Leadership in Sustainable Infrastructure
Leadership en Infrastructures Durables

Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

SUSTAINABLE SAFETY IN LABOR-INTENSIVE OPERATIONS: AN INNOVATIVE PERSPECTIVE

Nipesh Pradhananga [1], Nirajan Mani 2, and Sudip Subedi [3]
[1] Florida International University, USA
[2] Fitchburg State University, USA
[3] Florida International University, USA
[4] npradhan@fiu.edu

ABSTRACT

Maximizing safety often means operating a construction site at its highest sustainable level of safety. This sustainable level of safety is of major interest for safety managers because knowledge of such level can help them identify areas and opportunities of enhancing safety on the jobsites. Safety strategies and plans are made by the managers based on their perception of such sustainable safety. No formalized method exists to determine such level of safety for a construction site. OSHA regulations provide a general guideline but do not consider specific site conditions. The regulations also do not provide insight on what can be done beyond the mandatory requirements to maximize the level of safety and what level of safety can be attained and sustained on a site. To address this problem, this paper proposes a novel framework to identify the sustainable level of safety for a given condition at site. The method builds upon a two-way approach in which a theoretical maximum level of safety and observed level of safety govern the sustainable safety at site. The method also intends to explore the inefficiencies at the jobsite and help identify the areas of improvement. The scope of the paper is limited to labor-intensive lifting operation and relies on skeletal data collected by Kinect camera for illustration purposes. The paper outlines the method and the components of the framework and provides an illustration through a lab-based experiment. The method can potentially help the safety managers to improve their strategies based on real data collected from the actual site and set realistic goals for safety management on construction sites. The method can also be implemented to automatically analyze safety and make recommendations based on real-time data collected from the site.

Keywords: - Safety Management, Sustainable Safety, Worker Safety, Real-time Posture Tracking, Construction Operation Analysis

1. INTRODUCTION

After 1990, the significant efforts towards sustainability paradigm in the built environment resulted a notable movement on sustainable construction (Kibert 2016). Researchers and practitioners initiated to explore sustainable construction strategies (Govindan et al. 2016) in terms of the application of sustainable materials. Bringing a green building design and application of sustainable materials in the construction of infrastructure is not a complete solution to achieve sustainable construction. Existing research and construction practices in sustainable construction are focused also on achieving the targeted cost, quality, and time. But an important metric is completely missed - safety, which has significant contribution towards achieving a complete sustainable construction.

Safety is one of the most concerning metric in the construction industry because this industry has consistently suffered from the highest number of occupational injuries and fatalities among all industries (BLS 2012). Statistics shows that construction industry in US spent $10 billion to fatal and non-fatal related injuries in 2008 (NSC 2008). The goal of U.S. construction industry is to achieve zero accidents and fatalities at workplace, which is still a long way to go (Dai et al. 2012). Since past few decades, several studies have been conducted on safety performance measurement, benchmarking, and safety management (Dai et al. 2012, Fang et al. 2004) to understand what is achievable and what level of safety can be sustained on a construction site. Contractors and professionals never feel relaxed to ensure safety and avoid accidents (Zhang and Chen 2015) because there are still several weaknesses in the current safety practices (Choudhry and Zahoor 2016). It shows that complete safety management is still a challenging task for project management team. In addition, workers' safety becomes paramount because it has direct impact on productivity, profitability, and employees' morale.

Traditionally, safety management strategies are developed by the top-level management team from their experiences and available historical records. These strategies are developed to enforce and sustain a certain level of safety on the construction site. This level is usually governed by prior experience at other jobsites. Then, they usually implement these strategies to all their projects directly through a top-down approach (Mani et al., 2014). But, there are several known and unknown factors that impact safety directly and indirectly. These factors can be unique to each project and the strategies might need constant update or a strategy developed for one site might not even be applicable to other sites. A formalized approach of identifying the sustainable level of safety for a given working condition, hence, remain unresolved. This scenario demands a project-based sustainable safety management strategy and a systematic method for evaluation of absolute efficiency of safety management strategies. To fulfill this demand, this research presents a systematic framework for determining sustainable level of safety for labor-intensive operations, which is described in the following sections.

The framework leverages the emerging trend of real-time data collection and utilizes it for illustration of the framework. Although the framework can be implemented without the involvement of real-time data, practicality and feasibility of the method depend upon the degree of automatic analysis and availability of data for the operation in question.

2. SAFETY DYNAMICS: THEORETICAL BACKGROUND

The fundamental concept of this research framework is developed based upon productivity dynamics described by Son and Rojas (2011), Mani et al. (2014), and Kisi et al. (2016). They introduced a method of computing optimal productivity of an activity using Productivity Frontier and Actual Productivity as shown in Figure 1. They showed that the optimal productivity that can be achieved for a construction activity is less than the theoretical maximum productivity (Productivity Frontier) due to the System Inefficiencies and more than the observed productivity (Actual Productivity) due to the existence of Operational Inefficiencies. They validated the framework by collecting data pertaining to a labor-intensive activity.

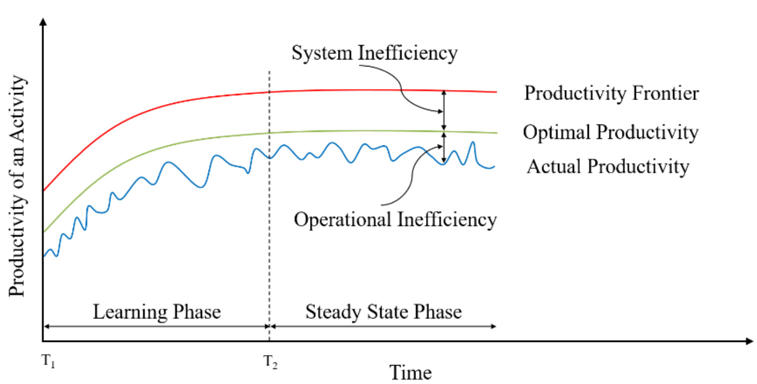

Figure 1: Productivity Dynamics (Mani et al., 2014)

Based on the concept, this paper has identified four different level of safety dynamics: (i) OSHA Standard, (ii) Observed Safety, (iii) Sustainable Safety, and (iv) Safety Frontier, as shown in Figure 2. OSHA standard is the minimum safety level required by OSHA standards for a given task and field conditions. Observed safety is the level of safety observed in the field. It can be below or above minimum level of safety required by OSHA standards. Sustainable safety is defined as the highest level of safety that can be achieved and sustained under good management and typical field conditions. Since management is a function of the performance of project managers and their project team, a good management here is considered as the best acceptable level of proficiency of project team. Typical field conditions are project site circumstances as per construction industry standard excluding typical events of natural disasters and labor-union conflicts. The safety frontier is the theoretical maximum level of safety conceivable under perfect conditions. Similar to Mani et al. (2014), perfect condition is an ideal state where all factors affecting construction workers' safety are at their most favorable levels, such as good weather, highly motivated and trained workers with flawless artisanship, optimal safe utilization of materials and equipment, ergonomically safe posture or poses of workers, no interference from other trades, no design errors, no equipment failure, no fatigue, no injury, no loss of life, and precise understanding of the design intent, among others.

Besides, unlike productivity where the optimization function is only defined by output per unit time, safety is less quantitative in terms of analysis. Numerous factors govern the safety situation of a jobsite and the operation that is being considered. A better representation of safety dynamics would be a radar chart shown in Figure 2. The radial lines represent the factors that affect worker safety on a construction site. The factors can be categorized into personal, organizational, regulatory or environmental. For each factor, the level of current safety situation can be determined by observing the site or by real-time data collection. Also, there exist a theoretical maximum level of safety that can possibly be achieved for the given situation. Based on these two, the sustainable level of safety can be calculated. The OSHA standard will give a general regulatory guideline associated with the operation. OSHA regulation is independent of the observed safety or safety frontier but is expected to be followed in the site. For the chosen set of factors, Figure 2 will give the safety status and will also provide insight on the areas of improvement at a glance.

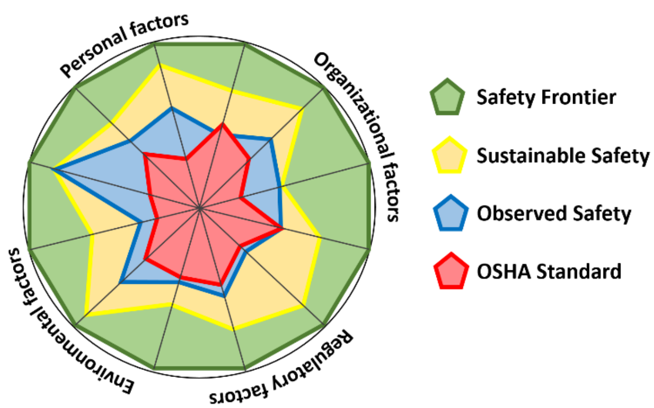

Figure 2: Radar chart with Safety Dynamics components for various factors

The elements present on the site that hinder the achievement of such maximum levels of theoretical or practical safety conditions are termed as inefficiencies. This research has identified two types of inefficiencies (system and operational) like previous researchers. System inefficiencies imply the loss in level of safety due to factors that are not under the control of a safety manager, such as environmental conditions (high humidity, cold or hot temperatures), breaks, workers' health, absenteeism driven by health or family issues, interference from other trades, design errors, behavior and intention of workers, and unsafe or uncertainty conditions due to mechanical failures of equipment, among others. Operational inefficiencies imply to the loss in level of safety due to factors that are under the control of a safety manager, such as poor sequencing of activities, inadequate and improper or unsafe utilization of equipment or tools, excessive overtime, untrained or unskilled workers, poor lighting conditions, mismatch between skills and task complexity, and carelessness of workers, among others. The illustration in the following sections is expected to further make the arguments concrete.

3. OBJECTIVES AND SCOPE

The main objective of this paper is to outline the steps required to determine the sustainable safety for a labor-intensive operation. The steps are introduced along with an example of a simple lumber lifting operation. The paper reports preliminary observations from data analysis but does not intend to validate the methodology. The methodology requires intensive experiments and rigorous computational analysis for validation. This paper introduces the concepts and methodology pertaining to only manual labor-intensive repetitive construction operations. For demonstration, this paper only discusses one factor - the posture angle of the worker, which is the angle made by the worker's torso with the vertical. This angle is chosen because it is the critical factor in lifting activities and can lead to long-term injuries (Cheng et al. 2012). Determination of some factors used in the research and practical application of the proposed approach requires data collection from a real site and is not within the scope of this paper.

4. METHODOLOGY AND ILLUSTRATION

The study envisions a two-way approach in which the sustainable safety depends upon: (i) computation of theoretical maximum level of safety (safety frontier) that can be expected for a given condition and (ii) observed level of safety on site. Figure 3 outlines the framework of this study. To determine sustainable safety, researchers introduces, safety frontier—a theoretical maximum level of safety conceivable under perfect conditions—and then determines system inefficiencies. This framework estimates the upper threshold of sustainable safety by deducting system inefficiencies from safety frontier. Subsequently, the lower threshold of sustainable level of safety is determined by deducting operational inefficiencies from the observed safety. Then, by averaging these lower and upper thresholds, sustainable safety can be determined.

This framework is illustrated by conducting a study on "lumber lifting" task. The researchers first identified different stages (actions) involved in the lumber lifting task and performed hierarchical analysis of this task. Considering body postures at different actions involved in this task, sample data was collected in the controlled indoor environment. By thorough analysis of data, this study determined the sustainable safety and discussed about various safety levels and inefficiencies.

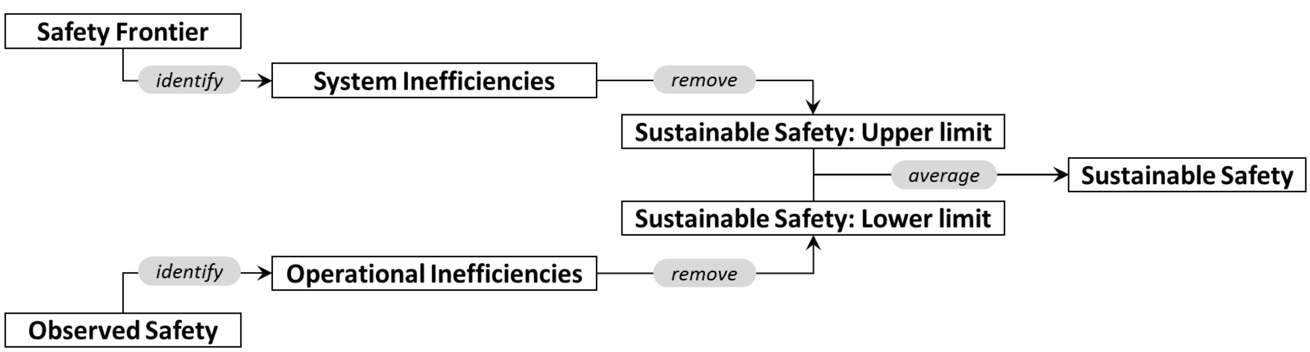

Figure 3: Framework to determine the sustainable safety

Hierarchical analysis: A construction operation can be broken down in many ways. Tucker and Guo (1993) classified construction operation into area, activity, and task. Everett and Slocum (1994) broke down construction field operations into seven hierarchical taxonomies: project, division, activity, basic task, elemental motion, orthopedics, and cell. In this study, the researchers broke down an operation into four level hierarchy of subsystems, namely activity, task, action, and movement, following Mani et al. (2016). This breakdown was adapted based on the need for detecting and analyzing workers' behavior in terms of safety and ergonomics.

This framework has been described with an example of a lumber-lifting task. Initially, this task broke down into five actions as discussed below. A brief introduction of actions involved in this task, are as follows.

i. **Approaching to lift lumber.** This is a process of walking from the standing position to the position as near to lumber as possible and getting ready to sit for lifting the lumber. This action involves various movements, such as walking, standing, and get ready to sit for lifting the lumber.

ii. **Squatting to lift lumber.** A process of squatting to lift lumber includes two different movements, such as sitting into the lifting position and backing as straight as possible from the standing position.

iii. **Sitting in safe lifting position to lift lumber.** To lift the lumber safely, it is necessary to sit in safe lifting position and then grab the lumber with safe gripping. Therefore, this action involves two movements: sitting and grabbing the lumber.

iv. **Standing up with lifted lumber.** This is the process of standing straight up with the lifted lumber from the sitting position.

v. **Hauling lumber.** This is the process of walking with the lumber to the hauling place with back as straight as possible. The hauling action involves different movements, such as walking towards destination, standing on the position, squatting to drop the lumber, dropping the lumber, and standing straight up.

4.1 Sample data collection

Sample data was collected for a lifting activity and observations were made based on the hierarchical breakdown structure discussed above. Like Ray and Teizer (2012), a Kinect v2 camera was used to collect posture angle of a subject while performing a lifting task. The subjects for this study were students who had knowledge about the OSHA safety standards and well established lifting technique. The Kinect camera was placed facing the subject and the video camera was placed perpendicular to the Kinect such that both could record the postures while lifting the lumber. The video recording was synchronized with the Kinect camera for manual visualization of whole lifting process. Two subjects were asked to lift the lumber more than 35 times each. The subjects were instructed to try different lifting postures to demonstrate all potential postures for the study (shown in Figure 4). The resulting data was time normalized to remove time factor from the analysis and focused only on safety. Figure 4 illustrates the performance of students and various actions involved in this task.

4.2 Analysis of Framework Components

The components of the framework are discussed below with respect to this hierarchical breakdown structure of a lifting task.

4.2.1 Safety frontier

The safety frontier can be attained by kinematic analysis of the human joints during lifting. The posture which has minimum effect of the lifting to the joints in consideration while lifting is the safety frontier. The safety frontier might never be attainable at construction site due to the presence of system and operational inefficiencies at site.

For this illustration, the observed data for each posture were analyzed. The postures were classified into contributory and non-contributory postures. The contributory postures (or movements or actions) are the value-adding postures, which are necessary to accomplish the task (Mani et al. 2016). Non-contributory postures, actions, or movements are those, which do not contribute to complete the task, such as worker talking with co-worker while approaching the lumber, disturbance by other workers, leaving the workstation for non-related work, standing unnecessarily at one position (idle condition), sitting too far from the lumber before grabbing it (which is unsafe), looking towards unnecessary directions and wasting time while holding or lifting the lumber. In posture level analysis, all contributory postures were identified and excluded non-contributory postures. From the identified contributory postures of all the workers, the maximum safety level postures for each movement to accomplish the "lumber lifting" task were selected and the safety frontier was determined. It should be noted that kinematic analysis was not performed for this illustration. Actual safety frontier can be expected to be different from the one obtained from this analysis. The analysis demonstrates a method that can be utilized in the absence of sophisticated computational model to perform kinematic analysis of the movement.

4.2.2 Observed safety

The observed safety is the actual level of safety while performing the task at the construction site by the workers. This could vary depending upon the nature of the work and the personal attitude of the workers. A huge variation was seen in the postural data of different lifting task. Figure 4 shows the graphical representation of this variation. The Y-axis represents the angle that the torso made with the vertical. The X- axis is time which is normalized for all the 75 lifts to eliminate the time factor from the analysis. Since the analysis is done only for safety, the participants were instructed to complete the task without considering the time taken to complete the task. That means it would not matter if the participants work slowly or fast but what only matters is if they are working safely. In real scenario, productivity will be another function to optimize while maximizing safety of the workers.

4.2.3 System and operational inefficiencies

Aksorn and Hadikusumo (2004), Serpell and Alarcon (1998), Al Haadir and Panuwatwanich (2011), and Sawacha and Naoum (1999) have identified some of the safety related factors contributing the system and operational inefficiencies that impact on safety in the site, such as group norms, inappropriate personal attitude & motivation, inappropriate supervision, lack of communication, lack of safety education and training, lack of skills, lack of management support, lack of team work, and unfavorable site conditions. The data was analyzed to determine the presence of any of these inefficiencies and the magnitude and effect of such inefficiencies were assigned based on manual judgement and on-site observations.

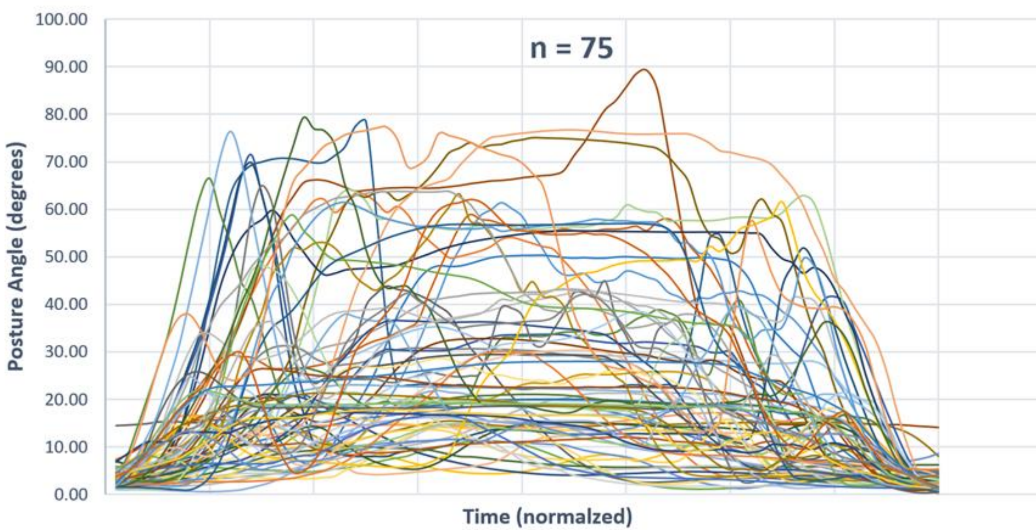

Figure 4: Postural variations during a lifting operation

4.2.4 Sustainable safety

Based upon this proposed framework (Figure 3), after deducting losses of safety level due to all system inefficiencies factors from the safety frontier, the upper threshold of the sustainable safety is obtained. The lower threshold of the sustainable safety is obtained by adding observed safety and lost safety level due to all operational inefficiencies. Then, by averaging both upper and lower level, the sustainable safety can be achieved. From the lab experiment, the angle of body postures was measured while performing this task. A graph was plotted to show the results of this study as shown in Figure 5.

4.2.5 OSHA standards

OSHA standards are not dependent on the experiment or the data. But the regulations need to be followed on construction sites. Therefore, OSHA standards has been identified as one of the component of the theoretical framework. Though OSHA doesn't set specific standard for lifting, it recommends the employers to provide safe lifting training to employees. The National Institute of Occupational Health and Safety (NIOSH) has also developed an equation to access the lifting condition. And, there is a well-established proper lifting technique followed by the OSHA in safety training. Although observed safety can be above or below OSHA standard, the sustainable safety is always expected to be higher than OSHA standard. The primary objective of this paper is not just to examine the OSHA standards, but to provide insight to the safety management team of a project about potential gap between sustainable safety in the site and existing actual observed safety (and/or OSHA standards).

4.3 Illustration of expected results

Like mentioned earlier, the actual analysis requires rigorous study and sophisticated computational analysis and will also benefit from expert advice. For illustration, a preliminary plot is shown in Figure 5. Figure 5 divides the task into five actions and shows how the analysis can be performed in a lower level hierarchical structure. The figure merely provides an approximation of what can be expected from the actual analysis and does not represent the actual result. Figure 5 only considers one factor, the postural angle of the worker. Consideration of multiple factors will yield a radar chart like the one shown in Figure 2.

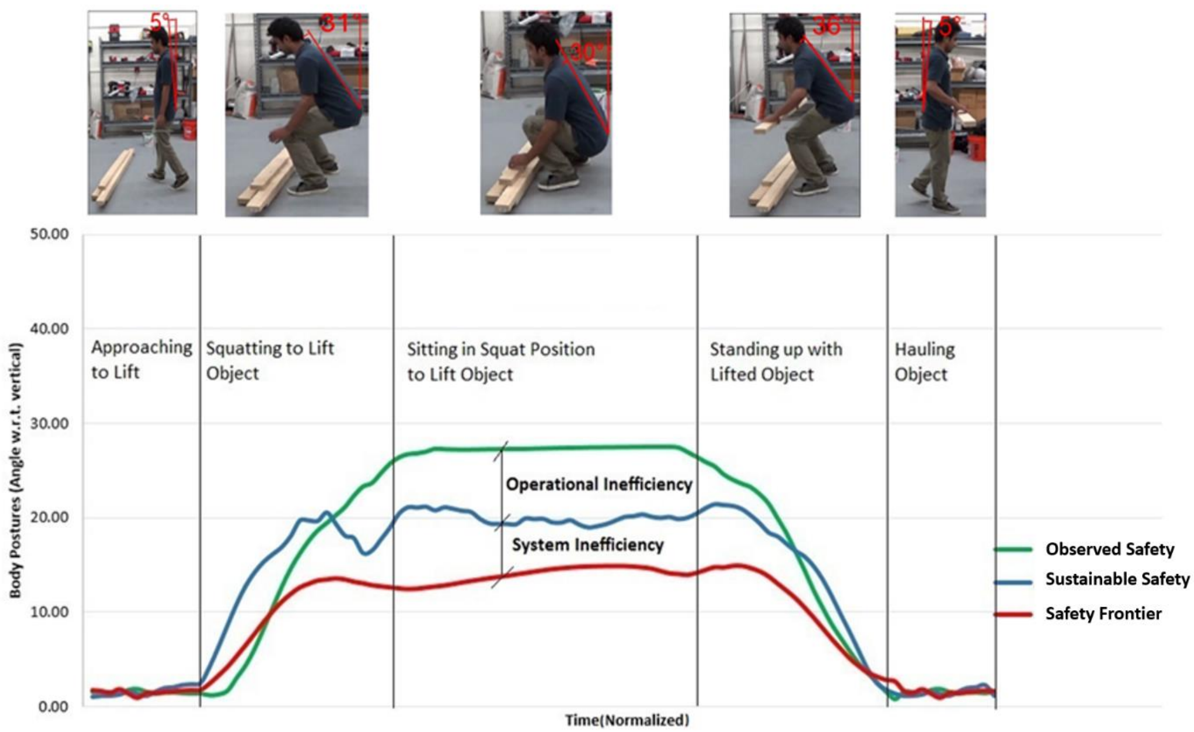

Figure 5: Safety dynamics with different safety levels for a lifting task

5. LIMITATIONS

This paper reports the preliminary study on safety dynamics and illustrates the process of determining the sustainable safety for a labor-intensive lumber lifting task. Further study is required to identify all possible system and operational inefficiencies factors. More experiments are required to analyze the safety frontier based upon contributory and non-contributory actions involved in the task.

The major benefit of such a system lies in automation and real-time data collection and analysis. It is a tedious process to be performed manually and the output from manual analysis might not yield promising results. But if the factors are identified and data is collected and analyzed automatically, this method can monitor the site continuously can constantly identify the opportunities of improving safety conditions on a jobsite.

6. CONCLUSIONS AND RECOMMENDATIONS

Historical data or past experiences help project managers in making safety strategies for a project. Such strategies might not address the unique characteristics of a site and may not reflect the actual necessity of that project. To determine the absolute efficiency of safety management strategies, it is necessary to conduct project-specific safety analysis because every project has unique characteristics. Considering such reality, this study introduces safety frontier, sustainable safety, and observed safety under the umbrella of safety dynamics and proposes a framework to estimate sustainable safety so that project manager would be able to benchmark for comparing actual observed safety level with sustainable safety to get absolute efficiency of the safety strategies. Since this is a novel concept in construction engineering and management domain, it is necessary to conduct and validate this concept through several experiments both in laboratory and field environment before it can be implemented in the construction industry. This study is a first step of analyzing the safety dynamics in this area. Thus, it takes a simple “lumber lifting” task to test its framework.

This study contributes to the body of knowledge by presenting an innovative approach of analyzing safety dynamics in the construction engineering and management domain. It also brings an innovative perspective of safety, sustainable safety, which can potentially be a significant parameter of sustainable construction. From this study, it was found that the introduction of sustainable safety can potentially provide construction managers the yardstick benchmark to compare the existing observed safety level at site and plan accordingly to get as near as possible to the maximum sustainable level of safety by identifying the operational and system inefficiencies. After identification of the inefficiencies, the out-of-control system inefficiencies factors can be screened and focus can be given on mitigation of operational inefficiencies factors.

7. REFERENCES

Aksorn, T., and Hadikusumo, B. H. W. (2008). “Critical success factors influencing safety program performance in Thai construction projects.” *Safety Science*, 46(4), 709–727.

Al Haadir, S., and Panuwatwanich, K. (2011). “Critical success factors for safety program implementation among construction companies in Saudi Arabia.” *Procedia Engineering*, 14, 148–155.

Bureau of Labor Statistics (2012). “Injuries, illnesses, and fatalities.” <http://www.bls.gov/iif/> [Online, cited November 13, 2012].

Cheng, T., Migliaccio, G. C., Teizer, J., and Gatti, U. C. (2012). “Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers.” *Journal of Computing in Civil Engineering*, *27*(3), 320-335.

Choudhry, R. and Zahoor, H. (2016). “Strengths and Weaknesses of Safety Practices to Improve Safety Performance in Construction Projects in Pakistan.” *J. Prof. Issues Eng. Educ. Pract.*, 10.1061/(ASCE)EI.1943-5541.0000292, 04016011.

Dai, J., Mulva, S., Chanmeka, A., Suk, S., and Yun, S. (2012). “Corporate safety performance benchmarking in construction.” *Proc. Construction Research Congress*, ASCE, 1430-1439.

Everett, J. G., and Slocum, A. H. (1994). “Automation and robotic opportunities: construction versus manufacture.” *J. of Constr. Eng. Manage.*, 120(2), 443-452.

Fang, D., Huang, X., and Hinze, J. (2004). “Benchmarking studies on construction safety management in China.” *J. Constr. Eng. Manage.*, ASCE, 130(3), 424-432.

Govindan, K., Shankar, K. M., and Kannan, D. (2016). Sustainable material selection for construction industry–A hybrid multi criteria decision making approach. *Renewable and Sustainable Energy Reviews*, 55, 1274-1288.

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*. John Wiley & Sons.

Kisi, K. P., Mani, N., Rojas, E. M., and Foster, E. T. (2016). “Optimal productivity in labor-intensive construction operations: Pilot study.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0001257, 04016107.

Laufer, A. and Ledbetter, W. (1986). "Assessment of Safety Performance Measures at Construction Sites." J. Constr. Eng. Manage., 10.1061/(ASCE)0733-9364(1986)112:4(530), 530-542.

Mani, N., Kisi, K. P., and Rojas, E. M. (2014). “Estimating labor productivity frontier: A pilot study.” *Proc. Construction Research Congress,* ASCE, 807-816.

Mani, N., Kisi, K. P., Rojas, E., M., & Foster, E. T. (2016). “A case study on estimating labor productivity frontier.” *Proc. 52nd ASC Annual International Conference*, Provo, Utah.

National Safety Council (2008). “Injury facts (2008 edition).” <https://www.usw12775.org/uploads/InjuryFacts08Ed.pdf,> [Online, cited July 30, 2012].

Ray, S. J., & Teizer, J. (2012). Real-time construction worker posture analysis for ergonomics training. *Advanced Engineering Informatics*, *26*(2), 439-455.

Sawacha, E., Naoum, S., and Fong, D. (1999). “Factors affecting safety performance on construction sites.” *International Journal of Project Management*, 17(5), 309–315.

Serpell, A., and Alarcón, L. F. (1998). “Construction process improvement methodology for construction projects.” *International Journal of Project Management*, 16 (4), 215–221.

Son, J., and Rojas, E. M. (2011). “Impact of optimism bias regarding organizational dynamics on project planning and control.” *J. Constr. Eng. Manage*, 137(2), 147-157.

Tucker, R. L., and Guo, S. J. (1993). “Automated needs determination using analytical hierarchical process (AHP) approach.” *Automation and Robotics in Construction X*, Houston, Elsevier, 39-46.

Zhang, W. and Chen, X. (2015). “A construction safety management system from contractors’ perspectives. *ICCREM*, 134-143.