A linear goal programming model for optimizing the usage of safety measures on construction sites

Ming-Fung Francis Siu
Department of Building and Real Estate,
Faculty of Construction and Environment,
The Hong Kong Polytechnic University, Hong Kong, China.
francis.siu@polyu.edu.hk

S. L. Tang
Faculty of Science and Technology,
University of Macau, Macau, China.
irsltang@gmail.com

Corresponding author's email address: irsltang@gmail.com

ABSTRACT

In Hong Kong, the construction safety performance was poor but has improved in the past 15 years because the Labour Department has made remarkable progress in promoting safety and health in the workplace. Through the establishment of safety legislation, enforcement of existing and new legislation, industry promotion, and staff training, the safety awareness of employers and employees has increased. For example, under the "Pay For Safety Scheme (PFSS)", the contractors are required to set aside a sum of money in their bills of quantities for implementing safety measures on site. However, the method to optimally utilize such a sum of money so the overall profit is maximized remains unaddressed. This research study proposes a linear goal programming model to determine the optimal usage of safety measures (i.e., optimally utilizing the sum of money set aside) for improving construction safety. The goals of the model are to maximize the profits of both the main contractor and the sub-contractor. The constraints denote the achievements of safety measures in the provision of safety officers, safety committee meetings, safety walks, welfare facilities, safety training, and safety auditing. This paper intends to present the framework of the model. In the future, a case study will be conducted in full scale by expanding the model using the actual collected data and available statistics, thus the optimum usage of safety measures in real practice will be determined.

KEYWORDS

Linear goal programming, optimization, safety measures, Pay For Safety Scheme, Hong Kong.

1. INTRODUCTION

In the Hong Kong construction industry, the accident rate per 1,000 workers dropped significantly from 82.5 in 2002 to 33.6 in 2017, according to the statistical data published by the Labour Department of Hong Kong (Labour Department 2017). The Labour Department has made remarkable progress in promoting safety and health in the workplace. Through the establishment of safety legislation, enforcement of existing and new legislation, industry promotion and staff training, the safety awareness of employers and employees has increased. One successful public sector initiative for improving construction safety performance is the development and implementation of "Pay For Safety Scheme (PFSS)" that was developed in 1996 (Works Branch 1996).

In Hong Kong, the traditional procurement method is commonly used as the project delivery method in the construction sector. The construction contract is usually awarded to the contractor who bids the project with the lowest price. Before the implementation of the PFSS, the sum of money paid for implementing the safety-related items was not measured and identified in the tender document. Therefore, the contractors are likely not to budget the safety measure items to maintain a low bid and hence the competitiveness of the bid. In 1996, Works Branch under the Development Bureau introduced the PFSS in government construction contracts. Under the PFSS, all payable safety items and measures related to safety management that a contractor should carry out are included in a separate bill of quantities (i.e., site safety section). This sum is approximately 2% of the contract sum. Safety measures such as safety officers, safety committee meetings, safety walks, welfare facilities, safety training, and safety auditing shall be provided. When contractors comply with each of these safety items and have been certified as satisfactorily performed, payment for these items will be made on a monthly basis (ETWB 2000).

For example, as given in Poon *et al*. (2008), a *safety officer* shall be employed for a construction site employing more than 100 employees in total to maintain workplace safety and educate workers about safety at work, according to Chapter 59Z of the Factories and Industrial Undertakings (FIU) regulation. The main duties of the safety officer are to advise the proprietor if the safety measures are adequately provided in the interest of the safety and health of persons, and to determine if there is any machinery, plant, equipment, appliance, or work process carrying on which is liable to cause the risk of bodily injury to any person. The *safety committee* shall be responsible for maintaining the safety standard at the project (site) level. The safety committee meeting is organized once per week. The safety officers of the main contractor and the safety representatives (usually of the same rank as safety officers of the main contractor) of the sub-contractor shall participate the meeting. During the meeting, the overall site safety conditions shall be reviewed; any unsafe site operational procedures shall be rectified; the site safety performance shall be reported and forecasted so as to improve safety conditions on site.

Besides, *safety walk* shall be performed once per week by the safety officers of the main contractor and sub-contractor, and sometimes together with the clerks of works. A comprehensive checklist is used during the safety walk for inspecting the job site. Regular inspections enable a review of workplace activities and the presence of any hazards in and around the site. *Welfare facilities* shall be provided for the well-being of the workers. For example, sheltered rest areas are to be provided for workers to prevent heat stroke by taking a rest; drinking water facilities are to be provided for workers in a clean and hygienic condition; shower facilities are to be provided for workers to take a shower so dust or any harmful substances can be removed from a person's body. *Safety training* shall be provided by the safety officers or trainers everyday throughout the project period. By taking this everyday training, the workers shall have a better understanding of risky conditions that their safety awareness shall be fostered. The worker shall take immediate remedial actions to eliminate any unsafe conditions and acts. Furthermore, *safety auditing* shall be conducted by a third party to identify the rooms for improvement of the safety measures used in the company. This auditing exercise is normally performed every half a year.

The merit of the PFSS scheme is to pay for those ingredients to promote the implementation of a safety management system in a contract. The quantity surveyors of the main contractor are allowed to set aside a sum of money in the bills of quantities for carrying out the safety measures on site. Usually, 2% of the contract sum shall be budgeted. Constrained by the sum of money (2% of contract sum), the contractors are granted the flexibility to price the schedule of rate of safety measures which shall be implemented on site. However, currently a main contractor prices and determines the schedules based on intuition. The analytical method to optimally utilize such a sum of money for maximizing the profit along the supply chain of sub-contractors remains unexplored.

Therefore, this research study proposes a linear goal programming model for determining the quantities/frequencies of safety measures, by fully utilizing the sum of money set aside for improving construction safety. The goals of the model are expressed to maximize the profits of both the main contractor (priority 1) and the sub-contractor (priority 2). The constraints are given to indicate the achievements (i.e., quantities/frequencies) of safety measures in the provision of safety officers, safety committee meetings, safety walks, welfare facilities, safety training, and safety auditing. In the following section, the mathematical model is proposed. Conclusion is then drawn by proposing the future research.

2. PROPOSED GOAL PROGRAMMING MODEL

In this section, a novel goal programming model is proposed to mathematically quantify the degree of achievement of applying particular construction safety measures by fully utilizing the bills (or the sum set aside) for safety measures such that the profits of the main contractor (priority 1) and the sub-contractor (priority 2) can be maximized. The mathematical model is expressed from Equation (1) to Equation (16). Equation (1) expresses the objective function, and Equation (2) through Equation (16) are the constraints (Tang 1999, Chapter 7).

Equation (1) denotes the objective function. The function maximizes the profits of both the main contractor and the sub-contractor. The main contractor's safety cost is defined as the main contractor's expense for applying the safety measures, while the sub-contractor's safety cost is defined as the sub-contractor's expense for applying the safety measures. Thus, the profit maximization can be expressed as minimizing the sum of the under-achievement of the safety costs of main contractor and that of the sub-contractor given as the variables $d^-_{\text{Safety cost (Main contractor)}}$ and $d^-_{\text{Safety cost (Sub-contractor)}}$ respectively. Notably, the parameters P_1 and P_2 correspondingly state the priorities of minimizing the safety cost associated with the main contractor and the sub-contractor.

$$\text{minimize } P_1 d^-_{\text{Safety cost (Main contractor)}} + P_2 d^-_{\text{Safety cost (Sub-contractor)}} \tag{1}$$

Equation (2) is the constraint expressing the amount of safety cost for budgeting main contractor's safety measures. Safety cost is charged by the main contractor to provide particular safety measures with particular quantities/frequencies. The provision of the safety measures includes a number of safety officers $N_{\text{Safety officers (Main contractor)}}$ at an unit rate of $C_{\text{Safety officers (Main contractor)}}$, a number of safety committee meetings $N_{\text{Safety committee meetings (Main contractor)}}$ at an unit rate of $C_{\text{Safety committee meetings (Main contractor)}}$, a number of safety walks $N_{\text{Safety walks (Main contractor)}}$ at an unit rate of $C_{\text{Safety walks (Main contractor)}}$, a number of safety welfare facilities $N_{\text{Safety welfare facilities (Main contractor)}}$ at an unit rate of $C_{\text{Safety welfare facilities (Main contractor)}}$, a number of safety training $N_{\text{Safety training}}$ at an unit rate of $C_{\text{Safety training}}$, and a number of safety audits $N_{\text{Safety audits}}$ at an unit rate of $C_{\text{Safety audits}}$. The variables $d^-_{\text{Safety cost (Main contractor)}}$ and $d^+_{\text{Safety cost (Main contractor)}}$ respectively give the under-achievement and over-achievement of main contractor's safety cost.

$$\begin{aligned}
&C_{\text{Safety officers (Main contractor)}} N_{\text{Safety officers (Main contractor)}} + \\
&C_{\text{Safety committee meetings (Main contractor)}} N_{\text{Safety committee meetings (Main contractor)}} + \\
&C_{\text{Safety walks (Main contractor)}} N_{\text{Safety walks (Main contractor)}} + \\
&C_{\text{Safety welfare facilities (Main contractor)}} N_{\text{Safety welfare facilities (Main contractor)}} + \\
&C_{\text{Safety training}} N_{\text{Safety training}} + \\
&C_{\text{Safety audits}} N_{\text{Safety audits}} + \\
&d^-_{\text{Safety cost (Main contractor)}} - d^+_{\text{Safety cost (Main contractor)}} \\
&= \text{Safety cost}_{\text{Main contractor}}
\end{aligned} \tag{2}$$

Equation (3) expresses the safety cost for budgeting sub-contractor's safety measures. Safety cost is charged by the sub-contractor to provide particular safety measures with particular quantities/frequencies. The provision of the safety measures includes a number of safety officers $N_{\text{Safety officers (Sub-contractor)}}$ at an unit rate of $C_{\text{Safety officers (Sub-contractor)}}$, a number of safety committee meetings $N_{\text{Safety committee meetings (Sub-contractor)}}$ at an unit rate of $C_{\text{Safety committee meetings (Sub-contractor)}}$, a number of safety walks $N_{\text{Safety walks (Sub-contractor)}}$ at an unit rate of $C_{\text{Safety walks (Sub-contractor)}}$, a number of safety welfare facilities $N_{\text{Safety welfare facilities (Sub-contractor)}}$ at an unit rate of $C_{\text{Safety welfare facilities (Sub-contractor)}}$. The variables $d^-_{\text{Safety cost (Sub-contractor)}}$ and $d^+_{\text{Safety cost (Sub-contractor)}}$ respectively give the under-achievement and over-achievement of sub-contractor's safety cost.

$$\begin{aligned}
&C_{\text{Safety officers (Sub-contractor)}} N_{\text{Safety officers (Sub-contractor)}} + \\
&C_{\text{Safety committee meetings (Sub-contractor)}} N_{\text{Safety committee meetings (Sub-contractor)}} + \\
&C_{\text{Safety walks (Sub-contractor)}} N_{\text{Safety walks (Sub-contractor)}} + \\
&C_{\text{Safety welfare facilities (Sub-contractor)}} N_{\text{Safety welfare facilities (Sub-contractor)}} + \\
&d^-_{\text{Safety cost (Sub-contractor)}} - d^+_{\text{Safety cost (Sub-contractor)}} \\
&= \text{Safety cost}_{\text{Sub-contractor}}
\end{aligned} \tag{3}$$

Notably, as mentioned in the previous section, the representatives of the main contractor and sub-contractor are required to participate in the safety committee meetings together at the same time. Thus, the frequencies of safety committee meetings in association with the main contractor and the sub-contractor must be the same, as denoted by Equation (4).

$$N_{\text{Safety committee meetings (Main contractor)}} - N_{\text{Safety committee meetings (Sub-contractor)}} = 0 \tag{4}$$

Similarly, the representatives of the main contractor and sub-contractor are required to participate in the safety walks together at the same time. Thus, the frequencies of safety walks in association with the main contractor and the sub-contractor must be the same, as denoted by Equation (5).

$$N_{\text{Safety walks (Main contractor)}} - N_{\text{Safety walks (Sub-contractor)}} = 0 \tag{5}$$

In addition, Equation (6) indicated that the total sum of the main contractor's safety cost and sub-contractor's safety cost is less than or equal to the 2% of the contract sum.

$$\text{Safety cost}_{\text{Main contractor}} + \text{Safety cost}_{\text{Sub-contractor}} \leq 2\% \times \text{Contract sum} \tag{6}$$

A number of the safety officers, which are hired by the main contractor and sub-contractor, are required on site. Equation (7) and Equation (8) give the constraints for determining the number of safety officers provided by the main contractor and sub-contractor respectively. In Equation (7), the number of main contractor's safety officers $N_{\text{Safety officers (Main contractor)}}$ is calculated by $\frac{N_{\text{Workers (Main contractor)}}}{100}$ where the parameter $N_{\text{Workers (Main contractor)}}$ represents the number of construction workers hired by the main contractor. That means the number of safety officers is calculated based on every 100 workers, as is stipulated in the FIU regulation. The variables $d^-_{\text{Safety officers (Main contractor)}}$ and $d^+_{\text{Safety officers (Main contractor)}}$ respectively give the under-achievement and over-achievement of the provision of main contractor's safety officers.

$$N_{\text{Safety officers (Main contractor)}} + d^{-}_{\text{Safety officers (Main contractor)}} - d^{+}_{\text{Safety officers (Main contractor)}} = \frac{N_{\text{Workers (Main contractor)}}}{100} \tag{7}$$

Similarly, as shown in Equation (8), the number of sub-contractor's safety officers $N_{\text{Safety officers (Sub-contractor)}}$ is calculated by $\frac{N_{\text{Workers (Sub-contractor)}}}{100}$, where the parameter $N_{\text{Workers (Sub-contractor)}}$ represents the number of construction workers hired by the sub-contractor. The variables $d^{-}_{\text{Safety officers (Sub-contractor)}}$ and $d^{+}_{\text{Safety officers (Sub-contractor)}}$ respectively denote the under-achievement and over-achievement of the provision of sub-contractor's safety officers.

$$N_{\text{Safety officers (Sub-contractor)}} + d^{-}_{\text{Safety officers (Sub-contractor)}} - d^{+}_{\text{Safety officers (Sub-contractor)}} = \frac{N_{\text{Workers (Sub-contractor)}}}{100} \tag{8}$$

The safety committee meetings shall be held once per week. Equation (9) constrains the number of safety committee meetings $N_{\text{Safety committee meetings (Main contractor)}}$ in association with the main contractor as $\frac{T_{\text{Project}}}{7}$, where the parameter T_{Project} represents the total project duration in calendar days. The variables $d^{-}_{\text{Safety committee meetings (Main contractor)}}$ and $d^{+}_{\text{Safety committee meetings (Main contractor)}}$ respectively denote the under-achievement and over-achievement of the safety meeting provided by the main contractor.

$$N_{\text{Safety committee meetings (Main contractor)}} + d^{-}_{\text{Safety committee meetings (Main contractor)}} - d^{+}_{\text{Safety committee meetings (Main contractor)}} = \frac{T_{\text{Project}}}{7} \tag{9}$$

Equation (10), similar to Equation (9), constrains the number of safety committee meetings $N_{\text{Safety committee meetings (Sub-contractor)}}$ in association with the sub-contractor as $\frac{T_{\text{Project}}}{7}$. The variables $d^{-}_{\text{Safety committee meetings (Sub-contractor)}}$ and $d^{+}_{\text{Safety committee meetings (Sub-contractor)}}$ respectively denote the under-achievement and over-achievement of the safety meeting provided by the sub-contractor.

$$N_{\text{Safety committee meetings (Sub-contractor)}} + d^{-}_{\text{Safety committee meetings (Sub-contractor)}} - d^{+}_{\text{Safety committee meetings (Sub-contractor)}} = \frac{T_{\text{Project}}}{7} \tag{10}$$

The main contractor shall hold the safety walks once per week. Equation (11) constrains the number of safety walks $N_{\text{Safety walks (Main contractor)}}$ as $\frac{T_{\text{Project}}}{7}$. The variables $d^{-}_{\text{Safety walks (Main contractor)}}$ and $d^{+}_{\text{Safety walks (Main contractor)}}$ respectively denote the under-achievement and over-achievement of the safety walks provided by the main contractor.

$$N_{\text{Safety walks (Main contractor)}} + d^{-}_{\text{Safety walks (Main contractor)}} - d^{+}_{\text{Safety walks (Main contractor)}} = \frac{T_{\text{Project}}}{7} \quad (11)$$

The sub-contractor shall hold the safety walks once per week. Equation (12) defines the number of safety walks $N_{\text{Safety walks (Sub-contractor)}}$ as $\frac{T_{\text{Project}}}{7}$. The variables $d^{-}_{\text{Safety walks (Sub-contractor)}}$ and $d^{+}_{\text{Safety walks (Sub-contractor)}}$ respectively represent the under-achievement and over-achievement of the safety walks provision.

$$N_{\text{Safety walks (Sub-contractor)}} + d^{-}_{\text{Safety walks (Sub-contractor)}} - d^{+}_{\text{Safety walks (Sub-contractor)}} = \frac{T_{\text{Project}}}{7} \quad (12)$$

The safety facilities shall be provided by the main contractor every day. Equation (13) calculates the number of safety welfare facilitates $N_{\text{Safety welfare facilities (Main contractor)}}$ as T_{Project}. The variables $d^{-}_{\text{Safety welfare facilities (Main contractor)}}$ and $d^{+}_{\text{Safety welfare facilities (Main contractor)}}$ respectively denote the under-achievement and over-achievement of the main contractor's facility provision.

$$N_{\text{Safety welfare facilities (Main contractor)}} + d^{-}_{\text{Safety welfare facilities (Main contractor)}} - d^{+}_{\text{Safety welfare facilities (Main contractor)}} = T_{\text{Project}} \quad (13)$$

Similarly, the safety facilities shall be provided by the sub-contractor every day. Equation (14) calculates the number of safety welfare facilities $N_{\text{Safety welfare facilities (Sub-contractor)}}$ as T_{Project}. The variables $d^{-}_{\text{Safety welfare facilities (Sub-contractor)}}$ and $d^{+}_{\text{Safety welfare facilities (Sub-contractor)}}$ denote the under-achievement and over-achievement of the sub-contractor's facility provision respectively.

$$N_{\text{Safety welfare facilities (Sub-contractor)}} + d^{-}_{\text{Safety welfare facilities (Sub-contractor)}} - d^{+}_{\text{Safety welfare facilities (Sub-contractor)}} = T_{\text{Project}} \quad (14)$$

Likewise, the safety training shall be provided every day. Equation (15) calculates the number of safety training $N_{\text{Safety training}}$ provided by the main contractor's safety officer as T_{Project}. The variables $d^{-}_{\text{Safety training}}$ and $d^{+}_{\text{Safety training}}$ denote the under-achievement and over-achievement of the safety training provision respectively. Usually sub-contractors do not provide safety training.

$$N_{\text{Safety training}} + d^{-}_{\text{Safety training}} - d^{+}_{\text{Safety training}} = T_{\text{Project}} \quad (15)$$

Lastly, the safety audits shall be conducted every half a year. As shown in Equation (16), the number of safety audits of the safety management system is indicated as $N_{\text{Safety audit}}$. It is calculated as the total project duration divided by 182 days. The variables $d^{-}_{\text{Safety audit}}$ and $d^{+}_{\text{Safety audit}}$ denote the under-achievement and over-achievement of the safety audits. Usually, sub-contractors do not conduct safety audits.

$$N_{\text{Safety audits}} + d^{-}_{\text{Safety audits}} - d^{+}_{\text{Safety audits}} = \frac{T_{\text{Project}}}{182} \quad (16)$$

Based on the above mathematical model, the optimum number (quantities/frequencies) of safety measures can be determined. As such, the sum of money set aside for improving construction safety performance can be effectively utilized by maximizing the total profit of both the main contractor and the sub-contractor.

3. CONCLUSIONS AND FUTURE RESEARCH

This research contributes to the existing body of knowledge by proposing a goal programming model to mathematically determine the optimal number (quantities/frequencies) of safety measures, by fully utilizing a sum of money which is budgeted for the main contractor and sub-contractor to provide the required safety measures on construction sites under the “Pay For Safety Scheme (PFSS)” initiated by the Hong Kong Government.

The objective function of the proposed goal programming model is to minimize the under-achievements of safety costs of the main contractor and the sub-contractor while meeting the quantities/frequency requirement of applying particular safety measures as specified in PFSS. As such, the overall profit along the supply chain of contractors can be maximized. The constraints denote the achievements of the main contractor’s safety measures in the provision of safety officers, safety committee meetings, safety walks, welfare facilities, safety training, and safety auditing, along with the achievements of the sub-contractor’s safety measures in the provision of safety officers, safety committee meetings, safety walks, and welfare facilities. If there are more than one sub-contractor (sub-contractor 1 with priority 2), we can add to the model the second sub-contractor (sub-contractor 2 with priority 3), and so on.

A computer programme for the use of solving the goal programming model can be attained by using mathematical solvers such as Matlab, Cplex, or simply Excel Solver (if you have the Excel software on your computer, you will be able to solve the goal programming model). The inputs of the programme are the unit costs of the respective safety measures provided by the main contractor and sub-contractor, along with the amount of contract sum, the total number of workers on site and the duration of the contract. These quantitative values are used for solving the mathematical model. The outputs of the programme are the optimal quantities/frequencies of particular safety measures that shall be applied on site. In the future, a case study will be conducted in full scale by expanding the model using the actual collected data and available statistics, thus the optimum usage of safety measures in real practice will be determined.

4. REFERENCES

1. Environment, Transport and Works Bureau (ETWB) (2000). *Chapter 12—Pay for safety scheme*. Hong Kong: Environment, Transport and Works Bureau, Hong Kong SAR government (Revision Ref. No. R9, C12-P01, Version November 2000).

2. Labour Department (2017). *Summary of occupational safety and health statistics—1st three quarters of 2017*. The Commissioner for labour, Labour Department, 16/F, Harbour Building, 38 Pier Road, Central, Hong Kong.

3. Poon, S. W., Tang, S. L., and Wong, F. K. W. (2008) *Management and economics of construction safety in Hong Kong*. Hong Kong University Press, Hong Kong.

4. Tang, S.L. (1999) *Linear optimization in applications*. Hong Kong University Press, Hong Kong.

5. Works Branch (1996). *Technical circular No. 4/96: Pay for safety scheme (PFSS)*. Government secretarist, Hong Kong, March.