Minimizing Project Cost by Integrating Subcontractor Selection Decisions with Scheduling

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Abstract. Subcontracting has been a worldwide practice in the construction industry. It enables the construction enterprises to focus on their core competences and, at the same time, it makes complex project possible to be delivered. Since general contractors bear full responsibility for the works carried out by their subcontractors, it is their task and their risk to select a right subcontractor for a particular work. Although subcontractor management has been admitted to significantly affect the construction project’s performance, current practices and past research deal with subcontractor management and scheduling separately. The proposed model aims to support subcontracting decisions by integrating subcontractor selection with scheduling to enable the general contractor to select the optimal combination of subcontractors and own crews for all work packages of the project. The model allows for the interactions between the subcontractors and their impacts on the overall project performance in terms of cost and, indirectly, time and quality. The model is intended to be used at the general contractor’s bid preparation stage. The authors claim that the subcontracting decisions should be taken in a two-stage process. The first stage is a prequalification – provision of a short list of capable and reliable subcontractors; this stage is not the focus of the paper. The resulting pool of available resources is divided into two subsets: subcontractors, and general contractor’s in-house crews. Once it has been defined, the next stage is to assign them to the work packages that, bound by fixed precedence constraints, form the project’s network diagram. Each package is possible to be delivered by the general contractor’s crew or some of the potential subcontractors, at a specific time and cost. Particular crews and subcontractors can be contracted more than one package, but not at the same time. Other constraints include the predefined project completion date (the project is not allowed to take longer) and maximum total value of subcontracted work. The problem is modelled as a mixed binary linear program that minimizes project cost. It can be solved using universal solvers (e.g. LINGO, AIMMS, CPLEX, MATLAB and Optimization Toolbox, etc.). However, developing a dedicated decision-support tool would facilitate practical applications. To illustrate the idea of the model, the authors present a numerical example to find the optimal set of resources allocated to a project.

1. Introduction

Construction is specifically prone to business cycles in the economy. Maintaining production capacities (that mostly means skilled workforce) on a fixed level regardless of the number and type of orders in the market is not possible. Therefore, contractors tend to find a market niche and specialize in certain trade or type of service, accepting the role of subcontractors, or strive to excel in bringing together specialized contractors to deliver complex projects - and act as general contractors or construction
managers. This approach of focusing on core competencies to lower operating costs, usually at the expense of the single contractors’ capacity, is observed worldwide [1], though it becomes criticized for exploitation of workforce [and subcontractors and promoting adversarial relationships [2, 3, 4, 5], causing management problems to the detriment of product quality [6], or facilitating fraud [7].

Subcontracting of works has to be agreed with the client. The client (according to public procurement law in EU countries) is entitled to require that the general contractor’s bid contains information on parts of the order the contractor intends to subcontract, or a list of potential subcontractors [5, 6]. Therefore, the contractor often has to decide on subcontracting already at the stage of bid preparation. The general contractor relies on the bid prices submitted by the subcontractors to estimate the final bid sum for the project. The decision made at this stage also influences the project’s schedule and duration.

The subcontractors’ selection, due to its complexity, is usually conducted on the basis of the management’s experience and intuition. It is therefore necessary to develop methods supporting decisions in the field of subcontractors’ selection and project scheduling under limited availability of own resources and the necessity of cooperation with subcontractors in project execution.

As types and sizes of subcontracting firms are diverse, it is not certain if a generic set of evaluation criteria can be applied universally [9, 10]. The general contractor’s management need to rate the competitors considering their bids and several factors related to the specific project, to the managerial and technical skills of the potential subcontractors. For instance, these factors may include the quality of production, efficiency, employment of qualified staff and crew, reputation of the company, accessibility, records of timely completion of contracts, etc. [11], [12].

In the literature, some quantitative models have been developed to aid general contractor management in dealing with the subcontractors’ rating problem. Most of them base on the multi-criteria utility theory. Albino and Garavelli [13] proposed using the neural network to support management in a subcontractor rating. Arslan et al. [11] worked out an evaluation system called WEBSES by which the subcontractors can be evaluated based on a combined criterion including cost, quality, time and adequacy as the main criteria, constructed within the Internet-based environment. Nonetheless, the existing methods do not consider directly the influence of subcontractor selection on the project’s duration.

Selecting the most appropriate subcontractors for relevant works influences the duration, cost and economic efficiency of the project. Therefore, Jaskowski [14] proposed a metaheuristic approach to facilitate the problem of subcontracting (whether yes or not) and subcontractors’ selection based the criteria crucial for the project’s efficiency and the general contractor's objectives (i.e. minimizing the project’s duration and cost, and keeping subcontracting to a minimum – if the general contractor is interested in making full use of their own resources). An evolutionary algorithm was adapted for solving the triple-criteria schedule optimization problem in deterministic conditions.

The decision whether to subcontract or not as well as decisions on subcontractor selection should be based on price and non-price criteria (time, quality) crucial for the overall project’s performance in terms of its duration, cost and quality of works. Polat et al. [15] used a genetic algorithm to facilitate the process of subcontractors’ selection considering these criteria, but not directly addressing the possibility to allocating the general contractor’s own crews. Thus, this approach can be used after the decision to subcontract is made.

The authors maintain that a two-stage framework should be applied to facilitate subcontracting decisions. The first stage consists in prequalification of subcontractors, but is not the object of this paper can be supported with existing methods commonly used in construction for contractors’ evaluation, and which are not developed in the paper. The second stage enables appropriate subcontractors’ selection – identified previously as reliable and satisfying quality demands – and scheduling of their work considering general contractor resources and project durations limits. A mathematical model of the problem is presented in the next section.
2. Mathematical formulation of the contractor selection and scheduling problem

The construction project is modelled as an activity-on-node network. Precedence relations between activities are modelled by a graph \( G = (V, E) \), directed and acyclic, with a single initial node and a single final node, where \( V = \{0, 1, 2, ..., n\} \) is a set of activities (construction processes), and the arcs \( E \subseteq V \times V \) represent precedence relations between the activities.

\( R \) is the set of resources available to the project. It comprises two disjunctive subsets, namely \( RGC \) – the subset of the general contractor’s (GC’s) crews, and \( RSC \) – the subset of subcontractors. For each activity \( j \in V \), a set \( R_j \subseteq R \) of resources able to complete it is defined. For each resource \( r \in R_j \), the following parameters are to be determined on the basis of the GC’s calculations and subcontractor bids:

\[ t_{j,r} \in \mathbb{N} \quad \text{duration of the activity } j \in V \quad \text{and} \quad k_{j,r} \in \mathbb{R}^+ \quad \text{cost of the activity } j \in V. \]

The variables \( s_j, \forall j \in V \), stand for activities’ start times.

A decision which resource (a particular GC’s crew or a subcontractor) is allocated to conduct a particular activity is modelled by means of a binary variable \( x_{j,r} \in \{0,1\} \). The variable assumes value of 1 if the activity \( j \in V \) is to be executed by the resource \( r \); otherwise, it equals 0.

Some resources can be allocated to a number of processes, but these processes cannot be concurrent. Therefore, each resource \( r \in R \) is assigned a set of pairs of processes \( J_r \subseteq V \times V \), \((u,v) \in J_r \iff r \in R_u \land r \in R_v \land u < v\); activities \( u \) and \( v \) cannot be scheduled in the same path of the project network. If a resource is assigned to a pair of processes \( (u,v) \in J_r \), \( x_{u,r} = 1 \land x_{v,r} = 1 \) these processes cannot run at the same time, but have to be completed in sequence. The sequence is modelled by means of binary variables: \( y_{u,v} \in \{0,1\} \), defined for \( \forall (u,v) \in J_r \) and for \( \forall r \in R \). The variable \( y_{u,v} \) equals 1 if activity \( u \) is to be completed before activity \( v \); if not, it equals 0.

The decision making process is aimed at selecting options of resource assignment and scheduling their work in such a way that the total cost \( K \) of a project is minimal and the project’s duration does not exceed the time of completion, \( T \). Moreover, the cost of subcontracted works cannot be greater than a predefined limit, \( K_{SC} \). The mathematical model of this problem is described as follows:

\[
\min K = \sum_{j \in V} \sum_{r \in R_j} k_{j,r} \cdot x_{j,r} \quad (1)
\]

\[
D_i = \sum_{r \in R_i} t_{i,r} \cdot x_{i,r}, \quad \forall i \in V \quad (2)
\]

\[
\sum_{r \in R_j} x_{j,r} = 1, \quad \forall j \in V \quad (3)
\]

\[
s_0 = 0 \quad (4)
\]

\[
s_i + D_i \leq s_j, \quad \forall (i,j) \in E \quad (5)
\]

\[
s_u + D_u \leq s_v + M \cdot (1 - y_{u,v}) + M \cdot (2 - x_{u,r} - x_{v,r}), \quad \forall (u,v) \in J_r, \forall r \in R \quad (6)
\]

\[
s_v + D_v \leq s_u + M \cdot y_{u,v} + M \cdot (2 - x_{u,r} - x_{v,r}), \quad \forall (u,v) \in J_r, \forall r \in R \quad (7)
\]

\[
s_i + D_i \leq T \quad (8)
\]

\[
\sum_{j \in V} \sum_{r \in R_j \cap R_{GC}} k_{j,r} \cdot x_{j,r} \leq K_{SC} \quad (9)
\]

\[
s_j \geq 0, \quad \forall j \in V \quad (10)
\]
The objective function (1) minimizes the total project cost. Equation (2) determines duration $D_i$ of an activity $i$ – it has been introduced as an auxiliary formula to simplify the formulas and (5) – (8).

According to condition (3), each activity can be executed only by one resource, selected from the available resources. The first activity of the project (i.e. an activity that has no predecessors) starts at the moment of 0 (4). According to the condition (8), the project duration is not allowed to exceed the time for completion, and the cost of subcontracted works should be lower than $K_{SC}$ – condition (9). Condition (5) defines the successors’ start dates according to the “no earlier than” constraint.

Formulas (6) and (7) define start times of processes $R_{u,v}$. If these processes are not to be executed by the same resource $r$, ($x_{u,v} \cdot x_{v,r} = 0$), both these conditions are automatically met ($M$ is an arbitrarily assumed, sufficiently large constant), and the processes may run concurrently. If the same resource $r$ is assigned to them ($x_{u,v} = 1 \wedge x_{v,r} = 1$), and if the variable $y_{u,v}$ assumes the value of 1, then, in accordance with condition (6), the process $v$ is allowed to start only after process $u$ has been completed; in this case, condition (7) is automatically fulfilled. If variable $y_{u,v}$ equals 0, then process $v$ must be completed before $u$ has been started – according to condition (7) and with condition (6) met automatically.

3. Application of the model

To illustrate the proposed approach to selecting subcontractors and to scheduling their work, it was applied for optimizing resource allocation in a project that consisted in building the facilities of a logistics hub: a high storage warehouse with office facilities, an office building, and a fire pump house with a water reservoir. The project was to be delivered by a general contractor (GC) who disposed of their own workforce, but considered subcontracting of at least some works.

The graph of technological precedence relationships between the activities (work packages) is presented in Figure 1.

Table 1 lists the bids for work packages presented by potential subcontractors and/or the time and cost of packages if to be completed by GC’s crews. Some subcontractors offered to deliver a number of work packages. It was assumed that the project was not allowed to take longer than $T = 150$ days, whereas the cost of subcontracted work should not exceed $K_{SC} = EUR 463,000$.

Table 2 lists the elements of non-empty sets ($J_r$) of pairs of processes that may be entrusted to the same contractor $r$ and that are not located in the same path in the network.
Table 1a. Bids for the Warehouse work packages no. 1-5

| No. | Work package    | Potential subs / GC’s crews | Activity duration, days | Activity cost, EUR 1000 |
|-----|----------------|----------------------------|-------------------------|-------------------------|
| 1   | Earthworks     | A 20                       | 90                      |
|     |                | B 18                       | 110                     |
|     |                | GC-1 17                    | 100                     |
|     |                | C 25                       | 100                     |
| 2   | Foundation     | D 20                       | 120                     |
|     |                | GC-2 20                    | 110                     |
|     |                | C 45                       | 150                     |
| 3   | RC frame       | D 40                       | 160                     |
|     |                | GC-2 42                    | 155                     |
|     |                | E 42                       | 300                     |
| 4   | Structural steelwork | F 40                  | 330                     |
|     |                | GC-3 40                    | 310                     |
|     |                | G 35                       | 250                     |
| 5   | Roof           | H 33                       | 250                     |
|     |                | I 30                       | 270                     |

Table 1b. Bids for the Office Building work packages no. 6-9.

| 6   | Earthworks     | A 12                       | 50                      |
|     |                | B 10                       | 55                      |
|     |                | GC-1 11                    | 52                      |
|     |                | C 15                       | 49                      |
| 7   | Foundation     | D 12                       | 55                      |
|     |                | GC-2 14                    | 50                      |
|     |                | C 25                       | 70                      |
| 8   | RC frame and walls | D 30                  | 65                      |
|     |                | GC-2 33                    | 72                      |
|     |                | G 19                       | 100                     |
| 9   | Roof slab      | H 15                       | 100                     |
|     |                | I 17                       | 90                      |

Table 1c. Bids for the Pump House & Reservoir work packages no. 10-13.

| 10  | Earthworks     | A 10                       | 35                      |
|     |                | B 9                        | 40                      |
|     |                | GC-1 8                     | 38                      |
|     |                | C 7                        | 33                      |
| 11  | Foundation     | D 7                        | 38                      |
|     |                | GC-2 6                     | 35                      |
|     |                | C 12                       | 50                      |
| 12  | RC frame       | D 14                       | 52                      |
|     |                | GC-2 10                    | 53                      |
|     |                | G 10                       | 60                      |
| 13  | Roof           | H 12                       | 58                      |
|     |                | I 8                        | 55                      |

The solution of the mathematical model based on the above input was calculated by means of LINGO 14.0 Optimization Modeling Software by Lingo Systems Inc. The project schedule for the optimal solution (with the minimal project cost of EUR 1,400,000) is presented in Figure 2. In this solution, only four work packages (5, 9, 10 and 13) are subcontracted.
Table 2. Elements of non-empty sets J

| Subcontractor / GC’s crew r | (u, v) ∈ Jr |
|-----------------------------|-------------|
| A (1, 6); (1, 10); (6;10)   |             |
| B (1, 6); (1, 10); (6;10)   |             |
| C (2, 7); (2, 8); (2, 11); (2, 12); (3, 7); (3, 8); (3, 11); (3, 12); (7, 11); (7, 12); (8, 11); (8, 12) |             |
| D (2, 7); (2, 8); (2, 11); (2, 12); (3, 7); (3, 8); (3, 11); (3, 12); (7, 11); (7, 12); (8, 11); (8, 12) |             |
| G (5, 9); (5, 13); (9, 13)  |             |
| H (5, 9); (5, 13); (9, 13)  |             |
| I (5, 9); (5, 13); (9, 13)  |             |
| GC-1 (1, 6); (1, 10); (6;10)|             |
| GC-2 (2, 7); (2, 8); (2, 11); (2, 12); (3, 7); (3, 8); (3, 11); (3, 12); (7, 11); (7, 12); (8, 11); (8, 12) |             |

The model facilitates assessing the impact of the constraints of the project’s time for completion and the value of subcontracted works on the selection of resources and resulting project time and cost. Referring to the illustrative example: if the assumptions on maximum allowable project duration and maximum value of subcontracted work were ignored, the lowest project cost would be EUR 1,317,000. In this case, the project would take 194 days, and the GC’s crews would not be used at all. If there were no constraints on the value of subcontracted work, the shortest possible duration of the project would be 147 days, but the project cost would grow to EUR 1,411,000, with the subcontracted works of EUR 765,000.

4. Conclusions
Subcontracting is a common practice in the construction industry. Since general contractors are responsible to the owners for the works carried out by the subcontractors, they have to select them and coordinate their works using reliable methods that support optimal decision making. Choosing the right subcontractor for the right job influences the quality of work as well as the construction progress and cost.

Although subcontractor management has been recognized to significantly affect a construction project’s performance, current practices and past research deal with subcontractor management and scheduling separately. The proposed framework to support subcontracting decisions – integrating subcontractor rating and scheduling – enable the general contractor to select the optimal subcontractor and own crew combination for all work packages of the project, by considering the interactions between
the subcontractors and their impacts on the overall project performance in terms of cost and time. It enables the general contractor to analyse subcontractor bids not only in terms of cost, but also in the aspect of time. This expands the set of subcontractor’s bid assessment criteria, providing them with opportunity to compete not only with price, but also with completion time.

Naturally, the proposed approach is a far going simplification – the model is deterministic and assumes that the complete input from all subcontractors is available as the GC prepares the proposal.

The presented mathematical model of the subcontractors’ selection and the scheduling problem can be solved using widely available solvers (e.g. LINGO, AIMMS, CPLEX, MATLAB and Optimization Toolbox, etc.). However, it is recommended to develop a solving procedure and implement it using dedicated decision-support software.

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