A Framework Design for Optimizing Scaffolding Erection by Applying Mathematical Models and Virtual Simulation

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ABSTRACT

Temporary structures like scaffolding have a significant impact on the quality, safety and profitability of construction projects. Workplace Health and Safety (WHS) Authorities in Australia have found that 40% of all scaffolding projects do not comply with national safety and design standards. Thereby the practical guidance in scaffolding cases should be treated as a critical research focal point in conjunction with the general Australia-wide Occupational Safety and Health (OSH) requirements, acts and regulations. At present, limited research attention has been placed on the impact of design and validation of scaffolding erection and dismantling on OSH, especially considering working at height. To address this issue, this paper aims to develop a framework of mathematical optimization algorithms for scheming the scaffolding erection and dismantling during the planning process, and exploring on how to combine the mathematical methods to produce a good solution in a relatively short time by taking consideration of special characteristics and complications of scaffolding. The framework can resolve the relatively multi-objective optimization issues and produce the optimal solutions with higher complexity. In parallel, virtual simulation scenario to digitalize the optimized work schemes of scaffolding is also proposed within the framework. In this sense, several sources of risks in scaffolding erection and dismantling including work area design and lay-out (e.g., inadequate space for task type), the nature of equipment or tool, erection and dismantling sequences load and working environment will be comprehensively optimized and visually simulated. It is envisaged that this integrated framework that combines the mathematical algorithms and virtual representation might, for the first time, automate the most effective way of controlling the risks in the context of scaffolding practice.

INTRODUCTION

Construction concerns a wide range of activities with different natures. As highlighted in the industrial support letters, scaffolding becomes an irremovable concern to industries across oil and gas, building, and infrastructure, considering the relatively low productivity and high labor shortage and cost in this country. Poor design, planning and scheduling of scaffolding often lead to issues such as idling, rework, unnecessarily long travelling time between activities, which substantially reduce productivity. Scaffolding refers to the high framework supporting system for workers to stay and transport materials at height vertically and horizontally. In construction sector, it is normally used in exterior walls and other places of multi-storey buildings (Treloar et al. 2011). Scaffolds can also help construction workers install and maintain the peripheral safety nets. The scaffolding materials are usually chosen from bamboo, wood, metal or synthetic materials (Ahmad 2000). In addition, it is also widely used in the other industries such as advertising, transportation, civil engineering, mining and other sectors (Weiss et al. 2006).

In recent years, the universality of scaffolding application has drawn the public attention to in terms of safety. There is a high occurrence of safety accidents in scaffolding construction (Yu et al. 2013). Detecting the hazards of a site that could cause harmful effects on workers is crucial for successful safety management, because a hazardous work environment affects not only site safety but also the time and cost of the project (Ciocca et al. 2009). There are numerous factors that cause serious injury or death, for example, overturning or collapse due to scaffolding instability, falling from height during constructing and dismantling, and so on. As the causes to scaffolding accidents normally vary and are complex, if the hazardous they are incorrectly foreseen, workers will still suffer from the potential risks. On the other hand, to prevent from danger, workers might pay more attention to their workspace, slow down their operations and spend more time on preparing preventive measures. This will undermine the productivity as well. In this sense, excessive or unnecessary Occupational Safety and Health (OSH) warning may result in both delays in the schedule and impacts on the costs (Cole 2012). The study therefore aims at addressing scaffolding OSH issues by applying mathematical models as important analysis tools. The focal point is placed at optimizing scaffolding schedule for the sake of reducing the occurrence rate of scaffolding accidents.

LITERATURE REVIEW

Scaffolding OSH issues exist in its life cycle from planning, design, erection, real-time monitoring, dismantle, to relocation. Scaffolding processing could be regarded as experimental science so scaffolding OSH optimization is about the efficiency of converting inputs into outputs through the process. The inputs to the process are materials, work crew, equipment, etc. The constraints include different codes of practice, safety rules and specifications of the building work and workforce. The outputs from the process are selection of scaffolding design, erection and dismantling scheme, and their associated schedule and resource requirements, estimated cost, and so on. The emphasis should be placed on producing a series of outputs that have been optimized to inform safety design without impacting productivity. Very few research works are devoted to scaffolding optimization issue, despite its crucial importance (Rubio-Romero 2013). Given that scaffolding plays a major role in falls from height on construction sites, Saurin and Guimarães (2006; 2008) studied the ergonomic risks involved in the working postures adopted when handling loads on scaffolds. Cutlip et al. (2000) and Diering (2009) identified unsuitable approaches in scaffolding maintenance work from ergonomic perspective. Toole (2005) underlined many construction accidents, e.g., working at height, scaffolding collapse, etc. are caused by poor design before construction is initiated.

The solution is produced by Rubio et al. (2005), which is that a clear and coherent definition of safety in the context of construction equipment in temporary work should be taken into account at any stage of the project. Based on the safety codes of practice, Halperin and McCann (2004) examined 113 scaffolds cases implemented in the nationwide of the USA. They recommend a series of selections of scaffolding types for different construction sites. Regulatory changes of scaffolding design and assembly have also impact on the productivity of working on scaffolds, which has been researched by Yassin and Martonik (2004). They conducted a review study of the accident records and statistical data on officially detected failures to comply with legal requirements, and proofed compliance with the revised scaffold safety practice would provide a safer workplace and generate a significant cost saving in the construction industry. It is thus envisaged that the main measure for producing safety plans in scaffolding activities is to establish the necessary tasks to be undertaken (Saurin et al. 2004). Unfortunately, all these studies made no clarification on the coordination between safety planning and scheduling, which is also believed as a contributory factor to scaffolding accidents on construction sites (Yi and Langford 2006).

This study lays the core foundation for the design and implementation of Design Support System (DSS) for scaffolding safety process. In the proposed DSS prototype, it contains the following modules: optimization engine, Virtual Design and Construction (VDC), and onsite video monitoring. The study is developing them accordingly. Optimization engine is the core of DSS system. It encapsulates mathematical modelling and problem solving identified from above. The inputs of the engine can be collected from the properties of target scaffolding cases including safety rules derived from work in progress, material, work crew team, information plan, workspace, erection and dismantle sequence and safety rules (Bernold and Simaan 2010). After optimization, the outputs will be the optimal solutions for planning, design, erection, monitoring, dismantle, and relocation, etc. It will go through further screening processes and be demonstrated in the VDC environment with operability checking including accessibility of scaffolding components, collision detection, assembly sequence and 4D construction simulation, walkthrough, and so on.

SAFETY AND SCHEDULING OPTIMIZATION ENGINE

As the primary objective of scaffolding OSH planning is to minimize the accident risk, the risk itself must be first identified as specifically as possible. Table 1 states the risk sources that affect OSH. Various factors include human, environmental, process and so on.

Table 1. Risk identification of scaffolding engineering activities.

Scaffolding Activity	Cause of Risks		
	Source of Risks	**Conditions for Occurring Risks**	**Possible Outcomes**
Prepare Scaffolding Scheme	Managerial Personnel	1. Lack of schemes 2. Lack of technical details 3. Lack of approval	Collapse
Technical Clarification and Receipt	Managerial Personnel	1. Lack of communicate with onsite workers 2. Lack of instruction	Collapse
		1. Not sign the receipt of scaffold 2. Sign without evaluation	Collapse
Workforce	Scaffolder	1. Not meet OSH standard 2. Dismantle connective components randomly	Fall from height
		1. Not follow scheme	Collapse
		1. Violate OSH codes of practice 2. Lack of personal protective measures, e.g., not wear safety belt, helmet, etc. 3. Work in bad weather	Fall from height
Scaffolding Framework	Material	1. Scaffold bridge, scaffold floor, scaffold trestle, scaffolding bearer, scaffolding platform, stud, traversing lever, lock, etc. not meet quality standard 2. Component bending, corrosion, welding and rust issues	Collapse
	Facility	1. Scaffold is uneven and without stow-wood 2. Stud lacks base, stow-wood and traversing lever 3. No drainage design	Collapse
Preventive Measures	Facility	1. No prevention net around scaffold 2. No guardrail	Fall from height
Load	Load	1. Overloading 2. Load distribution is not uniform	Collapse
Build Scaffolding Platform	Facility Material	1. Miss scaffold floor and trestle somewhere 2. Scaffold platform not stable 3. Miss lock 4. Use materials with wrong specifications	Fall from height
Dismantle	Scaffolder	1. Not remove components in order 2. Throw components randomly 3. Stack components unstably 4. Work in bad weather	Object strike

The safety planning plus scheduling would definitely involve risk identification, evaluation, and control. Similar the study in (Yi and Langford, 2006), addressing OSH issues in scaffolding is composed of the following three steps:

1. Identifying alternatives of each activity;
2. Estimating risk associated with each alternative
3. Enhancing safety through scheduling optimization.

The traditional scheduling optimization is only considering time and cost (Zheng, 2004). Few of them have taken consideration of safety. It has been identified that scaffolding is one of the most hazardous job in construction industry. Thus, the planning of scaffolding should put more emphasis on safety rather than time and cost. To achieve this task, we first need to identify the alternatives and estimate their risks for each activity involved in scaffolding. Every activity in the schedule has its own starting and finishing time. In mathematics, we adopt an activity-on-node network representation for the graph, where there are J nodes which are labelled as $i = 1, \cdots, J$ such that each node has a lower number than its successor nodes. Assume that the activity $i, i = 1, \cdots, J$, has $a(i)$ alternatives of which alternative $j, j = 1, \cdots, a(i)$ requires t_{ij} time and c_{ij} cost. We further assume that if k and r are two alternatives for activity i such that $k < r$, then $t_{ik} < t_{ir}$ and $c_{ik} < c_{ir}$. Introduce two dummy activities 0 and $J + 1$ for the start and finish nodes, respectively, and assume that the time and cost requirements for them both zero. Now the scheduling of the scaffolding is transform to select a particular alternative for each activity. Define

$$\sigma = \{(i, j): \ i = 1, \cdots, J\}$$

where the alternative j is selected for the activity i. The overall time

$$t(\sigma) = \sum_{i=1}^{J} \sum_{j=1}^{a(i)} t_{ij} x_{ij},$$

and the cost

$$c(\sigma) = \sum_{i=1}^{J} \sum_{j=1}^{a(i)} c_{ij} x_{ij}$$

Now our task is to estimate the risk for each alternative of each activity. Let the total risk be R_{ij}. In Mol (2003), R_{ij} can be computed through the following formula:

$$R_{ij} = P_{ij} \times H_{ij} \times T_{ij} \times E_{ij},$$

where $P_{ij} = \text{process risk score}$, $H_{ij} = \text{human resources risk score}$, $T_{ij} = \text{technology risk score}$ and $E_{ij} = \text{physical environment risk score}$. The factors P_{ij}, H_{ij}, T_{ij} and E_{ij} can be estimated through the historical data. Then, the total risk $R(\sigma)$ can be computed as

$$R(\sigma) = \sum_{i=1}^{J} \sum_{j=1}^{a(i)} R_{ij} x_{ij}.$$

To represent the precedence relationships among the activities, we suppose that $s_i (s_i \geq 0)$ be the start time for activity i and $S(i)$ be the set of immediate successors of i. Now we formulate the scheduling of the scaffolding as the following multi-objective optimization problem:

$$\min \ \{t(\sigma), c(\sigma), R(\sigma)\} \tag{1}$$

subject to the following constraints:

$$\sum_{j=1}^{a(i)} x_{ij} = 1, \quad \text{for all } i = 1, \cdots, J, \tag{2}$$

$$\sum_{j=1}^{a(i)} t_{ij}x_{ij} + s_i \leq s_k, \quad \text{for all } k \in S(i),\ i = 1, \cdots, J \tag{3}$$

$$x_{ij} \in \{0,1\}, \qquad \text{for all } i = 1, \cdots, J, j = 1, \cdots, a(i), \tag{4}$$

In the above formulations, (1) is the objective function where not only time and cost are included, but also the criterion of safety is included, (2) together with (4) ensures that exactly one alternative is chosen for each activity and (3) maintains the precedence relationships among the activities. Let this optimization problem be referred to as Problem (TCR). It is obvious that Problem (TCR) is a multi-objective integer optimization problem. There are two challenges to solve such an optimization problem: multi-objective and integer constraints (Zamani 2013). Multi-objective is usually transformed to single-objective through weighting them as a single-criterion. It is also can be handled through searching the optimal solution in the Pareto front. Here we would like to adopt the former method since the weighting method offers trade-off among different criteria clearly while the last method cannot. Solving the integer optimization problem is NP hard in theory. This means that we cannot find a computational method to solve this class of optimization problems in polynomial time in general. Generally speaking, there are two kinds of methods available for solving Problem (TCR). One is exact search method and the other one is heuristic search method. Exact search method is possible only for small and sometimes medium sized problems. For big instances, heuristic search method is inevitable. Exact search methods are including branch and bound, branch and cut and cutting plane method. All these methods are heavily dependent on construction of upper and lower bounds. Comparing with exact search methods, heuristic search based methods are more fruitful. The dominated heuristic search methods are metaheuristics which are improvement heuristics, including simulated annealing method, genetic method, swarm particle method, ant colony method, shuffled leap frog algorithm, firefly algorithm and cuckoo search method. They tend to produce very good solutions in reasonable time. However, none of them is ensured to produce an optimal solution. In our optimization engine for the static scaffolding scheduling process, we would like to adopt several of these methods to solve Problem (TCR) and choose the best one among the produced solutions.

VALIDATION UNDER VDC

The optimized schemes are validated utilizing a state-of-the-art 3D game engine as visualization and simulation platforms for helping make decisions on selecting the most suitable alternatives provided by the optimization engine. For the purpose of validation, a rendering engine for 3D graphics and a high-precision physics engine for collision detection is employed (Figure 1). Models of different parts of the scaffolding are imported into the 3D game engine and rendered in real-time. A high-precision physics engine is adapted to simulate the stress state of different parts of the scaffolding. The users can navigate the virtual environment as well as construction simulation with a planned schedule to see whether the alternative achieves the design requirements (Pretzsch and Ďurský 2002). Furthermore, the object interference functions for accessibility and collision detection must be developed. The system formulates the functions of tracking data processing, storage and synchronized visual representation to users.

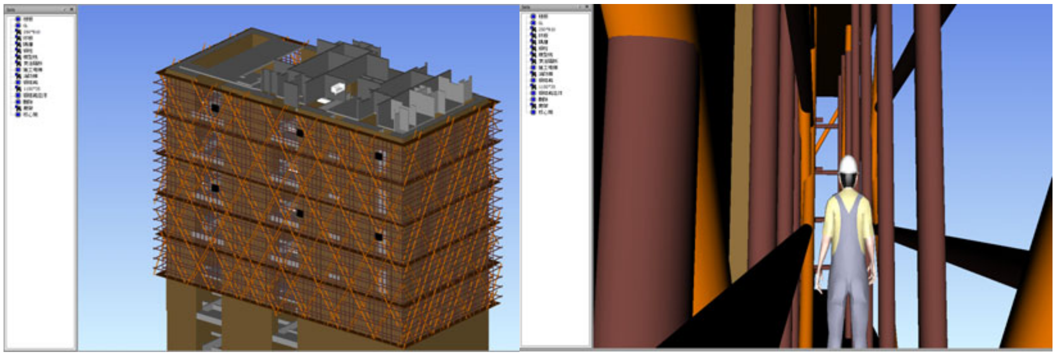

Figure 1. VDC interface.

CONCLUSION

This paper proposes the framework of scheduling with safety planning in one of the critical construction activities, scaffolding. By studying the hazardous sources in scaffolding activities, the paper enhances understanding of when and where the workforce may be vulnerable to serious accidents and the level of danger and consequences that the hazards may result in. The framework integrates the mathematical model formulates a targeted optimization by optimizing scaffolding schedule that can assist in the coordinated efforts of OSH management and control, and achieving safe production. This applicability of this framework is tested under VDC platform in the scenario of scaffolding safety planning at the scheduling phase. The combination of mathematical model and VDC platform forms the eventual DSS, which facilitates the proactive prevention of the prospective accidents and the improvement of jobsite and workforce safety without sacrificing productivity.

ACKNOWLEDGEMENT

Part of this research was supported under Australian Research Council Linkage Project scheme (project number: LP130100451).

REFERENCES

Ahmad, M. (2000). “Analysis of Calcutta bamboo for structural composite materials”. Virginia Polytechnic Institute and State University.

Bernold, L.E. and Simaan, M.A. (2010). “Managing performance in construction, Wiley.com.

Ciocca, L., De Crescenzio, F., Fantini, M., and Scotti, R. (2009). “CAD/CAM and rapid prototyped scaffold construction for bone regenerative medicine and surgical transfer of virtual planning: a pilot study.” *Computerized Medical Imaging and Graphics*, *33*(1), 58-62.

Cole, H.P. (2012). "Workplace Injury and Illness, Safety Engineering, Economics and Social Capital". *Handbook of Occupational Health and Wellness* (pp. 267-295): Springer.

Cutlip, R., Hsiao, H., Garcia, R., Becker, E. and Mayeux, A. (2000). "A comparison of different postures for scaffold end-frame disassembly". *Applied Ergonomics*, 31, pp. 507–513

Diering, M. (2009). "Ergonomic Evaluation of Scaffolding Task Interventions for Power Plant Maintenance".

Halperin, K.M. and McCann, M. (2004). "An evaluation of scaffold safety at construction sites", *Journal of Safety Research*, 35 (2), pp. 141–150

Pretzsch, H.B. and Ďurský. J. (2002). "The single tree-based stand simulator SILVA: construction, application and evaluation", *Forest ecology and management*, 162(1), 3-21.

Rubio, M.C., Menendez, A., Rubio, J. C. , and Martínez, G. (2005). "Obligations and responsibilities of civil engineering for the prevention of labor risks: References to European regulations." *J. Prof. Issues Eng. Educ. Pract.* , 131 (1), 70–75.

Rubio-Romero, J.C., Carmen Rubio Gámez, M., and Carrillo-Castrillo, J. A. (2013). :Analysis of the safety conditions of scaffolding on construction sites". *Safety Science*, 55, 160-164.

Saurin, T.A., Formoso, C. T., and Guimarães, L. B. (2004). "Safety and production: an integrated planning and control model". *Construction Management and Economics*, *22*(2), 159-169.

Saurin and Guimarães (2006). "Ergonomic assessment of suspended scaffolds". *International Journal of Industrial Ergonomics,* 36 (3), pp. 229–237

Toole, T.M. (2005). "Increasing engineers' role in construction safety: Opportunities and barriers." J. *Prof. Issues Eng. Educ. Pract.* , 131 (3), 199–207.

Treloar, G., Fay, R., Ilozor, B., and Love, P. (2001). "An analysis of the embodied energy of office buildings by height". *Facilities*, *19*(5/6), 204-214.

Weiss, J., Takhistov, P., and McClements, D. J. (2006). "Functional materials in food nanotechnology. *Journal of Food Science*, *71*(9), R107-R116.

Yassin, E. and Martonik, D. (2004). "The effectiveness of the revised scaffold safety standard in the construction industry". *Safety Science*, 42 (10), pp. 921–931

Yi, K.J. and Langford, D. (2006). "Scheduling-based risk estimation and safety planning for construction projects". *Journal of construction engineering and management*, *132*(6), 626-635.

Yu, Z.X., Li, H., Cheng, T., Qin, L.P., Wu, Z.H., and Chen, Y. (2013). "Countermeasure to Collapse Accident during Use of Fastener-Style Steel Pipe Scaffolding". *Applied Mechanics and Materials*, *357*, 2905-2908.

Zheng, D.X., Ng, S.T., and Kumaraswamy, M.M. (2004). "Applying a genetic algorithm based multiobjective approach for time-cost optimization", *Journal of Construction Engineering and Management*, 130, 168-176.

Zamani, R. (2013). "An evolutionary search procedure for optimizing time–cost performance of projects under multiple renewable resource constraints", *Computers and Industrial Engineering,* to appear.