on ladders.
Energy and atmosphere		
Optimize energy performance	Reduce energy use by optimizing efficiency of window and mechanical systems, heat exchangers, LED light fixtures, and mechanical window shades.	Such systems increase the volume of mechanical, electrical, and plumbing (MEP) work that typically occurs at height or in confined spaces and workers may be exposed to chemicals used in the on-site filtration process.
On-site renewable energy	Specify photovoltaic (PV) panels or the requisite infrastructure for future installation of PV panels.	PV panels tend to be installed on roof surfaces, which increase the time that work with heavy and unwieldy objects is performed near exposed edges.
Enhanced commissioning	Begin the commissioning process early in the design process and execute additional activities after systems performance verification has been completed.	On-site visitors who may not be familiar with the specific means and methods of construction, increasing the probability of injury for such individuals.
Materials and resources		
Construction waste management	Prevent debris from being disposed in landfills and incineration facilities by redirecting recyclable and reusable materials to nearby recycling centers	Sorting materials involves “dumpster diving” where workers enter into waste and recycling containers to retrieve and sort recyclable materials. In such an environment workers are exposed to sharp, heavy, and unstable materials and experience muscle sprains, lacerations, and abrasions at a higher rate.
Indoor environmental quality		
Outdoor air delivery monitoring	Install monitored ventilation systems that maintain optimum airflow. These systems are generally accompanied by visual alert systems that inform occupants when airflow is impeded or when allowable air quality tolerances have been violated.	Workers constructing these systems must install additional wiring and controls at height.
Construction IAQ management plan	Install covers over open ducts during construction, avoid operating diesel equipment indoors, suppress dust, and protect stored materials against moisture damage.	Tasks and constraints result in increased exposure to fall hazards because workers must ascend and descend ladders more frequently and spend additional time working at height.
Low-emitting materials—adhesives/sealants	In an effort to reduce noxious and volatile indoor air contaminants, all adhesives and sealants must have a volatile organic compound content that complies with the South Coast Air Quality Management District (SCAQMD) Rule #1168	These low-emitting adhesives and sealants have been shown to involve more rework because of quality issues. Since reworking these materials involves grinding and sanding, workers are exposed to wood dust, silica, and other known carcinogens.
Indoor chemical and pollutant source control	Specify permanent entryways that are at least 10 feet long and separate exhaust systems for each space that may include harmful chemicals (e.g., coffee rooms and janitor’s closets).	These systems involve installing additional overhead ductwork and piping that exposes workers to additional work at height with sharp and heavy materials.
Controllability of systems—lighting	75% or more of all regularly occupied spaces must have daylight luminance levels of at least 25 footcandles and a maximum of 500 footcandles. These luminance levels are achieved by specifying skylights, atriums, and curtain walls.	Not only are fall hazards increased, but the number of overexertion injuries may also increase due to work overhead.

## Research Methods

For each credit, the perceived percent increase in risk was quantified for each of the 10 injury classifications published by Hinze and Russell (1995) using interviews with experienced design and construction professionals. Structured interviews were selected as the primary research method because archival injury data do not yet exist for LEED certified projects, and it is unrealistic to obtain the requisite empirical data through case studies. Interviews also provided the research team with the opportunity to obtain perception ratings from a large number of diverse professionals who have many years of experience with sustainable design and construction. Furthermore, the research team was able to systematically obtain and record data using a reasonably exhaustive system in a relatively short time frame with the resources available.

Though most interviewees lived in Colorado, most represent national firms that complete projects throughout the United States. Ultimately, 11 architects, 13 general contractors, and two subcontractors were interviewed in the initial data collection phase. To ensure that interviewees were able to compare LEED and traditional projects with respect to safety, it was of the utmost importance that the interviewees had extensive experience with both LEED and traditional projects. On average, the 26 interviewees had each completed nearly 100 traditional projects, four LEED certified projects, and had been working in the industry for 18 years at the time of the interview.

In addition to experience, it was also important that the interviewees had an unbiased perspective on both sustainability and safety. Thus, the research team targeted the lead architect rather than the LEED coordinator for architect representatives and superintendents rather than safety managers for the general contractors. Superintendents and project managers were believed to have the most holistic perspective and were able to discuss safety impacts in the context of other project management functions (e.g., quality and productivity management).

Each interview began with a thorough description of the research objectives and the structure of the interview questions. The credits that were the focus of the study were described and the portions of the results from previous literature were reviewed. To prevent bias in the subsequent interview process, respondents were informed of the credits under investigation, the typical methods to achieve the LEED credit, and the traditional methods used, but the specific safety risks were not provided. In addition to this background material, the injury classification code system was reviewed and definitions of the frequency, severity, and exposure elements of risk were provided. For each credit, interviewees were then asked to quantify the percent increase or decrease in frequency, severity, and exposure for each of the 10 injury classifications on the base-level safety risk. The percent increase for each LEED credit was quantified relative to the traditional design elements or means and methods of construction (i.e., base-level case). For example, for LEED credit 7.2 (heat island effect for roofs), the interviewee was asked to compare thermoplastic polyolefin (TPO) roofing membranes, the prevailing method used to reduce the solar reflectance index, to traditional ethylene-propylene-diene-monomer (EPDM) rubber membranes. Interviewees were only asked to discuss and rate sustainable building elements that they had experienced on their portfolio of projects. As a result, some sustainable building elements (e.g., vegetated roofs) are not included in this study.

Interviewees were given the opportunity to provide both positive and negative ratings and were encouraged to identify additional hazards or refute the data reported from previous studies. The research team continued to conduct interviews until replication

was observed in the results as suggested by Guest et al. (2006). Replication was said to occur when interviewees no longer identified new impacts to the frequency, severity, or exposure to any of the 10 injury classifications and when the standard deviation of the response was, on average, less than 10%. Though replication was achieved after approximately 20 interviews, a total of 26 were completed because of the local industry's interest in the topic.

The interview process was carefully designed using guidance provided by Taylor et al. (2009), Eisenhardt (1989), and Yin (2003) to enhance the reliability and internal, external, and construct validity of the results. To maintain consistency in the perspectives, the interviewer asked the participants to compare the following two scenarios for a moderately sized commercial building located in Colorado: (1) a project that did not include the LEED credit being discussed, and (2) a scenario, identical to the baseline, where the only difference would be the inclusion of the means and methods implemented to earn the particular credit. The resulting data were carefully monitored and cross referenced to identify repetition and patterns to establish internal validity. Reliability and construct validity were preserved by predefining a replication strategy, conducting interviews until a predetermined criterion was achieved, and using a structured interview script that is based on previous literature. Finally, external validity was promoted by conducting interviews with 26 highly experienced professionals who, collectively, had completed projects nationwide.

## Results

Once the interviews were complete, the data were aggregated by determining the mean ratings for each frequency, severity, and exposure for each injury classification and each credit. The resulting matrix of values is reported in Table 2. This table only includes values that represent the aggregation of five or more ratings. Categories that were only rated by four or fewer interviewees (i.e., less than 20%) were omitted from the results as they were not adequately substantiated by other participants. Struck-by, struck-against, caught-in, repetitive motion, and transportation are not shown in Table 2 because they received no ratings from designers or contractors during the data collection process.

It should be noted that during the interview process, two additional credits were found to involve design elements or construction methods that increased safety risk: brownfield redevelopment and daylighting. The brownfield redevelopment credit involves workers excavating, handling, and disposing of hazardous and contaminated materials. Often, the safety risk associated with these contaminants is not fully understood prior to construction. Additionally, the daylighting credit is typically achieved by designing and constructing atriums and skylights, which may result in serious fall hazards and overhead construction tasks.

LEED credits impact the frequency and severity of and exposure to hazards in different ways. The three most significant impacts to the frequency of injuries are on-site renewable energy (10.2% increase in frequency of falls to a lower level); innovative wastewater technologies (8.8% increase in frequency of exposures to harmful substances); and on-site renewable energy (4.2% increase in falls to the same level). The three greatest increases in exposure to known hazards are a 26.2% increase in lacerations, strains, and sprains in the "other" category for construction waste management; an 18.8% increase in the "other" category; and a 12.5% increase in exposure to overexertion hazards for innovative wastewater technologies. Another significant risk involves on-site renewable energy credit that results in a 9.2% increase in exposure to falls to lower because of the increased amount of time workers must

**Table 2.** Perceived Percent Increase in Safety Risk

LEED credit	Fall to lower			Fall to same			Overexertion			Exposure—harmful substances			Other			
	F	S	E	F	S	E	F	S	E	F	S	E	F	S	E	
Brownfield redevelopment																
Storm water quality control			6.5			0.2										
Heat Island effect—roof			4.4			4.6		12.5					0.2		18.8	
Innovative wastewater technologies										8.8	4.6	0.2			4.4	
Optimize energy performance			8.8	0.4		8.1									3.8	
On-site renewable energy	10.2	2.9	9.2	4.2	1.9	2.4							1.0	1.0		
Enhanced commissioning																11.1
Construction waste management													3.8	3.8	26.2	
Outdoor air delivery monitoring				0.6	0.4	0.5							1.2		1.1	
Construction IAQ management plan			4.6			9.9									2.0	
Low-emitting materials—adhesives/sealants															12.4	
Indoor chemical and pollutant source control						6.7									5.8	
Controllability of systems—lighting	0.2		1.3	0.2		7.7										
Daylight and Views	2.3	1.3	12.0	2.3	2.3	6.7										

Note: F = Frequency (incidents per unit of time); E = Exposure (time); S = Severity (impact per injury).

spend working at heights to install the photovoltaic panels. As can be seen from Table 2, most increases in risk involve increases in exposure to known hazards and increases in frequency of injuries from new work environments. Only a few sustainable designs and construction methods make incidents more severe. For example, innovative wastewater technologies result in a 4.6% increase in severity for illness from harmful substances; construction waste management has a 3.8% increase in severity for cuts, abrasions, and sprains; and the daylighting involves a 2.3% and 1.3% increase in severity for falls to same and falls to lower level, respectively.

Though most interviewees provided positive risk ratings indicating green buildings were more dangerous to build, many participants believed that outdoor air delivery monitoring systems and the low-emitting adhesives and sealants reduce the amount of risk on-site. For example, there was a -1% impact on both frequency and severity of exposure resulting from the use of low-emitting adhesives and sealants and a construction indoor air quality management plan.

Overall, there was strong agreement in the interviewees' ratings. Though the authors originally expected a high degree of variability in the responses because risk perceptions were being collected, the average standard deviation for the collective responses after all interviews were complete was 7.6%. This value represents an acceptable level of consensus in the expert group, particularly given that the research was not iterative. Typically, first-round safety risk perceptions tend to have standard deviations between 15 and 25% (Hallowell and Gambatese 2009).

### Analysis

The research team aimed to achieve the following objectives during the data analysis: (1) identify the overall impact of each credit on the salient safety and health risk categories by combining frequency, severity, and exposure ratings using Eq. (1); (2) measure the overall impact of each credit; and (3) identify the most impacted risk categories.

**Table 3.** Increase in Risk Associated with LEED Credits

LEED credit	Falls to lower	Fall to same	Overexertion	Exposure—harmful substances	Other	Total
Brownfield redevelopment	0%	0%	0%	4%	8%	12
Storm water 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
On-site 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	

To achieve the three objectives, the data were combined for each category by multiplying the frequency, severity, and exposure values to calculate cumulative risk. As indicated in the literature review, the product of these three values corresponds to the overall safety risk. The values shown in Table 3 represent the product of these values for each credit and each salient injury classification. Because the interviewees were asked to rate the percent increase or decrease in safety risk, the cumulative risk values in any specific case will depend on the base-level risk of the tasks. As can be seen from Table 3, the most significant impacts are a 36% increase in lacerations, strains and sprains (other category) for construction waste management because of the need for material recycling; a 24% increase in falls to lower level during roof work because of the installation of on-site renewable energy (e.g., PV panels); a 19% increase in eye strain when installing TPO membranes to reduce the heat island effect; a 14% increase in exposure to harmful substances when installing innovative wastewater technologies, a 13% increase in overexertion injuries when lifting heavier materials when installing roof membranes; and a 10% increase in slips and trips (fall to the same level) when new workers are on-site to plan for indoor environmental air quality. Fortunately, the analysis also shows that there is a 1% decrease in exposure to harmful substances resulting from the specification of low-emitting materials and an indoor air quality management plan.

When the increases in risk are summed across all risk categories, the most impactful credits are those associated with reducing the heat island effect (41), installing on-site renewable energy (37), and material recycling for construction waste management (36). The values reported in Table 3 for the total impact of each credit are a unit-less measure of the relative impact of each credit, which have no mathematical application during risk analysis. When the increases in risk are summed across all credits, one can see that the risk categories that are most impacted are other (107), falls to lower levels (67), and falls to the same level (60). Again, these values are reported above and in Table 3 to measure the *relative* impacts to each risk category only and these summed values cannot be integrated into mathematical risk analysis.

## Validation

To ensure validity of the findings and minimize researcher-induced bias, 11 additional interviews were conducted by six new researchers who were intimately familiar with the research objectives and protocol. Interviews were conducted over the phone with four new designers and seven new general contractors. The exact same original interview protocol was followed closely and the same structured interview template was used for the validation to ensure that the study could be replicated and to facilitate comparisons with the original data. The interviewees averaged 13 years of industry experience and, collectively, the group had been involved in a total of 550 traditional projects and over 100 LEED certified projects. These qualifications are comparable to the original respondent group. As with the original dataset, only risk categories with ratings provided by at least 20% of the validation interviewees were reported and analyzed.

To assess the validity of the original results, the research team compared the original data set to the validation data set. As expected, there was a slight variance in the responses (< 15%); however, there was not a statistically significant difference between the original and validation data ( $p$ -value > 0.20). Furthermore, when the ranks of the ratings were compared, strong trends emerged. As was the case in the original study, the validation results showed that falls to lower, exposure to harmful substances, overexertion, and

falls to same to be four of the five highest risk categories. Additionally, the credits with the highest increases in risk were on-site renewable energy, brownfield redevelopment, daylighting and views, optimizing energy performance, and construction waste management, which was very similar to the original data.

The major discrepancies between the preliminary data and the validation data were with the “other” risk category and the brownfield redevelopment credit. In the original study, the “other” category received high ratings for increases in risk while the ratings for the “other” category in the validation were relatively low. The writers attribute this difference to the variability in the categorization of the injuries by the new researchers. The original researcher classified all strains, sprains, and lacerations in the “other” category and the validation researchers classified these injury types by their primary causes such as struck-by and caught-in. Thus, the reader should note that the data reported in the “other” category in Tables 2 and 3 include strains, sprains, and lacerations that may result from other primary causes. For example, lacerations may result during material recycling as a result of a worker being struck-by unstable materials.

In addition to the “other” category, variation was observed for the brownfield redevelopment credit. In the validation study brownfield redevelopment was highlighted as one of the credits with the highest, negative impact on construction safety. According to the validation interviews, brownfield redevelopment results in an 8.5% increase in struck-by, a 0.5% increase in struck-against, a 9.6% increase in caught-in, 16.0% increase in overexertion, a 41.1% increase in exposure to harmful substances, and a 6.9% increase in transportation injuries when compared to construction operations that typically occur on greenfield sites. These values can be compared to those reported from the original study in Table 3. The writers attribute these difference to the fact that the previous studies (e.g., Fortunato et al. 2012; Rajendran et al. 2009) upon which the primary research effort was built had not identified this credit as problematic. Consequently, the high risk activities associated with this credit were only discovered after more than half of the original interviews were complete.

Despite the minor inconsistencies reported, the data comparison showed that the validation data are reasonably consistent with the original data set with approximately 85% agreement in the ranks of the credits and risk categories. Thus, the writers believe that the results are valid and reliable.

## Limitations

The primary limitation of this research was that the data were received solely through interviews with project participants and, therefore, the ratings are perceived ratings based on expert opinions. Additionally, all interviews were completed in Colorado and the majority of the participants were located in Colorado at the time of the interview, which theoretically limits the external validity of the results to this small region of the United States. However, most of the participants have performed work outside of the state on both LEED and traditional projects and accessed this experience when answering the interview questions. Thus, the writer believes that the reader may carefully extend some of the results and conclusions to the U.S. construction industry, but that theoretical limitations should be recognized. Lastly, it should be noted that the data collected are comparative ratings and not absolute ratings of safety risk. Consequently, the research team recognizes the need for a study that quantifies base-level risk for building construction tasks so that the data presented here

can be applied to obtain absolute risk values for high performance sustainable buildings.

## Conclusions and Recommendations

The results indicate that, of the 14 LEED credits identified by Fortunato et al. (2012) and Rajendran et al. (2009) as having safety impacts, those with the greatest impact include minimizing the heat island effect, inclusion of on-site renewable energy, construction waste management, innovative wastewater technologies, and optimizing energy performance. It should be noted that the highest level of LEED certification, LEED Platinum, can be achieved without implementing any of these five credits and the lowest level of LEED certified, simply called “certified,” can be achieved without implementing any of the 14 credits highlighted in this study. Thus, in addition to developing design interventions and effective construction management methods to reduce safety risk on these projects, owners and designers should consider seeking credit for other sustainable building elements that do not increase safety risk. However, many projects do include these credits to achieve LEED certification and therefore by providing designers and general contractors with the quantification of risk associated with each credit, different companies are given the ability to select the most appropriate levels of risk for their organization. Furthermore, organizations can maintain focus during construction on those credits they have selected which have a high level of risk in order to act proactively to mitigate the associated risks.

When the data were analyzed it became apparent that there was a trend in increase of strains, sprains, and lacerations; fall hazards; and slips and trips. With the exception of falls to lower levels, these risk categories tend to involve lower severity injuries, which are not as sensational as medical case injuries, disabling injuries, and fatalities. This may explain why the increased risks have not been discussed in literature until 2009.

The results can be used for several applications. First, the increases in risk can be considered as a competing criterion along with cost, aesthetics, function, quality, and schedule when selecting credits for inclusion on a project. Second, the data presented in this paper can be used as multipliers against the base-level condition during risk-based integration of safety with schedules. Recently, Yi and Langford (2006) proposed a resource loading function for integrating safety risk data with project CPM scheduling. These data can be used in this integration to evaluate the temporal impacts of sustainable technologies on the safety system. The writers suggest reviewing Yi and Langford (2006) and Esmaili and Hallowell (2011) for more information regarding risk integration with schedules. Finally, once base-level risk data are available for building construction tasks and construction methods, these data can be used for contingency planning and lifecycle analyses.

It should be noted that the increases in risk described may be the result of the risks of the design elements themselves, ineffective construction planning or execution, or a combination. It is not the writers' intention to imply that the sustainable materials, technologies, and designs alone are responsible for the increases in risk. Managing these risks is likely to require safety considerations during design and planning, more efficient communication among designers and constructors, and more effective safety planning and management during construction. Portions of this risk may also be related to the fact that many of the design and means and methods of construction implemented to achieve LEED certification are new to the industry. If this is true, identifying risk mitigation strategies will require additional research and development.

The writers recommend that future researchers identify and catalog promising risk mitigation strategies for the 14 LEED credits highlighted. Such strategies may include Design for Safety (DfS) techniques and construction safety management methods that are specifically created to mitigate the hazards identified in recent literature. Additionally, researchers may consider quantifying the base-level risk for common building elements so that this and other comparative analyses can be translated into absolute risk values that may be more effectively integrated with design, scheduling, and financial planning. Finally, researchers may wish to conduct a lifecycle safety risk analysis on high performance sustainable buildings that also includes the safety risks of the supply chain and maintenance work.

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